Calibration of the Isara 400 Ultra-precision CMM

I. Widdershoven, R. Donker, H.A.M. Spaan
IBS Precision Engineering, The Netherlands

widdershoven@ibspe.com

Abstract

This paper presents critical aspects of the calibration of the Isara 400 ultra-precision 3D CMM, such as the calibration of flatness and out-of-squareness of the system's mirror table. In addition, results of the 3D sensitivity calibration of a newly developed miniaturized tactile ultra-precision probe are presented.

1 Isara 400 design

In the field of ultra-precision 3D metrology, various small-volume coordinate measuring machines (CMMs) have been developed (e.g. [1], [2]), including the first Isara CMM, which was based on [3]. These machines typically feature measuring ranges ≤ 100 mm. The Isara 400 CMM is the latest development of IBS Precision Engineering for coordinate metrology of large, complex parts, featuring an expected 3D measuring uncertainty of 100 nm (2σ) within the complete measuring volume of 400x400x100 mm. The Isara 400 CMM is capable of measuring complex surfaces such as aspheres, free-forms or integrated optics with nanometre accuracy in 3D. In addition, application areas include geometrical inspection of a wide range of industrial parts, similar to conventional CMMs, but with much higher accuracy.

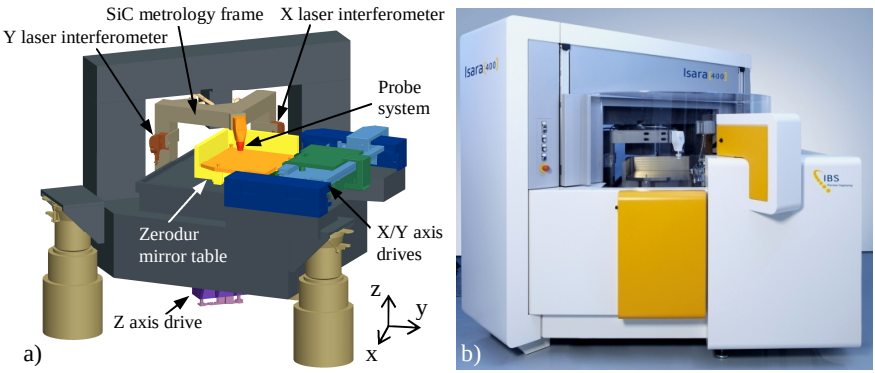
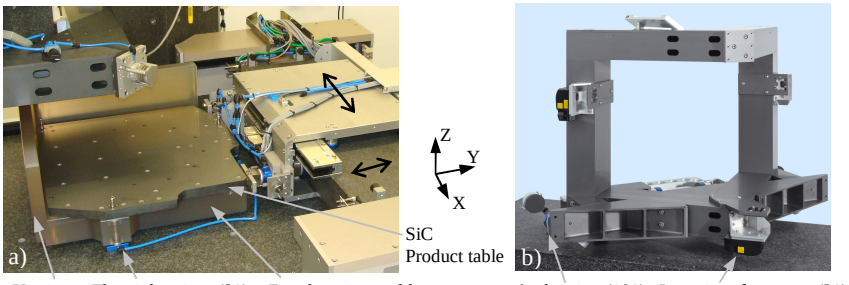


Figure 1: Design overview of the Isara 400 CMM; a) 3D design concept, without covers, b) photograph of the complete machine.

Figure 1 shows an overview of the complete machine. 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. 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" in 3D within the complete measuring volume. As a result, straightness errors and rotations of the three translation stages will have a negligible first order influence on the measurement result.



Y-mirror Flat air bearings (3*) Zerodur mirror table Air bearing (10*) Laser interferometer (3*)

Figure 2: a) Zerodur mirror table and X/Y drives; b) Silicon carbide metrology frame.

The product is mounted on the mirror table, which is moved in X- and Y-direction over a granite base plate, guided by air bearings in a 'floating table' configuration. The mirror table of the Isara 400 is a monolithic Zerodur part with three reflective sides. Figure 2a shows the mirror table and the X/Y-drives; for more details see [4]. Work pieces are not placed directly onto the Zerodur, but onto a removable silicon carbide (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.

The complete metrology frame moves in Z-direction, with guiding provided by air bearings against a vertical granite surface. This metrology frame, shown in figure 2b, is designed as an assembly of hollow beams of silicon carbide, resulting in a structure which is both stiff and lightweight, while also providing good thermal stability.

2 Mirror table calibration

The three sides of the mirror table serve as target mirrors for the laser interferometers and can thus introduce measuring errors due to flatness deviations and out-of-squareness. These deviations need to be calibrated and compensated. All mirror table calibration measurements are performed on the machine itself, in its final assembled position, so that the sagging of the mirrors due to gravity is included. The calibration strategies presented here build on the work described in [3], but effort has been made to simplify the procedure.

2.1 Flatness calibration

The flatness of the mirrors is calibrated by placing a flatness reference in the measurement volume of the machine and performing a flatness measurement with a highly accurate capacitance probe. The applied reference artefact is a Zerodur block, which has three sides with a reflective metal coating. Figure 3a shows a sketch of the setup for flatness calibration of the Z-mirror. The complete top surface of the artefact is measured with the capacitance probe; the measurement result is a sum of the flatness deviations of the mirror and the reference artefact. The flatness of the reference artefact is known from optical calibrations; subtracting this from the measurement result, only the flatness of the Z-mirror remains. A similar calibration is performed for the X- and Y-mirrors, by measuring the sides of the same artefact.

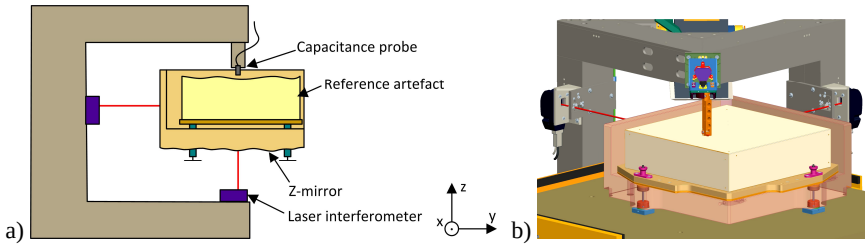


Figure 3: Flatness calibration of the Z-mirror; a) concept sketch; b) complete setup

2.2 Optical flatness calibration of reference artefact

The flatness of all three sides of the Zerodur reference artefact is calibrated using Fizeau interferometry. In each of these optical calibration measurements, the artefact is in the same orientation as it is during mirror table calibration on the Isara 400. The top surface of the artefact was measured in a custom interferometric test

configuration with the surface normal vertical and supported exactly as it is during calibration measurements on the machine, so no additional sagging needs to be taken into account. This optical calibration provides the flatness map shown in figure 4a. The expanded measurement uncertainty of the optical calibration is evaluated to be <10 nm (using an approach as described in [5]); figure 4b shows uncertainty map.

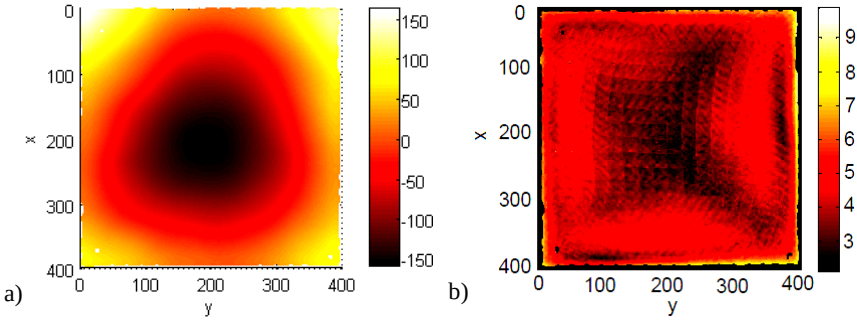


Figure 4: Optical flatness calibration of the artefact's top surface, performed by Zygo Corporation, all colour scales in nm; a) flatness map, b) uncertainty map (k=2).

2.3 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. As the out-of-squareness of the artefact has not been accurately calibrated, error separation needs to be applied.

The three sides of the artefact are measured by the capacitance probe; the mutual angle between the three measured planes is thus determined. This result is a combination of the out-of-squareness of the mirror table and that 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 $M1=\varphi-\alpha_{YZ}+90^{o}$, where φ and α_{YZ} are the out-of-squarenesses of the artefact and the mirror table, respectively. In the second orientation, the measured angle is $M2=\varphi+\alpha_{YZ}-90^{o}$. Because the contribution of α_{YZ} changes sign between the two measurement results, it is possible to determine

both φ and α_{YZ} from these two measurements: $\alpha_{YZ}=½\cdot(180-M1+M2)$ and $\varphi=½\cdot(M1+M2)$. A similar strategy is used for the other out-of-squareness errors.

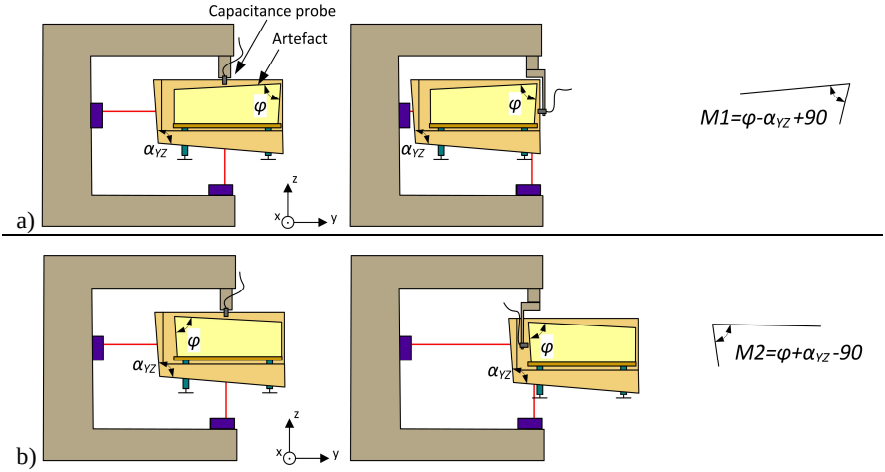


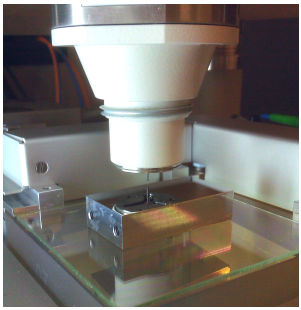
Figure 5: Out-of-squareness calibration of the Y- and Z-mirrors; a) artefact in orientation 1; b) artefact in orientation 2.

3 Tactile probe calibration

The design and calibration of the "Triskelion" probe system is described in detail in [6]. 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 newly developed miniaturized version of this probe system features a stylus with a tip diameter of about 70 µm. This small tip enables measurements of very small features, such as the inside diameter of very small holes (up to 1 mm depth).

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 6 (unfiltered data). For probe tip deflections ≤ 5 µm, measurement errors are < 10 nm per axis of the coordinate system and < 15 nm in 3D. In addition to the sensitivity calibration, a geometrical calibration of the (spherical)

probe tip is required; calibration of the absolute radius and a complete map of the sphericity errors will be the next step in the calibration of this probe system.

a) 

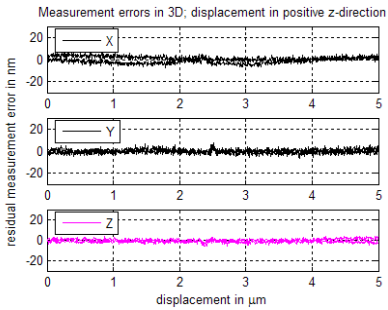
b) 

Figure 6: a) Photograph of miniature probe in CMM. b) Residual measurement errors (x,y,z) for probing in z-direction

4 Conclusions

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

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