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IMPROVEMENT OF MEASUREMENT ACCURACY BY COMBINED EVALUATION OF CMM AND TRACKING INTERFEROMETER MEASUREMENTS

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Abstract – This paper presents a novel approach to improve the accuracy of coordinate measuring machines (CMM) by integrating a single high precision tracking interferometer (TI) as an additional measurement axis. Improved positions are obtained by a combination of the CMM positions as read from the scales and the distances produced by the TI. Monte-Carlo simulations of length and flatness measurements show that the uncertainties can be reduced considerably by an appropriate configuration. First measurements confirm the results of preliminary simulations.

Keywords: Co-ordinate measuring machines
Tracking interferometer
Dimensional measurements

1. INTRODUCTION

Coordinate measuring machines (CMMs) have found wide-spread use in industry to ensure production quality. As their precision is sufficient in most applications, some measurement tasks (for instance gear measurements, measurements of large parts, calibration of artefacts) require a higher measurement accuracy, which cannot be achieved by state-of-the-art coordinate measuring machines. Several researchers are developing high accuracy CMMs by means of multilateration employing four or more tracking laser interferometers [1, 2]. Although they have the potential to achieve high accuracy in principle, these methods suffer from the high complexity and investment imposed by the interferometers. This paper presents a new approach based on a single tracking interferometer in combination with a CMM. Both, the CMM coordinates and the interferometer distance information are used to calculate an improved position in space. The novel approach can be applied to various measurement tasks, even for such complex measurements as gear standards (Fig. 1).

2. DISCRIPTION

The additional tracking interferometer is placed on the machine bed of the coordinate measuring machine, as shown in Fig.1. The interferometer automatically follows a reflector mounted close to the probe tip. The interferometer position can be chosen by the user according to his demands. It is calculated by an optimization procedure from the coordinates and the distances measured in only a few machine positions. Thus no extra alignment of the interferometer position is required. During the actual measurement the improved CMM positions in space are calculated from the CMM coordinates and the interferometric distances. For this purpose another optimization procedure based on the minimization of the weighted sum of distance and position deviations is employed.

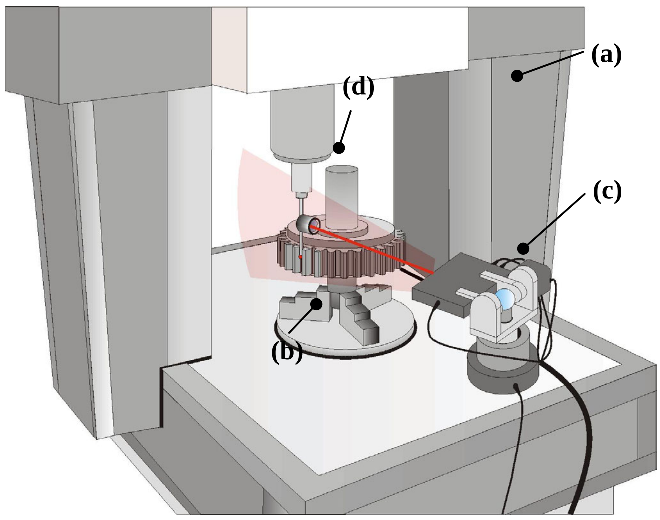

Fig. 1. Application example: Gear measurement on CMM with additional tracking interferometer
(a) co-ordinate measuring machine
(b) rotary table
(c) tracking interferometer
(d) gear profile standard

3. MEASUREMENT PROCEDURE AND EVALUATION

The improved positions are calculated from the readings obtained from the CMM scales and the distances measured by the interferometer on a point-by-point basis. This requires that the position $\vec{x}_0$ of the reference point and the dead path d_0 of the interferometer are known. To determine them, the CMM has to be moved into at least four different positions $\vec{x}_1,\ldots,\vec{x}_4$. These positions must not lie on a common line, plane or sphere. In each CMM position $\vec{x}_i$, a measurement of the distance d_i is made, which results in a discrepancy between the co-ordinate and the distance measurements. The unknown position $\vec{x}_0$ and the unknown dead path d_0 can be found by numerical minimisation of the sum of square errors covering all positions:

$$\sum_i \left(\left|\vec{x}_i - \vec{x}_0\right| - \left(d_i + d_0\right)\right)^2 \to \text{Min}$$

After the calibration of the TI is completed, the actual measurement is performed. During a measurement, the signal of the probing system, the machine scales and the interferometer signal are recorded simultaneously. The calculation of the improved CMM position $\vec{x}'$ is performed as follows: The improved position $\vec{x}'$ and the position $\vec{x}$ read from the machine scales are assumed to have a difference of $\Delta\vec{x}$. Their distances d and d' from the reference position differ by an offset Δd. The improved position is also related to the position $\vec{x}_0$ and the dead path d_0 of the interferometer:

$$\vec{x}' = \vec{x} + \Delta\vec{x}\,,\; d' = d + \Delta d\,,\; d' = \left|\vec{x}' - \vec{x}_0\right| + d_0$$

The co-ordinate and distance improvements can be found by mathematical optimisation. A target function has to be chosen, that puts a large weight on the distance measurements d' and a low weight on the position $\vec{x}'$.

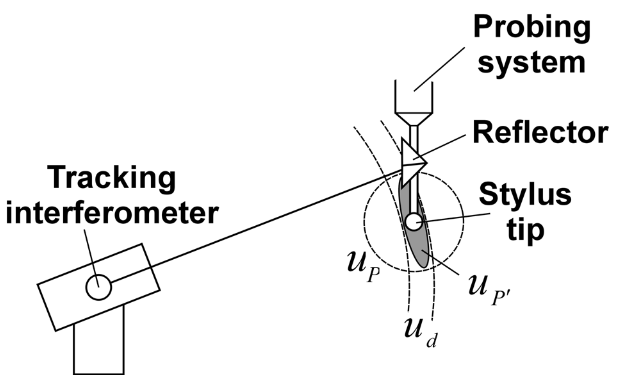

Fig. 2. Uncertainty ellipsoid

The reciprocal values of the uncertainties of the CMM scale positions u_P and of the interferometric distance u_d are appropriate choices:

$$\frac{\Delta x^2}{u_P^2} + \frac{\Delta y^2}{u_P^2} + \frac{\Delta z^2}{u_P^2} + \frac{\Delta d^2}{u_d^2} \to \text{Min}$$

In principle, the optimisation can be performed with any numerical method. As no directional information is drawn from the TI measurement, an uncertainty reduction of the position measurement can be achieved only in the direction of the straight line connecting the probing system and the interferometer position. If the uncertainty of the original position $\vec{x}$ is assumed to have the form of a sphere, the uncertainty of the improved position $\vec{x}'$ will take the form of an ellipsoid, as shown in Figure 2.

4. EVALUATION BY MONTE CARLO SIMULATION

A preliminary evaluation of the new method was done using Monte-Carlo simulations [3]. The simulations are based on a detailed kinematic model of a precision CMM with a length measurement uncertainty

$$U(L) = 1.5\ \mu\text{m} + 4\cdot 10^{-6}\cdot L.$$

The TI is assumed to have an uncertainty

$$U(L) = 0.1\ \mu\text{m} + 3\cdot 10^{-7}\ L.$$

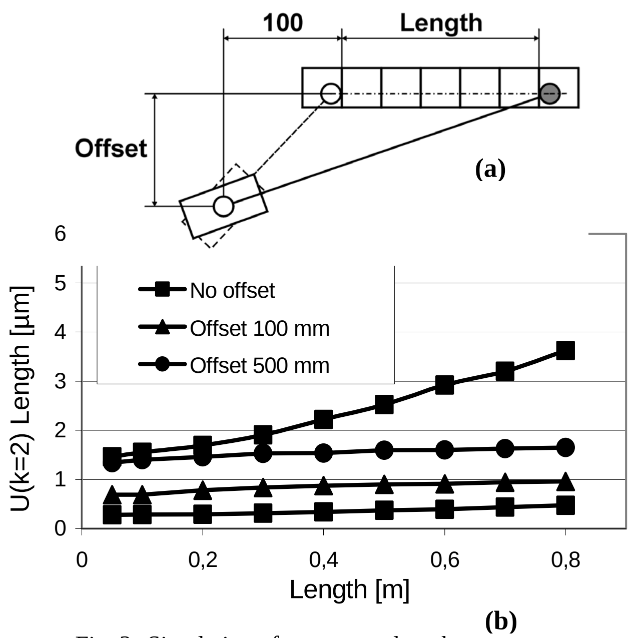

Fig. 3. Simulation of step gauge length measurements
(a) set-up (b) results

Figure 3 shows the results of simulations of length measurements on a step gauge, if the CMM co-ordinate measurements are corrected by interferometric distance measurements, in comparison to lengths obtained without correction. If the interferometer is placed exactly in line with the gauge (no lateral offset), the measurement uncertainty reaches the uncertainty of the interferometric distance measurement, if probing effects are not considered. In case of a lateral offset between the TI and the gauge, the TI measurement cannot fully compensate the CMM errors. The uncertainty of the length measurement increases, but remains below the uncertainty obtained without the TI.

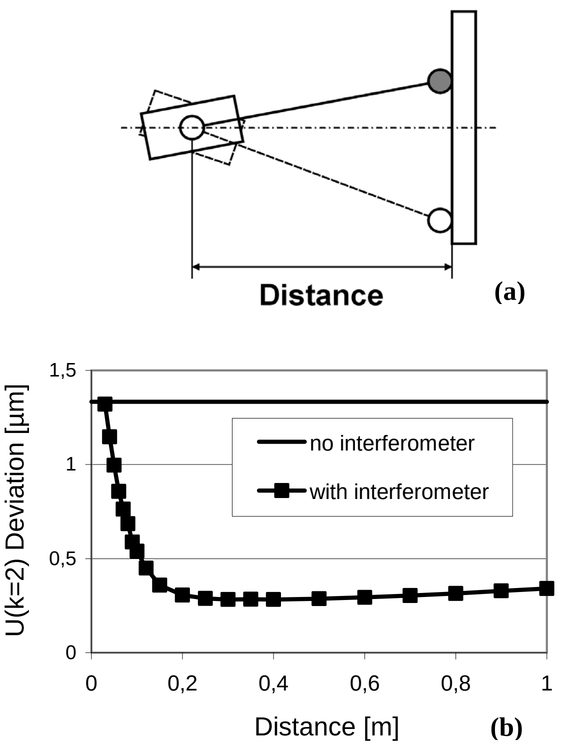

Fig. 4. Simulation of flatness measurements
(a) set-up (b) results

In Figure 4 the simulation results of a flatness measurement of a 100 mm × 100 mm flat with 5 × 5 probing points are shown. If the TI is placed very close to the flat, no uncertainty reduction is achieved, as most parts of the flat are not orthogonal to the laser beam. If the TI is moved away from the flat, all parts of the flat lie almost orthogonal to the laser beam, and the additional length measurement reduces the uncertainty of the form measurement considerably. Simulations of cylinder sector measurements show similar results. However, if the interferometer is moved too far away from the plane, the length-dependent component of the interferometer uncertainty will increase the uncertainty again.

5. EXPERIMENTAL VERIFICATION

To verify the efficiency of the novel approach first step gauge measurements were carried out with a commercial interferometer as our TI is still under development. The measurements were performed on a high precision CMM with a specified maximum permissible length error

$$E = 0.7\ \mu m + 1.7 \cdot 10^{-6} \cdot L$$

For the measurements a highly accurate step gauge was used with a specified calibration uncertainty of

$$U(L) = 0.2\ \mu m + 0.8 \cdot 10^{-6} \cdot L.$$

Length up to 900mm were measured.

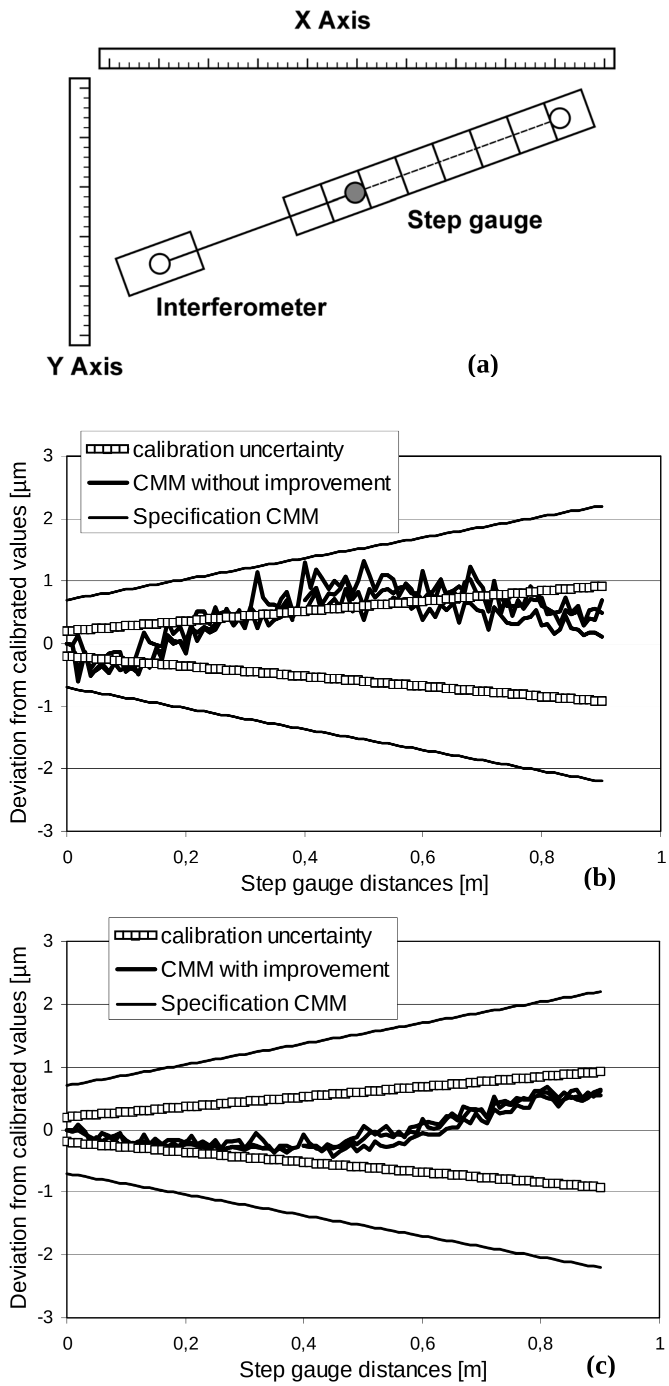

Fig. 5. Measurement results (3 repetitive measurements)
(a) set-up
(b) CMM without improvement
(c) CMM with improvement

The step gauge was placed on the x-y-plane of the CMM (Fig. 5a). The interferometer was aligned in line with the gauge. It is expected that by this specific measurement set-up, both the x- and y-coordinates of the CMM are improved according to the proposed method.
In Figure 5b and 5c the calibrated gauge distances are compared first to the measurement results of the CMM without improvement (Fig. 5b) and in the next diagram with improvement by using the additional laser distances (Fig. 5c).
The deviations between the calibrated step gauge values and the actual CMM measurements without correction are within the specification of the CMM (Fig. 5b). However, the reference values of the step gauge cannot be achieved within their calibration uncertainty. In contrast, Figure 5c shows the CMM results improved by the new method. Now the result of the measurements is within the calibration uncertainty of the step gauge. It can be seen that the correction improves the CMM measurements considerably.

6. CONCLUSIONS

The efficiency of the novel approach is demonstrated by Monte Carlo simulation and by first measurements on a step gauge. The simulations of length and flatness measurements show that measurement uncertainties can be reduced drastically. The first application to a step gauge measurement confirms the simulations. Currently the proposed procedure is applied to the measurement of gear profile standards.

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