Realization and calibration of the “Isara 400” ultra-precision CMM

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Abstract. This paper presents the realization of the Isara 400 ultra-precision 3D coordinate measuring machine, which features a measuring volume of 400 x 400 x 100 mm and a volumetric (3D) measurement uncertainty of 100 nm (2σ). In order to achieve these challenging specifications, specific calibration strategies need to be applied, such as the calibration of flatness and out-of-squareness of the system’s mirror table. In addition, a newly developed ultra-precision tactile probe system is described, featuring a probe tip with a diameter of 70 µm; results of the 3D sensitivity calibration of this probe are presented.

1. Introduction
The Isara 400 coordinate measuring machine (CMM) is the latest development of IBS Precision Engineering for coordinate metrology of large, complex parts with nanometer level measuring uncertainty. The expected 3D measuring uncertainty is 100 nm (2σ) within the complete measuring volume of 400 x 400 x 100 mm. The Isara 400 CMM is capable of measuring complex surfaces like aspheres, free-forms or integrated optics with nanometre accuracy in full 3D, and thus overcomes some of the limitations presented by the optical methods or contacting profilers which are currently used. In addition, application areas include the geometrical inspection of a wide range of industrial parts, similar to conventional CMMs, but with much higher measuring accuracy.

This paper presents the realized design as well as the most critical calibration strategies necessary to achieve the challenging accuracy specifications.

2. Design
The Isara 400 CMM features a measurement volume of 400 x 400 x 100 mm. Three plane mirror laser interferometers are applied as measuring systems for the machine axes. The interferometers each measure against the sides of a mirror table, on which the work piece is mounted. These interferometers are mounted in a single body metrology frame, which also holds the probe system (see figure 1a). The laser beams are aligned to the probe tip and their mutual alignment does not change during movement of the axes, thus fulfilling the Abbe principle [2] in 3D within the complete measuring volume. As a result, straightness errors and rotations of the three translation stages will have no first order influence on the measurement result. The influence of flatness and squareness errors of the three mirrors is eliminated by means of a series of on-machine calibration measurements.

In the configuration of the translation axes, a machine concept was chosen in which the variable product mass does not need to be moved vertically. The product is mounted on the mirror table, which moves only in X- and Y-direction over a granite base plate, guided by air bearings in a ‘floating table’
configuration. The complete metrology frame moves in Z-direction, with guiding provided by air bearings against a vertical granite surface (figure 1a). Figure 1b shows an overview of the complete machine.

![Figure 1. Design overview of the Isara 400 CMM; a) concept sketch; b) full 3D CAD design (without covers)](image)

The function of the metrology frame, shown in figure 3a, is to maintain the mutual position and alignment of the probe and the three laser interferometers with high stability. The metrology frame was designed as an assembly of hollow beams of silicon carbide (SiC), resulting in a structure which is both stiff and lightweight, while also providing good thermal stability.

The mirror table of the Isara 400 is a monolithic Zerodur part with three reflective sides. The mirror table is supported by three flat air bearings, whose preload is provided by the weight of the mirror table assembly with product. Figure 2b shows the mirror table and the X/Y-drives; for more details see [3]. Work pieces are not placed directly onto the Zerodur, but onto a removable SiC product table, which serves as an interface between product and mirror table. The weight of the product table with work piece is directly transferred through its mounting supports to the supporting air bearings, without causing additional deformation of the Zerodur mirror table.

![Figure 2. a) Silicon carbide metrology frame; b) Mirror table and X/Y drives.](image)

### 3. Mirror table calibration

The three plane mirrors of the mirror table serve as targets for the laser interferometers and can thus introduce measuring errors due to flatness deviations and out-of-squareness of the mirrors. These deviations need to be calibrated and compensated to fulfill the high accuracy demands. All mirror
Table calibration measurements are performed on the machine itself, in its final assembled position, thus the sagging of the mirrors due to gravity is included. The calibration strategies presented here build on the work described in [4], but effort has been made to simplify the procedure, for example by making use of the flatness data of a calibrated flatness reference artefact in stead of performing an elaborate series of reversal measurements with an artefact whose flatness is unknown.

3.1. Flatness calibration
The flatness of the mirror table is calibrated by placing a calibrated flatness reference in the measurement volume of the machine and performing a flatness measurement with a highly accurate capacitance probe. The reference artefact in this case is a Zerodur block, which has three sides with a reflective metal coating. Figure 3a shows a sketch of the setup for flatness calibrating of the Z-mirror. The complete top surface of the artefact is measured with the capacitance probe; the measurement result is the sum of the flatness deviations of the mirror and the reference artefact. As the flatness from the reference artefact is known from optical calibrations, this can be subtracted from the measurement result, leaving only the flatness deviation of the Z-mirror, which is then used to correct the measured displacements from the laser interferometers. A similar calibration is performed for the X- and Y-mirrors, by measuring the sides of the same artefact.

![Figure 3](image.png)

Figure 3. Flatness calibration of the Z-mirror; a) concept sketch; b) complete setup

3.2. Optical flatness calibration of reference artefact
A critical part of this calibration strategy is the calibration of the flatness reference. The Zerodur reference artefact is calibrated using Fizeau interferometry. This optical calibration provides the flatness mappings shown in figure 4, which can be subtracted from the flatness measurement described in the previous paragraph.

![Figure 4](image.png)

Figure 4. Results of the optical flatness calibration of the three sides of the artefact; colour scales in nanometres.

In each optical calibration measurement, the artefact is in the same orientation as it is during the calibration on the machine (figure 3b), so no additional sagging needs to be taken into account. The measurement uncertainty of the optical flatness calibration is less than 10 nm (k=2).
3.3. Out-of-squareness calibration

The orthogonality of the machine’s metrology coordinate system is determined by the orthogonality of the three mirrors of the mirror table. Any out-of-squareness between these mirrors will cause measurement errors. Using the same Zerodur artefact as described in the previous paragraph, the out-of-squareness of the three mirrors can be calibrated. The out-of-squareness of the artefact has not been accurately calibrated; error separation needs to be applied to distinguish between the out-of-squareness of the mirror table and that of the artefact.

All three coated sides of the artefact are measured by the capacitance probe, without changing the orientation of the artefact with respect to the mirror table. The mutual angle between the three measured planes is determined; this measurement result is a combination of the out-of-squareness of the mirror table and the out-of-squareness of the artefact. By measuring the artefact in multiple orientations, it is possible to perform error separation.

The procedure for one specific out-of-squareness angle is shown in Figure 5. The mounting orientation of the capacitance probe varies in order to measure several sides of the artefact. In the first orientation of the artefact, the measured angle between the two planes equals \( M1 = \phi - \alpha_{YZ} + 90^\circ \), where \( \phi \) and \( \alpha_{YZ} \) are the out-of-squarenesses of the artefact and the mirror table, respectively. In the second orientation, the measured angle is \( M2 = \phi + \alpha_{YZ} - 90^\circ \). Because the contribution of \( \alpha_{YZ} \) changes sign between the two measurement results, it is possible to determine both \( \phi \) and \( \alpha_{YZ} \) from these two measurements:

\[
\alpha_{YZ} = \frac{1}{2} \times (180^\circ - M1 + M2)
\]

\[
\phi = \frac{1}{2} \times (M1 + M2)
\]

A similar strategy is used for the other out-of-squareness errors.

![Figure 5. Out-of-squareness calibration of Y- and Z-mirrors; a) artefact orientation 1; b) artefact orientation 2.](image)

4. Tactile probe calibration

The design and calibration of the newly developed “Triskelion” probe system is described in detail in [1]. The design features an elastically suspended stylus, which is free to deflect in X-, Y- and Z-direction at its tip; this deflection is measured by three capacitance sensors which are integrated in the probe system.

A miniaturized version of this probe system features a stylus with a tip diameter of about 70 µm (see figure 6a). The small tip enables measurements of very small features, such as the inside diameter of very small holes (up to 1 mm depth). The elastic suspension of this miniaturized probe system was also redesigned to further reduce probing forces, to prevent work piece surface damage. Figure 6b shows a photograph of the realized probe.
The sensitivity calibration of this probe system is performed on an ultra-precision CMM. The probe is placed in contact with a flat work piece surface, which is located on the product table. Probe deflection is then applied by moving the table; the output signals of the probe and the interferometric table displacement are logged. Repeating this measurement for multiple probing directions yields a 3D sensitivity model. This model is validated by performing additional probing measurements. One such result is presented in figure 7 (unfiltered data). For probe tip deflections $\leq 5 \, \mu m$, measurement errors are $< 10 \, nm$ per axis of the coordinate system and $< 15 \, nm$ in 3D.

**Figure 6:** a) Photograph of miniaturized stylus. b) Realized miniature Triskelion probe

**Figure 7:** a) Miniature probe in CMM. b) Residual measurement errors (x,y,z) for probing in z-direction

**5. Conclusions**

The Isara 400 ultra-precision CMM has been realized and is currently operational at IBS Precision Engineering. Calibration of the mirror table deviations are critical to achieving the targeted volumetric uncertainty of 100 nm ($k=2$). A newly developed, miniaturized tactile probe system has been realized and the sensitivity calibration has been successfully performed.

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**References**

[1] H. A. M. Spaan, R. L. Donker, and I. Widdershoven, Isara 400: Development of an ultra-precision CMM for 3D measurement of large parts, *Proc. ASPE spring meeting*, 2009.

[2] E. Abbe, Meßapparate für Physiker, Zeitschrift Für Instrumentenkunde, 1890; 10: 446-448.

[3] R. Donker, I. Widdershoven, D. Brouns, H. Spaan, Realization of Isara 400: a large measurement volume ultra-precision CMM, *Proc. ASPE annual meeting*, 2009.

[4] T.A.M. Ruijl, Ultra Precision Coordinate Measuring Machine – Design, Calibration and Error Compensation, PhD thesis, Delft University of Technology, The Netherlands, 2001, ISBN 90-6464-287-7