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Proposal of "open-loop" tracking interferometer for machine tool volumetric error measurement

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The tracking interferometer, or the laser tracker, is a laser interferometer with a mechanism to control the laser beam direction to follow a retroreflector ("target"). Applying the multilateration principle, the target's three-dimensional position is measured. This paper proposes a novel concept of "open-loop" tracking interferometer, where the laser beam is controlled toward the command target position. Its advantage is in the elimination of the automated tracking mechanism, which may significantly reduce its manufacturing cost. The paper's emphasis is on analytical evaluation of its measurement uncertainty, introduced by the elimination of automated tracking mechanism. A prototype "open-loop" tracking interferometer is developed, and its measuring performance is experimentally investigated.

Metrology, Machine tool, Volumetric accuracy.

1. Introduction

Recently revised ISO 230-1 [1] defines the term "volumetric accuracy" of machine tools. ISO TC39/SC2 has been discussing the publication of a Technical Report (TR) on numerical compensation for machine tool volumetric errors [2]. Such efforts indicate that more machine tool manufacturers and users recognise the importance of evaluating the volumetric accuracy of a machine tool. Many latest commercial CNC systems have the functionality of numerically compensating for volumetric errors.

Suppose that the command tool centre position (TCP) in the machine coordinate system is given by $p^*\in\Re^3$. Denote its actual position by $p\in\Re^3$. The assessment of the volumetric accuracy requires the measurement of $\Delta p=p-p^*$ at arbitrary p^* in the machine's workspace.

The tracking interferometer (the term in [1]), or the laser tracker, is probably the only commercially available instrument capable of measuring Δp at arbitrary location within its workspace [3,4]. It is a laser interferometer with a steering mechanism to change the laser beam direction to automatically follow a retroreflector attached to the machine spindle (referred to as the "target" hereafter). Applying the multilateration principle [1], the target's position is estimated by the distances from typically four or more tracking interferometers to the target (see Fig. 1). Unlike conventional laser trackers (commercially available from, e.g. Leica Geosystems, Faro, API), which estimates the target's position from the distance and the laser beam orientation, the multilateration does not use the laser beam direction in its calculation, and thus does not require higher angular positioning accuracy to ensure higher measurement accuracy of target position. Its application to machine tool calibration has been long studied [5,6]. Its commercial product is available (Etalon [7]). Figure 2 illustrates a typical laser beam steering mechanism to automatically track the target [6,7]. The laser spot position on the quadrant photo-diode is fed back to control the laser beam direction.

In machine tool calibration, the target's command position is given. It is, furthermore, reasonable to assume that the target's positioning error is small enough to make its influence on the laser displacement sufficiently small ("cosine error"). Our proposal is, in such a condition, that the multilateration measurement can be done by controlling the laser beam toward the command target position. This eliminates the automated tracking mechanism, i.e. a photodiode and a feedback control system for laser beam direction. This may significantly reduce the manufacturing cost; it performs the multilateration measurement by using a laser interferometer and a two-axis numerically-controlled rotary drive only. In this paper, the proposed instrument is called the "open-loop" tracking interferometer; "open-loop" in the sense that the target's actual position is not fed back to the control of laser direction.

The paper's emphasis is on analytical evaluation of its measurement uncertainty, introduced by the elimination of automated tracking mechanism. The objective is to show that the proposed "open-loop" tracking does not significantly increase the measurement uncertainty compared to conventional automated tracking interferometers. A prototype is developed, and its measuring performance is experimentally investigated.

2. Proposed measurement procedure

2.1. Regulation of laser beam direction

Figure 3 illustrates the "open-loop" tracking interferometer setup. The laser beam direction is controlled by two rotary axes. Here the configuration with a horizontal rotary axis (called b-axis), mounted on a vertical rotary axis (c-axis), is assumed (see also Fig. 4). The retroreflector is attached to the machine spindle. Assume that:

1. The position of the intersection of b- and c-axes (called the tracking interferometer's position hereafter), denoted by $P_i^*\in\Re^3$, is roughly known.
2. The zero angular position of b- and c-axes is set such that the laser beam is roughly aligned to the machine's X-axis.

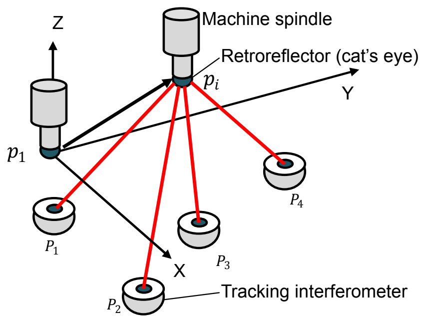

Figure 1. Measurement of target position, p_i, by the laser beam distances from multiple tracking interferometers, P_j (multilateration principle)

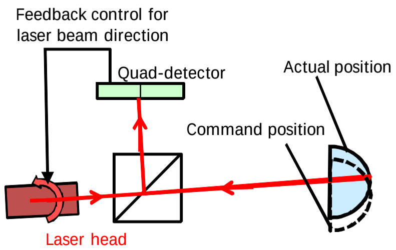

Figure 2. Typical laser beam steering mechanism in conventional automated tracking interferometer.

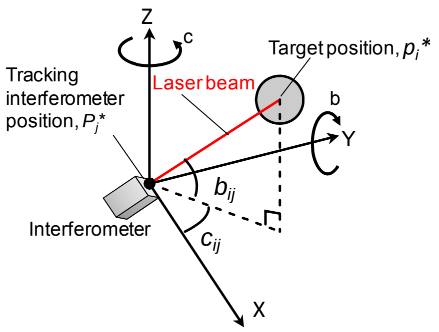

Figure 3. Position of tracking interferometer and target.

Then, by regulating b- and c-axis angular positions as follows, the laser beam is directed to the target's *i*-th command position, $p_i^* \in \Re^3$ (i=1,…, N_i):

$$c_{ij} = \arctan\left(\frac{p_i^*(2) - P_j^*(2)}{p_i^*(1) - P_j^*(1)}\right)$$
$$b_{ij} = \arctan\left(\frac{p_i^*(3) - P_j^*(3)}{\sqrt{\left(p_i^*(1) - P_j^*(1)\right)^2 + \left(p_i^*(2) - P_j^*(2)\right)^2}}\right) \quad (1)$$

2.2. Initial estimation of tracking interferometer position and zero angular positions

To calculate Eq.(1), 1) the tracking interferometer position, P_i^*, and 2) the zero angular position of b- and c-axes, must be roughly estimated. In our experiment, the c-axis zero angular position is set so that the laser beam is aligned normal to the machine tool's Y-axis reference straight line. As the retroreflector is moved to the Y-direction, the laser beam direction is modified such that the variation in the measured laser displacement is minimized. The b-axis zero angular position is set similarly.

Then, the (X,Z) position of b-axis average line is estimated by placing the retroreflector on the b-axis. As the b-axis rotates, the laser displacement is measured, and the retroreflector position is modified such that the variation in the laser displacement is minimized. The c-axis position is estimated similarly.

Clearly, there are many potential uncertainties in such estimation. For example, the machine's positioning error clearly influences the estimation of the tracking interferometer's position. The operations above only give initial estimates needed for the command generation in Eq. (1). Their estimation error's influence on the overall uncertainty will be studied in Section 4.

2.3. Algorithm to estimate target positions

When the target is positioned at the *i*-th command position, p_i^*, the laser beam is directed to the direction (b_{ij}, c_{ij}), given in Eq. (1), and the laser displacement, $d_{ij} \in \Re$, is measured.

The actual target position, p_i (i=1,…, N_i), can be estimated by solving the following minimization problem:

$$\min_{p_i, P_j, d_{0j}} \sum_{i,j} \left(\left\| p_i - P_j \right\| - d_{0j} - d_{ij}\right)^2$$

where d_{0j} represents the dead path length in the measurement at the *j*-th tracking interferometer position. This problem can be locally solved by the same algorithm developed for conventional automated tracking interferometers [5,6,7].

3. Experiment

3.1. Experimental setup

Figure 4 shows the developed prototype. A laser interferometer, DISTAX L-IH-302A by Tokyo Seimitsu Co., Ltd., is mounted on two rotary axes (b-axis on c-axis). A cat's eye retroreflector by Etalon AG is attached to the machine spindle as the target. A cat's eye retroreflector is a spherical glass of the pre-calibrated geometric accuracy with its hemispheric surface coated by the total-reflection metal-film deposition [8].

Figure 5 shows the machine tool configuration. Figure 6 shows the tracking interferometer's setup. Figure 7(a) shows tracking interferometer positions (Pos A to D) and the target's command trajectory. The same measurement was repeated at four different tracking interferometer positions. Within X800×Y800×Z800 mm, the target is positioned at total of 42 positions.

3.2. Experimental result

Figure 7 shows estimated target 3D positions. An error of the estimate from its command position is magnified 2,000 times. Fig. 7(b) shows its projection onto ZX plane.

For the comparison, squareness errors were measured using a square and a linear displacement sensor (see Table 1). The squareness errors are taken for comparison, since this machine has relatively large squareness errors, compared to e.g. straightness errors or linear positioning errors, as can be observed in Fig. 7. While $E_{C(0X)Y}$ (the squareness error of Y- to X-axis [1]) and $E_{C(0Y)Z}$ (Z- to Y-axis) show a good match, $E_{B(0X)Z}$ (Z- to X-axis) shows larger difference. It is to be noted that the machine's repeatability may partly cause the difference (the two measurements were not done in the same day). According to the uncertainty analysis to be presented in Section 4 (Fig. 8), the extended uncertainty (k=2) in the estimated $E_{B(0X)Z}$ is 45.4 µm/800mm, that in $E_{C(0X)Y}$ is 49.6 µm/800mm, and that in $E_{C(0Y)Z}$ is 122.9 µm/800mm.

4. Uncertainty analysis

The proposed "open-loop" tracking procedure has uncertainty contributors that are in principle negligible in conventional automated tracking interferometers. For example, when the

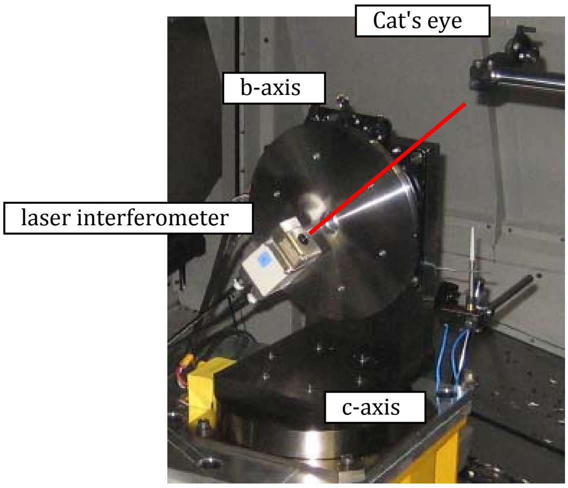

Figure 4. "Open-loop" tracking interferometer prototype.

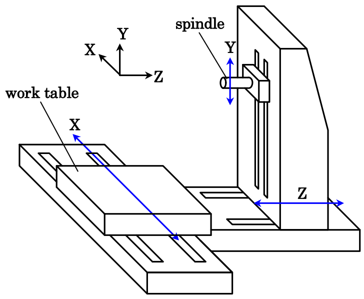

Figure 5. Machine tool configuration.

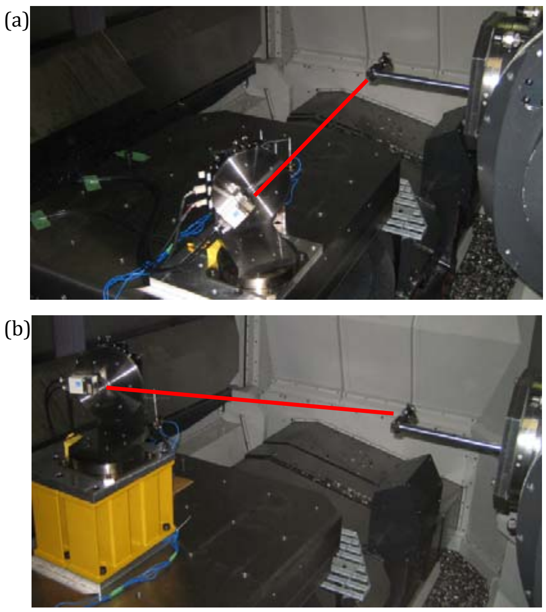

Figure 6. Experimental setup; (a) at Pos A, (b) at Pos D.

machine tool's positioning error is extremely large, the laser beam orientation error to the target centre would increase, which may cause significant "cosine error." To validate the proposed scheme, it is particularly important to show that the uncertainty contributors, existing only in the "open-loop" tracking measurement, do not impose significant influence on the overall measurement uncertainty, when the machine tool, as well as the measuring instrument and its setup, has practical "normal" accuracy. The present uncertainty analysis is essential to clarify the conditions that the machine tool, the measuring instrument, and the setup must meet.

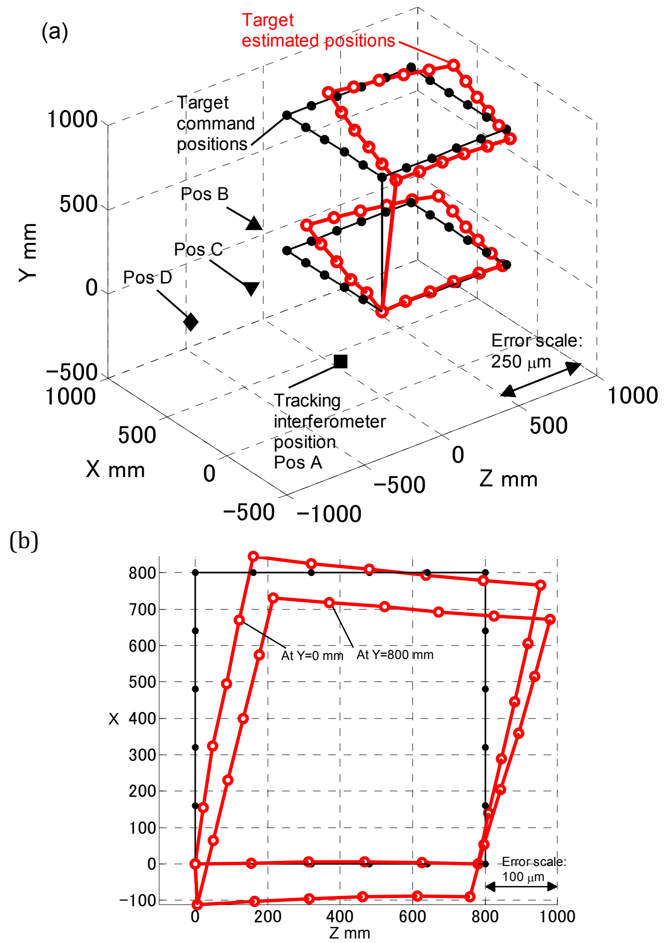

Figure 7. Command and estimated target positions; (a) 3D view (Pos A to D: tracking interferometer positions), (b) projection onto the ZX plane.

Table 1 Comparison of measured and estimated squareness errors

(μm/800mm)	$E_{B(0X)Z}$	$E_{C(0X)Y}$	$E_{A(0Y)Z}$
Measured by using a square	48.0	-28.8	-6.4
Estimated by "open-loop" tracker	78.8	-21.7	-9.3

4.1. Uncertainty budget for laser displacements

Table 2 shows the extended uncertainty, $U(k=2)$, of the laser displacement when the tracking interferometer is at Pos A, and the target is at (X, Y, Z)=(800, 480, 800) in Fig. 7. Some uncertainty contributions were assessed by actually measuring the experimental instrument. For example, the b-axis radial error motion is actually measured to assess u_{21}. Other contributors were assessed by using the instrument's catalogue. Table 2 just shows the analysis for a single target position; it is just an example to illustrate each contributor's influence.

The following contributors can be in principle negligible in the conventional automated trackers, but inherently exist in the proposed "open-loop" tracking interferometers:

- *Uncertainty in target position* (u_{414}, u_{424}): In the conventional "automated" tracking interferometer, the uncertainty in the laser beam orientation (u_4) can be negligibly small, if the tracking mechanism (Fig. 2) works perfectly. In the proposed scheme, the laser beam would never be directed to the exact centre of the retroreflector, since the exact position of the retroreflector is unknown. Its influence on the laser displacement is, however, the "cosine error" and negligible in this setup.

- *Uncertainty in initial estimation* (u_{411}, u_{413}, u_{421}, u_{423}): When the initial estimation of the instrument's rotary axis positions, presented in Section 2.2, has significant error, it also causes the laser beam direction error (see Eq.(1)). Its influence on the laser displacement is also the "cosine error" and is negligibly small. The influence of the initial estimation of the zero angular position of each rotary axis can be assessed similarly.

The contributors, u_1, u_2, u_{4*2}, and u_5 can be in principle present also in automated tracking interferometers. Table 2 indicates that their contribution is significantly larger than contributors above. The present analysis validates the authors' claim that the "open-loop" regulation of laser beam direction does not significantly contribute on the uncertainty of the multilateration measurement.

For the comparison with a conventional automated tracking interferometer, the length measurement uncertainty in LaserTRACER by Etalon AG [7] is, according to their catalogue, U(k=2)= 0.2 µm + 0.3 µm/m. For the target position in Table 2, this gives the length measurement uncertainty (k=2) of 0.56 µm. It is smaller than the combined uncertainty in Table 2. This difference is mostly caused by the radial error motion of our prototype's rotary axes (u_2 is Table 2), which can, in principle, exist also in conventional automated tracking interferometers.

4.2. Uncertainty in target position estimation

Then, the uncertainty propagation to estimated target positions is calculated by applying the Monte Carlo simulation to the calculation presented in Section 2.3. Figure 8 shows the extended uncertainty (*k*=2) of the two-norm of an error of each estimated target position, p_i. In the multilateration measurement, it is well known that the target position's estimation uncertainty may be significantly dependent on tracking interferometer positions [5,6,7]. By modifying tracking interferometer positions, the estimation uncertainty may be reduced.

5. Conclusion

Assuming that the machine tool's positioning error is small enough to make its influence on the laser displacement sufficiently small ("cosine error"), the multilateration measurement can be done by regulating the laser beam toward the command target position. The proposed scheme enables a user to perform the multilateration measurement by using a laser interferometer and a two-axis rotary drive only. The uncertainty analysis showed the laser beam's direction error, caused by the "open-loop" regulation, does not impose significant contribution on the measurement uncertainty, when the machine tool, as well as the measuring instrument and its setup, has practical "normal" accuracy. Experiments showed the performance of the developed prototype to estimate target positions over 800×800×800 mm workspace.

Table 2 Uncertainty budget (*k*=2) for laser displacement when the tracking interferometer is at Pos A, and the target is at (800, 480, 800) mm (see Fig. 7(a)).

	Influence on the uncertainty (*k*=2) of laser displacement				
Symbol			Contributors	*U*(k=2)	
u_1	Uncertainty in laser length (e.g. wavelength, dead path, environmental change) (details omitted)				0.49 µm
u_2	Uncertainty in interferometer position in laser beam direction				1.6 µm
	u_{21}		Radial error motion of b-axis	1.1 µm	
	u_{22}		Radial error motion of c-axis	1.1 µm	
u_3	Uncertainty in interferometer position in the direction normal to laser beam				0
u_4	Uncertainty in laser beam orientation				0.013 µm
	u_{41}		Uncertainty caused by b-axis	43 µrad	
		u_{411}	Uncertainty in zero angular position	3 µrad	
		u_{412}	Uncertainly in angular positioning	22 µrad	
		u_{413}	Uncertainty in centre position	35 µrad	
		u_{414}	Target position uncertainty due to machine's positioning error	7 µrad	
	u_{42}		Uncertainty caused by c-axis	113 µrad	
		u_{421}	Uncertainty in zero angular position	5 µrad	
		u_{422}	Uncertainly in angular positioning	103 µrad	
		u_{423}	Uncertainty in centre position	46 µrad	
		u_{424}	Target position uncertainty due to machine's positioning error	14 µrad	
u_5	Uncompensated geometric errors of b- and c-axes				0.034 µm
	u_{51}		Uncertainty in E_{A0C} (see [1] for the notation)	2 µrad	
	u_{51}		E_{B0C}	2 µrad	
	u_{51}		$E_{X(0C)B}$	5 µm	
	u_{51}		$E_{A(0C)B}$	3 µrad	

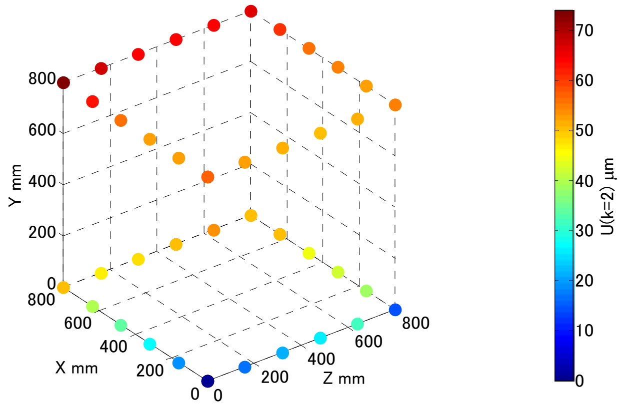

Figure 8. Assessed uncertainty in estimated target positions in the setup in Fig. 7. The colour represents the extended uncertainty (k=2) of the distance of the estimated target position to its command position

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