第 19 卷　第 9 期
2011 年 9 月

光学 精密工程
Optics and Precision Engineering

Vol. 19　No. 9
Sep. 2011

Reading Guidance of papers received in ICOPEN2011

The International Conference on Optics in Precision Engineering and Nanotechnology (ICOPEN) was organized by the Optics and Photonics Society of Singapore (OPSS) from 23-25 March, 2011 and held in the Singapore EXPO. The Conference is featured with prominent keynote speakers from the international arena, as well as over 100 speakers in the relevant fields, coming from around the world.

Optics is considered to be a new driving force in the fields of precision engineering and nanotechnology. This Conference was timely to bring together the leading researchers both from industry and academia to discuss the leading-edge technologies and research progress in these related fields. A number of papers were selected to be published in the *Journal of Optics and Precision Engineering*. These selected papers relate to comtemporary topics or research fields, including small optical probes for optical coherence tomography, aspherical microlens modules for high speed data transmission, an evaluation method for nano-stage movement, TIR illumination technology for defect inspection, tandem photovoltaic cells, a large deformation measurement technique, design and calibration of ultra-precision CMM, nonlinear optical properties of lead sulfide nanoparticles, applications of fiber Bragg gratings, nano-scale thin metal films, *etc*. Details are available in the following papers.

文章编号　1004-924X(2011)09-2236-06

“Isara 400”超精密坐标测量机的设计与标定

Henny Spaan*, Ivo Widdershoven, Rilpho Donker
(IBS Precision Engineering, Esp 201, 5633AD, Eindhoven, The Netherlands)

摘要：介绍了 Isara 400 3 维超精坐标测量机标定的关键技术，包括平台标定和系统镜面台非垂直度标定。同时，提出了一种新的超精接触探针系统，给出了这种 3 维灵敏度探针的标定结果。

关　键　词：纳米技术；坐标测量机；接触探针；标定
中图分类号：TH72　　**文献标识码：**A　　**doi：**10.3788/OPE.20111909.2236

Design and calibration of “Isara 400” ultra-precision CMM

Henny Spaan*, Ivo Widdershoven, Rilpho Donker

(*IBS Precision Engineering*, *Esp* 201, 5633*AD*, *Eindhoven*, *The Netherlands*)
* *Corresponding author*, *E-mail*: *spaan@ibspe.com*

Abstract: This paper presents critical aspects of the calibration of the Isara 400 ultra-precision 3D Co-

---

Received date: 2011-03-08; **Revised date:** 2011-04-30.

Foundation item: Supported by Nano CMM(No. FP6-026717-2) and Production 4μ(No. FP6-2004-NI-4)

ordinat Measuring Machine(CMM), 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 and the results of the 3D sensitivity calibration of this probe are presented.

Key words: nanotechnology; Coordinate Measuring Machine(CMM); touch probe; calibration

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 mm × 400 mm × 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. 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.

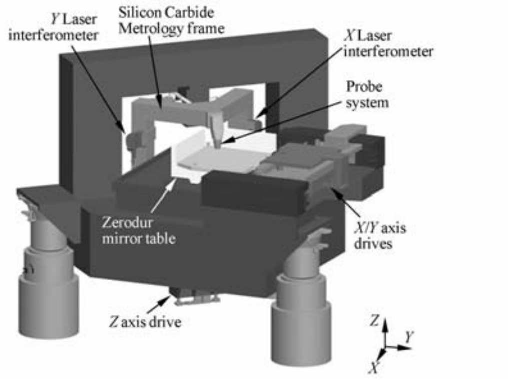


Fig. 1　3D design concept of the Isara 400 CMM

Fig. 1 and Fig. 2 show 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 no first-order influence on the measurement result.

Fig. 2　Photograph of the Isara 400 CMM

The product is mounted on the mirror table, which moves only in the 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. Fig. 3 shows the mirror table and the X/Y-drives; for more details see [1]. Work pieces are not placed directly onto the Zerodur, but onto a removable silicon carbide (SiC) product table, which serves as an interface between the product and the mirror table. The weight of the product table with the 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 the Z-direction, with guiding provided by air bearings against a vertical granite surface. The me-

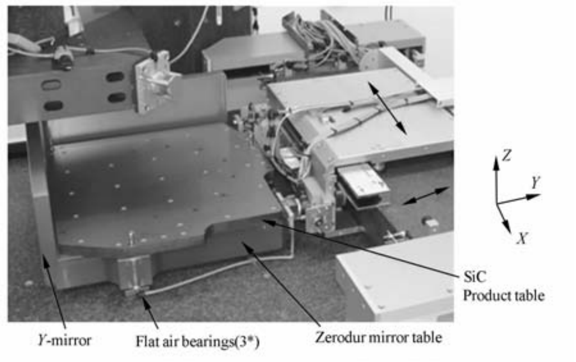


Fig. 3 Zerodur mirror table and X/Y drives

trology frame, shown in Fig. 4, 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.

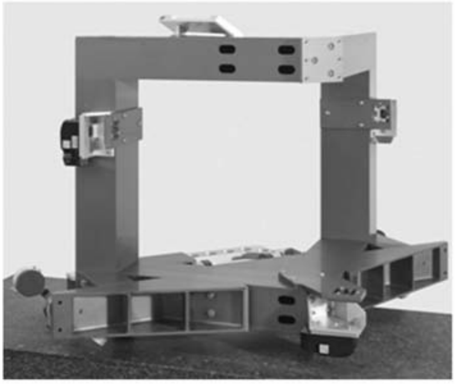


Fig. 4 Silicon carbide metrology frame

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 [2], 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.

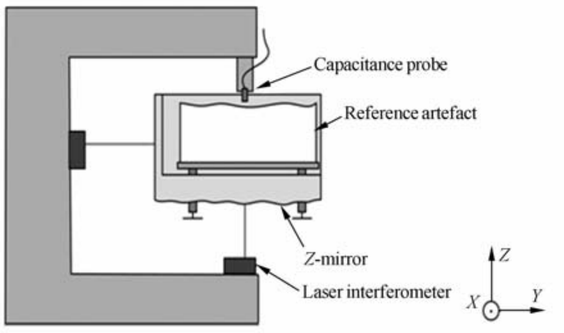


Fig. 5 Flatness calibration of the Z-mirror (concept sketch)

Fig. 5 and Fig. 6 show 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 the sum of the flatness deviations of the mirror and the reference artefact.

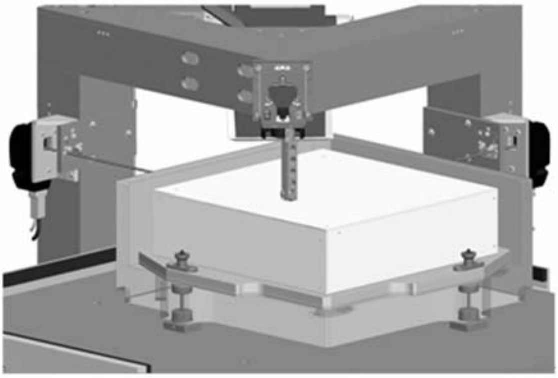


Fig. 6 Flatness calibration of the Z-mirror (3D model)

The flatness from the reference artefact is known from optical calibrations; by subtracting this from the measurement result, only the flatness deviation of the Z-mirror remains. A similar calibration is performed for the X- and Y-mirrors, by measuring the sides of the same artefact.

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 Fig. 7. The expanded measurement uncertainty of the optical calibration is evaluated (using an approach as described in [3]) to be <10 nm; Fig. 8 shows the uncertainty map.

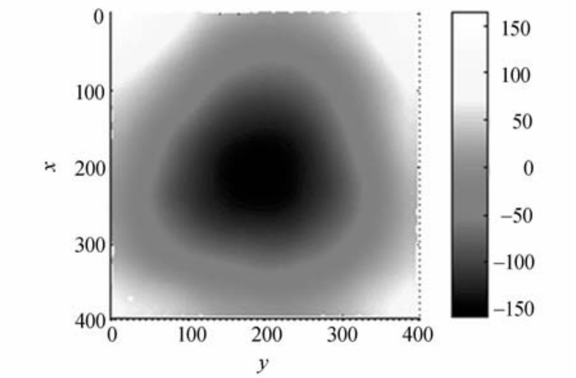


Fig. 7　Flatness map from optical flatness calibration of the artefact's top surface, performed by Zygo corporation (colour scale in nm)

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.

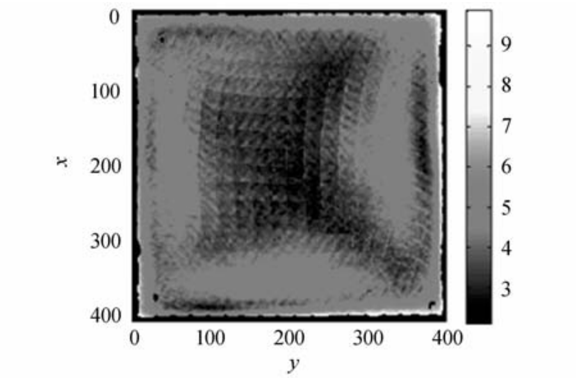
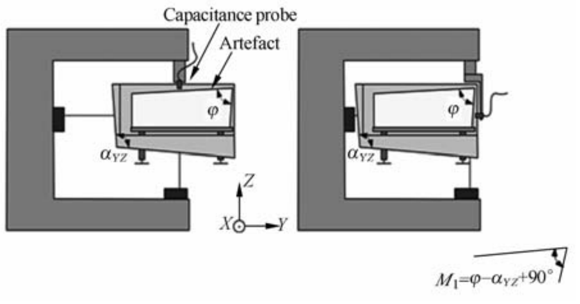
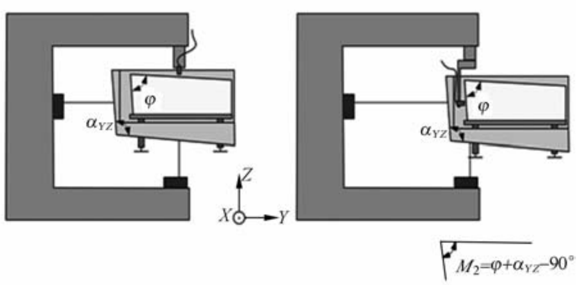


Fig. 8　Uncertainty map from optical flatness calibration of the artefact's top surface (colour scale in nm)

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.



(a) Artefact in orientation 1



(b) Artefact in orientation 2

Fig. 9　Out-of-squareness calibration of the *Y*- and *Z*-mirrors

The procedure for one specific out-of-squareness angle is shown in Fig. 9. 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 $M_1=\varphi-\alpha_{YZ}+90^\circ$, 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 $M_2=\varphi+\alpha_{YZ}-90^\circ$. 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: $\alpha_{YZ}=1/2\cdot(180^\circ-M_1+M_2)$ and $\varphi=1/2\cdot(M_1+M_2)$. A similar strategy is used for the other out-of-squareness errors.

3 Tactile probe calibration

The design and calibration of the "Triskelion" probe system is described in detail in [4]. The design features include an elastically suspended stylus, which is free to deflect in the *X*-, *Y*- and *Z*-direction at its tip; this deflection is measured by three capacitance sensors which are integrated into the probe system. A newly developed miniaturized version of this probe system features a stylus with a tip diameter of about 70 μm. The small tip enables measurements of very small features, such as the inside diameter of very small holes (up to 1 mm depth).

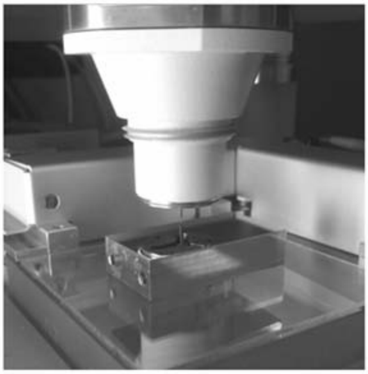


Fig. 10 Photograph of miniature probe in CMM

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 Fig. 11 (unfiltered data). For probe tip deflections ≤5 μm, measurement errors are <10 nm per axis of the coordinate system and <15 nm in 3D.

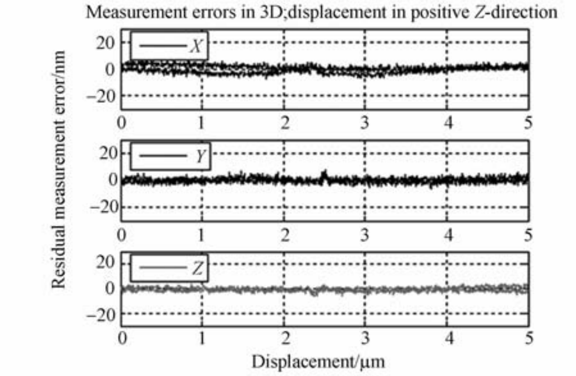


Fig. 11 Photograph of miniature probe in CMM

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.

5 Acknowledgements

The work presented in this document is part of the European sixth framework programme projects NanoCMM, FP6-026717-2 and Production4μ, FP6-2004-NI-4.

The authors wish to thank ZYGO Corporation for their contribution regarding the optical calibration of the reference artefact.

References:

[1] DONKER R L,WIDDERSHOVEN I, SPAAN H A M. Isara 400: enabling ultra-precision coordinate metrology of large parts[C]. *Proceedings of the 10th International Euspen Conference*, *June* 2010.

[2] RUIJL T A M. *Ultra Precision Coordinate Measuring Machine - Design, Calibration and Error Compensation*[D]. Delft University of Technology, Netherlands, 2001.

[3] EVANS C J,SMITH C,SOOBITSKY J,*et al*.. Full area calibration of large optical flats[C]. *Proceedings of the ASPE spring topical conference*, *April* 2009.

[4] HENNY A M, RILPHO L, IVO WIDDERSHOVEN. Isara 400: development of an ultra-precision CMM for 3D measurement of large parts[C]. *Proceedings of the ASPE Spring Topical Conference*, *April*,2009.

Authors' biographies:

Henny Spaan, PhD. is a managing director of IBS Precision Engineering, Eindhoven, the Netherlands, which he created in 1993 in parallel with finishing his PhD in precision engineering at Eindhoven University. Since then he has evolved the company into an internationally recognized expert in ultra precision metrology systems with its headquarters in Eindhoven (NL), subsidiaries in Evry (F), Stuttgart (D) and agents in Japan, Korea and USA. E-mail: spaan@ibspe.com