Error mapping of large CMMs by sequential multi-lateration using a laser tracker

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Abstract
A new method for error mapping and verification of large CMMs is presented. It only makes use of the high-precision interferometric signal of a conventional laser tracker in order to produce a “Virtual 2D-Artefact” (set of planar reference positions) by planar multi-lateration. The method is easy to use and very accurate compared to others.

Introduction
Especially in car and aircraft industry large co-ordinate measuring machines (CMMs) are widely used. Since they are employed for quality assurance, their performance and accuracy has to be verified at regular intervals. However, well-accepted methods for the performance verification of large CMMs do not exist as yet.

At present geometric errors of large machines can only be assessed with conventional tools like laser interferometers, level meters or straight edges. These methods, however, are very time-consuming, uneconomical and do not enable the full analysis of all errors. On the other hand, for small and medium-sized CMMs (measuring volume < 1 m³) methods for the assessment of CMM errors are well established, especially artefact-based methods. They enable the full analysis of all geometric errors by measurement of calibrated ball or hole plates [1]. However, this technique can not be applied to large CMMs, because the artefacts cannot be simply upscaled. They become too heavy and hard to handle. Elasticity and thermal behaviour of the artefacts also become crucial [2].

The Physikalisch-Technische Bundesanstalt (PTB) therefore has developed a new technique for the error mapping of large CMMs. This new technique is based on sequential multi-lateration and makes use of the high-precision interferometric signal of a commercial laser tracker in order to produce a set of planar reference co-ordinates. This set of co-ordinates can be seen as a “Virtual 2D-Artefact” comparable to the ball plate mentioned above [1].

Principle
The new technique of error mapping is based on the concept that two- or even three dimensional positions can be determined exclusively by length measurements [3,4,5]. This procedure is called multi-lateration. All lengths are measured only using one conventional laser tracker. In turn the tracker is placed in three or even more positions.

The laser tracker measures the distance to a triple mirror attached to the ram of the CMM. For mapping all geometric errors the CMM moves the mirror in defined horizontal and vertical planes. Fig. 1 shows the basic set-up for measuring a horizontal plane. The laser tracker A, placed approximately to that plane for reasons of accu-
racy, follows the movements of the CMM automatically. At defined positions $P_i$, the CMM stops and the tracker statically records the distance to the mirror. After a first run it is necessary to move the tracker to at least two other locations ($B$, $C$) to measure the lengths to the same positions of interest. This procedure enables to calculate precisely co-ordinates of the positions $P_i$ using exclusively the high-precision interferometric distance measurements of the laser tracker, i.e. the less accurate angular encoders of the tracker are not used. While three laser tracker positions are sufficient in principle, it is in general beneficial to sample a fourth set of distances (Position D). If the tracker positions are arranged symmetrically close to the boundary of the CMM measuring volume, one reaches a certain degree of homogenous accuracy of the positions $P_i$.

Assuming that each set of distances was sampled to the same set of nominal positions $P_i$ ($i=1...n$) and that all positions $P_i$ are coplanar, the length measurements $L_{j,i}$ ($j=A...D$) can be expressed in terms of the unknown laser tracker positions and the unknown machine positions $P_i$ by the equation system (1).

$$L_{j,i} = \sqrt{(x_j - x_{P_i})^2 + (y_j - y_{P_i})^2 + z_j^2} = E_{j,i} + \Delta E_j$$

(1)

In Eqs. (1) $x_{P_i}$, $y_{P_i}$ are the co-ordinates of the machine position $P_i$ and $x_j$, $y_j$, $z_j$ are the co-ordinates of the laser tracker in position $j$ ($z_j$ denotes the “out of plane distance” for each laser tracker). The left side of Eqs. (1) takes into account, that the absolute lengths $L_{j,i}$ are not available, because laser trackers are in general relative measuring devices. Therefore an unknown length offset $\Delta E_j$ is introduced, which is common to all length measurements from the same tracker position $j$. $\Delta E_j$ is a correction to the indicated length measurement $E_{j,i}$ of the laser tracker.

In practice, some 50 to 100 positions $P_i$ are measured, resulting in a highly over-determined equation system (1). Solving the equations simultaneously we get iteratively a solution for all co-ordinates of the machine positions $P_i$ plus the laser tracker positions (which are irrelevant for machine calibration). Discrepancies between the equations are minimised by a least square adjustment.

**Technical realisation**

To perform the measurements a commercially available laser tracker and a custom designed corner cube reflector were used. For our purpose, a unit was designed, where the reflector is...
mounted on a precision rotary axis in a way that the point of reflection is adjusted to be in the axis of rotation. The reflector can be rotated by a stepper-motor to align it approximately to the direction of the laser beam.

For the laser tracker, customised software was developed, which also controls the alignment of the reflector unit and stores the length data in an unambiguous data format. Fig. 2 shows the set-up during the experimental measurements for a horizontal plane.

**First application and results**

Experiments have been performed in co-operation with Volkswagen and AICON (metrology and engineering company) on a numerically corrected horizontal arm CMM of a measuring volume of 5m x 2m x 1.5m. Fig. 3 shows the measuring set-up in a vertical plane. The complete measurement of that plane has not taken more than 3 hours including 4 relocations of the laser tracker.

![Fig. 3: Set-up adopted in a vertical plane. A, B, C, D indicate laser tracker positions, dots mark machine positions, lines are observed distances, and ellipses indicate the uncertainty range of the positions P.](image)

After evaluating all measurements, inconsistencies in the multi-lateration net remain due to the uncertainty of the measured lengths. These inconsistencies or residuals result from the repeatability of the machine, the ambient conditions, the uncertainty of the rotation axes of the tracker etc and can give an idea of the uncertainty of the

![Fig. 4: Observed positions errors of a large horizontal arm CMM](image)
method. The standard deviation of the lengths residuals is in a range of 2 µm and the maximum deviation is 8 µm for the 5m-CMM under test. This is a very satisfactory result, considering that the specification limits for the very most CMMs of this size are 10-50 times higher.

For the determination of systematic machine errors the differences between the positions \( P_i \) and the indicated positions \( P'_i \) of the CMM has been computed. **Fig. 4** shows the result in a plane perpendicular to the horizontal arm. Visible are very systematic error vectors in a range of 100-150 µm.

In the last step it is possible to process the observed position errors by the software Kalkom [6]. This software can compute all so called “rigid body errors” of a CMM plus the dominant elastic errors [2]. As an example, **Fig. 5** shows the straightness and the pitch error of the X-axis of the CMM.

**Conclusion**

For verification and error mapping of large CMMs an accurate procedure has been presented based on the concept of multi-lateration. By this patent pending method it is possible to assess systematic errors, even of very large CMMs with high accuracy. To perform the measurements, a conventional laser tracker and a custom designed reflector unit are used. In the near future, it is planed to do extensive experiments that include comparisons with other error mapping techniques to verify the proposed methods.

**References**


