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COMPARISON OF ERROR MAPPING TECHNIQUES FOR COORDINATE MEASURING MACHINES USING THE PLATE METHOD AND LASER TRACER TECHNIQUE

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Abstract − The accuracy of coordinate measuring machines (CMMs) strongly depends on geometrical errors that effect the measurements. Several methods for mapping these errors have been developed and some have been implemented. Examples are the direct measurement analysis by means of interferometers, straight edges, squareness standards or the analysis by application of artefacts like ball or hole plates or by using the multilateration approach using high accurate tracking laser interferometers. In this paper a comparison between the well established ball or hole plate method against the new multilateration approach will be presented and discussed. The measurements were carried out on a high accurate and commercial CMM at the Physikalisch – Technische Bundesanstalt (PTB) in cooperation with the National Institute for Standards in Egypt (NIS). For error mapping a ceramic hole plate 960 mm x 960 mm with a grid spacing of 60 mm and a commercial Laser Tracer (LT) were used. Both were originally developed at PTB. The result of the comparison shows that the differences between all estimated rotational axis errors are within 1 arc second. The differences of most of the translatorical errors are less than 1 micrometer. Consequently, both error mapping methods can be used alternatively. Moreover, the paper will show that the multilateration approach can cover a long range of the working volume of machines, is easy for handling, and reduces the time of measurements.

Keywords: error mapping, geometric errors, CMM

1. INTRODUCTION

Mechanical components must be measured to ensure that they satisfy their design specifications. As one of the most powerful metrological instruments, coordinate measuring machines, are nowadays widely used for a large range of such measurement tasks. They are used to check if a product has been manufactured within the tolerances, as well as for identifying trends in the manufacturing process.

The increased accuracies of mechanical components require a reduction in the uncertainties of measuring. This creates the need for higher accuracy performance of CMMs. The accuracy of CMMs strongly depends on the geometrical errors that effect the measurements. The determination of geometrical errors for CMMs has a long scientific history and several methods have been presented. These methods can be separated into three different classes:

Direct measurement techniques, by means of measuring the individual geometrical errors directly using laser interferometer, straight edges, squareness standards or electronic level meters [1].

Artefacts, by application of artefacts like ball or hole plates [2, 3, 4 and 5], the errors can be determined by evaluation of the measurement data gathered with the artefact.

Indirect measurement techniques, by the use of interferometric length measurements along fixed lines [6 and 7].

Recently, PTB developed a method based on the use of laser trackers [8] to generate “virtual” planar reference patterns from interferometric length measurements [9]. This method was successfully applied to the assessment of geometry errors of large horizontal CMMs in the automotive industry. Based on this method, “PTB” and Physical National Laboratory in England “NPL” jointly developed a new approach which uses a spatial grid of positions and a 3-dimensional set of tracker positions to directly derive the systematic parameters from interferometric length measurements [10]. The new design (laser tracer) which was developed by PTB is a new self tracking interferometer which delivers highest precision distance measurements to a moving reflector. The accuracy of the laser tracer is independent from all mechanical imperfections. The interferometer moves in a gimbal mount around a fixed sphere serving only as a reference mirror for the interferometer. Due to this principle, radial and lateral deviations of the mechanical axes of rotation do not significantly affect the measurement accuracy. The accuracy of the laser tracer depends significantly on the quality of the reference sphere surface and its unchanged position in space. To minimize its influences, the reference sphere has a form error below 30 nm. It is mounted on an invar stem to avoid any displacements due to thermal expansion.

A comparison of error mapping for a UPMC1200 CMM has been performed at PTB using the laser tracer and 2-D reference plate. The 2-D reference plate was a ceramic plate 960 mm * 960mm with 64 holes of 60 mm center to center spacing. The results of both error mapping procedures were

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studied and verified. The obtained geometric errors show complicance within sub microns for most parameters.

2. MEASUREMENT SET UP AND SEQUENCE OF MEASUREMENTS

The comparison was carried out on a tactile coordinate measuring machine with three translatoric axes. The measuring volume of the machine is (1150 mm × 1000 mm × 1000 mm) installed in a measurement room with active air and wall temperature control (20°C ± 0.1 K). . The length measuring performance specified by manufacturer is $MPE_E = 0.8$ µm + 1.7 * 10^{-6} * L and the probe specification is MPE_P =0.8 µm.

2.1 Reference plate

The reference plate method is based on the measurement of a calibrated reference hole or ball plate [11]. The plate used for the comparison is 960 mm x 960 mm in dimension. It is made of ceramic with 64 holes. The grid spacing between the holes of the plate is 60 mm.

In order to determine the 21 geometrical errors of the CMM, the reference plate has to be measured in general at four different locations within the measuring volume as shown in figure 1. In two locations the plate has to be measured with different probe offsets (see table 1).

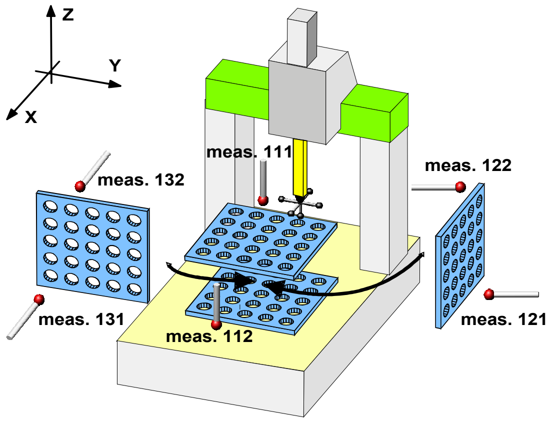


Figure 1 Different locations of the plate on CMM table in general.

As the dimensions of the reference plate do not match sufficiently to the length of the CMM guideways, in this case the plate has to be shifted in overlapping positions in order to cover the whole measuring volume of the CMM see figure 2.

The reference plate was adjusted approximately in parallel to the respective coordinate plane. For the vertical positions the plate was placed in the center of the measuring volume. Two of the four horizontal positions were located close to the machine table. The others were located near to the limits of Z axis.

To be able to determine all rotational errors same plate positions were measured with different length and orientation of probe styli in respect to the stylus reference point. The offset of the probe at each position given in table 1.

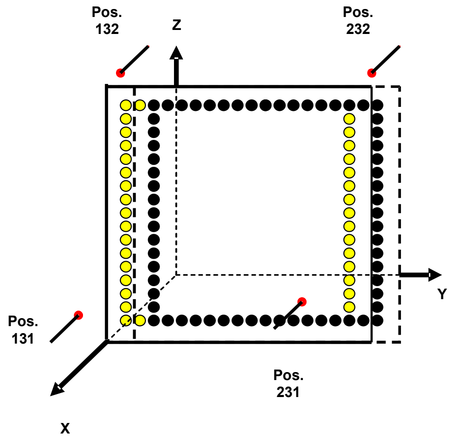


Figure 2 The plate was shifted 120 mm to have the vertical positions 231,232.

Position no.	Probe offset in mm		
	X	Y	Z
Upper horizontal position"111"	0	0	-60
Shifted upper horizontal position "211"	0	0	-60
Lower horizontal position "112"	0	0	-60
Shifted lower horizontal position "212"	0	0	-60
Vertical position in XZ plane "122"	0	160	0
Vertical position in XZ plane "121"	0	-160	0
Vertical position in YZ plane "131"	-160	0	0
Vertical position in YZ plane "132"	160	0	0
Shifted vertical position in YZ plane "231"	-160	0	0
Shifted vertical position in YZ plane "232"	160	0	0

Table 1 Probe offset at each position.

All geometrical errors can be derived according to [11] using the deviations between the measured and their calibrated plate coordinates.

2.2. Laser tracer

The concept of the multilateration method is based on the measurement of relative distance changes between a fixed reference point and points relative to the CMM head. These measurements are carried out by means of a tracking interferometer, a so called laser tracer [10]. The accuracy of the laser tracer is independent from all mechanical imperfections. The interferometer moves in a gimbal mount around a fixed ball serving only as a reference mirror for the interferometer. Radial and lateral deviations of the mechanical axes of rotation do not significantly affect the measurement accuracy. The accuracy of the laser tracer depends significantly on the quality of the reference ball surface and its unchanged position in space. The reference ball has a form error below 30nm and mounted on an invar stem to avoid any displacements due to thermal expansion.

The laser tracer was placed at different positions on the CMM table as shown in figure 3.

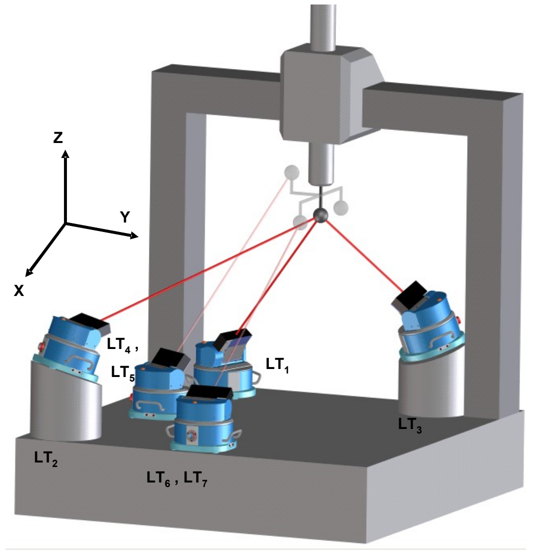


Figure 3 Different positions of laser tracer on CMM table.

The measurements were performed with a retro reflector (cat eye) which was mounted to the ram axes of the CMM in different length offsets and orientations. The offsets are given in table 2.

Position no.	Laser tracer position in mm			Reflector offset in mm		
	X	Y	Z	X	Y	Z
LT_1	0	0	0	0	0	5
LT_2	x	0	z/2	0	0	5
LT_3	0	y	z/2	0	0	5
LT_4	x/2	0	0	-260	0	15
LT_5	x/2	0	0	0	-210	185
LT_6	x	y/2	0	0	-210	185
LT_7	x	y/2	0	210	0	15

Table 2 Reflector offset at different laser tracer positions

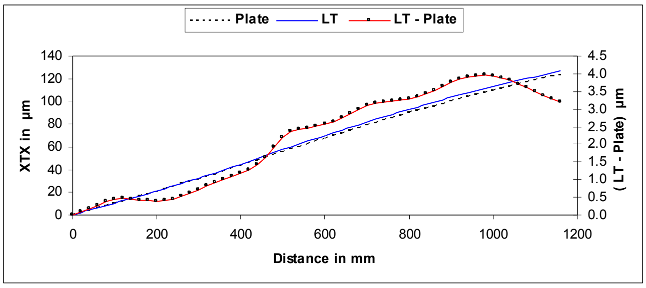
For each laser tracer position, the reflector was moved along a pre-defined path and stopped at certain positions. At each grid position, the associated measured distance was recorded by means of the laser tracer. Using all measured distances the actual positions of the reflector were calculated by multi lateration and compared against the nominal positions of the CMM. Finally the 21 parametric errors of the CMM were calculated from the differences between the actual and nominal positions.

3. RESULTS OF THE ESTIMATION OF PARAMETRIC ERRORS OF THE CMM

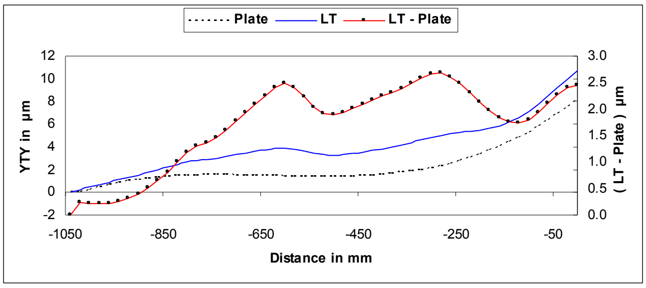
As the analysis of the geometric errors for the ball plate [11] and the laser tracer method [10] was performed with two different software tools, the error mapping results had to be transformed first in a comparable data format.

Figure 4 (a, b) shows, for example, the positional errors and the differences obtained from measurements with the hole plate and by means of the laser tracer. Figure 4a illustrates the positional error (XTX) along the x-axis and figure 4b shows the positional error (YTY) in y-axis direction.

The comparison clearly demonstrates that the positional errors obtained from measurements reveal deviations up to 4 µm in the x-axis and up to 2 µm in the y-axis. In particular the large deviation of 4 µm in (XTX) lies outside the estimated uncertainty for this error, which raises the question about the reason for this discrepancy.



(a)



(b)

Figure 4 Examples of estimated positional errors measured by means of the plate vs multi-lateration method: (a) position error of x-axis and (b) position error of y-axis.

Reasons for the great deviation in the x-axis could be:

- changes of plate holes since last calibration
- hysteresis effects at the boundaries of axes
- drift effects
- inaccuracies due to a incomplete measuring procedure for mapping errors using a laser tracer (i.e. absence of additional measurement positions)
- remaining errors caused by systematic deviations of environmental sensors of the laser tracer, in particular for temperature and air pressure.

Therefore, further investigations on the linear position error (XTX) had been done, which means, that in a first step the calibration data of the ceramic plate was compared to data of a smaller zerodure plate.

The zerodure plate has dimensions of 550 mm by 550 mm. It consists of 44 holes, each with diameter of 20 mm and a center to center spacing of 50 mm. It was calibrated with an uncertainty of $U(L)=\sqrt{(0.4\mu m)^2+(L\times 0.5.10^{-6})^2}$ for distances between arbitrary holes.

For the purpose of comparison the ceramic plate and zerodure plate were placed on the CMM table horizontally at the same level. Some predefined distances between holes were measured for each of the two plates at the same nominal positions along the x-axis of the CMM. The deviations between the actual measured distances and the calibrated values were calculated for both plates and chart in figure 5.

The comparison shows, that there is a significant length difference between the ceramic plate and the zerodure plate which amounts to 2.3 µm as shown in figure 5. On the other hand the length measured on the zerodure plate fits very well to the CMM x-scale, which, in this case, was calibrated by the laser tracer.

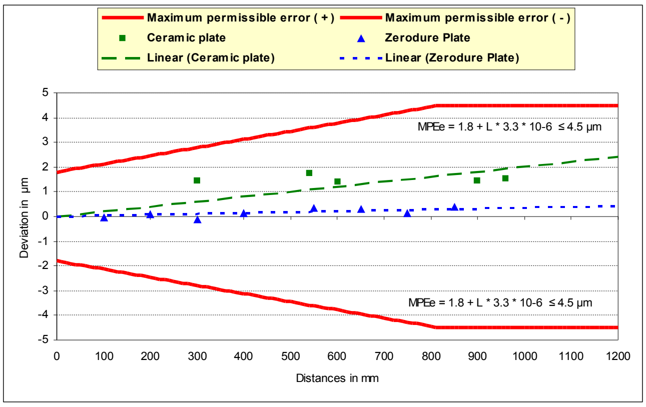


Figure 5 Length deviations between ceramic plate and zerodure plate along the x–axis

Thus only a fraction of the large deviation in (XTX) (approximately 2 µm of 4 µm) can be explained due to a systematic effect. An unexplainable deviation of about 2 µm still remains.

In the following further geometric CMM errors obtained from measurements carried out in the year 2007 will be presented. An example for the roll error (XRX) is given in figure 6. Both roll errors, determined by plate method and multi-lateration technique, coincide within 3 µrad.

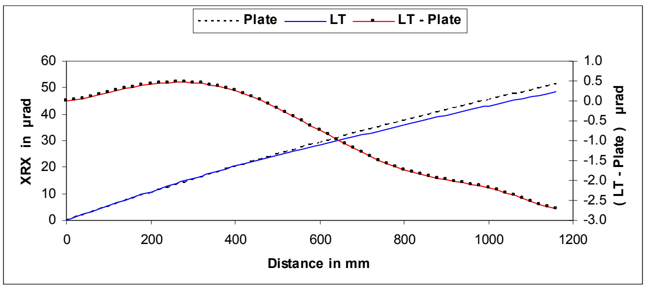
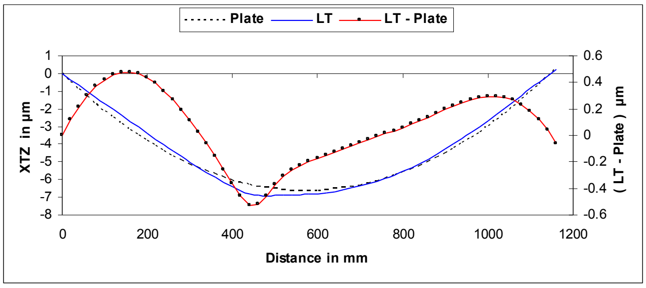


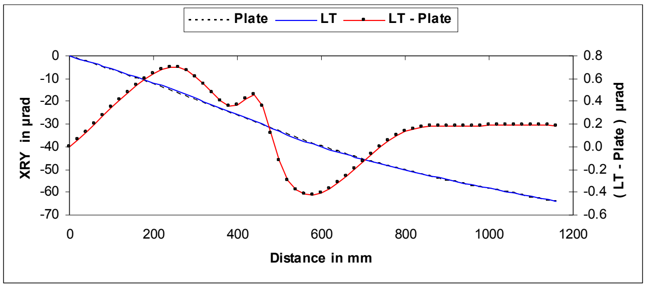
Figure 6 Estimated roll error "XRX" measured by means of the plate vs multi-lateration method.

Furthermore examples for straightness errors (XTZ), pitch errors (XRY)and yaw errors (YRZ) obtained from measurement carried out in 2007 are given in figure 7 (a,b,c) which show compliance within 1 µm for straightness and 1.5 µrad for pitch and yaw. These deviations lie within the estimated measurement uncertainty.

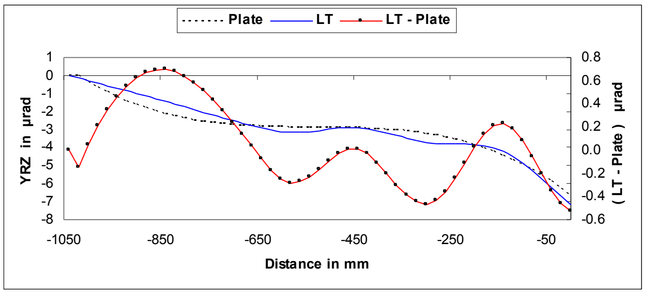
As geometrical errors subject to change significantly due to machine usage and environmental conditions, further sets of measurements were performed at the end of 2008, in order to redetermine the geometrical errors of the CMM using both methods, the reference plate and laser tracer, following the same procedure as applied in the year before.



(a)



(b)



(c)

Figure 7 (a,b,c) comparison of straightness, pitch and yaw errors measured by means of the plate vs multilateration method

Last but not least these measurements served also the verification of the achievable accuracy.

Examples of the estimated geometrical errors and the differences obtained from measurements with the hole plate and the laser tracer in 2008 are given in figure 9.

It is shown that

- the position errors (XTX) and (YTY) obtained from both methods have the same trend and show a compliance within 2 µm.
- the roll error (XRX) coincide within 3.5 µrad.
- the straightness error (XTZ), the pitch error (XRY) and the yaw error (YRZ) show compliance within 0.8 µm for straightness and 0.9 µrad for pitch and yaw.

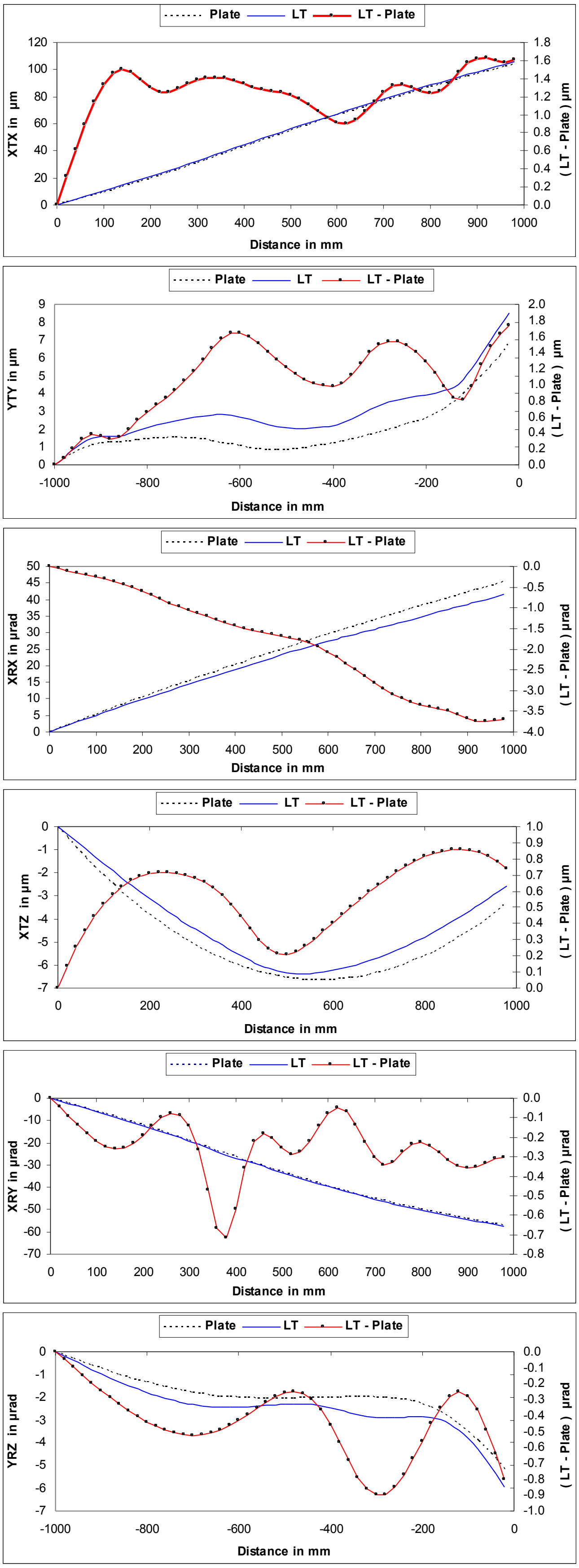


Figure 9 Examples of calculated geometrical errors and the differences, obtained from measurements with the hole plate and the laser tracer performed in year 2008

4. CONCLUSION

The geometric machine errors obtained using the reference plate method and the multi-lateration technique by means of a laser tracer show a compliance of most parameters within 1 micrometer for translatorical errors and about 1 µrad for rotational errors. The maximum deviations are 2 µm and 3.5 µrad respectively, thus the measured deviations are within the expanded measurement uncertainty of both methods. The expanded uncertainty achievable for both methods and the CMM measuring volume in the investigation is at present estimated to be ≤ 1 µm for position and straightness errors and to be in the range of 1 to 2µrad for rotational errors.

In this paper we demonstrate the validity of the laser tracer method for assessing the geometrical errors of CMMs. The multilateration procedure and the reference plate method yield comparable results. Deviations can be explained by the measurement uncertainty achievable by both approaches. The tracer method is easier to handle, reduces the time of measurements significantly compared to the plate method and covers a long range of machine working volumes.

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