Isara 400 features

In various fields of manufacturing and research, a growing demand for ultra-precise 3D measurement of large products exists. To fulfil this demand, IBS Precision Engineering is developing a new ultra-precision coordinate measuring machine (CMM) with an unprecedented ratio of measurement volume vs. measurement accuracy. This article presents the design concept, various design details and the realization of the Isara 400 CMM.

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In collaboration with Philips Applied Technologies, IBS PE previously developed the Isara CMM, an ultra-precision 3D coordinate measuring machine (CMM), based on the design by Ruijl [1], with a measuring volume of 100 x 100 x 40 mm and a 1D measuring uncertainty of 15 nm; see Figure 1. Similarly, other ultra-precision measuring machines [2] [3] have been developed, which also typically feature measuring ranges ≤ 100 mm. In response to the demand for 3D measurement of larger products with features that require nanometer measuring uncertainty, the new Isara 400 ultra-precision CMM is being developed.

Figure 1. The first Isara CMM.

‘mega volume’ vs ‘nano accuracy’

Isara 400 concept

The new 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 2.
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 [4] 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; see Figure 3. The product is mounted on the mirror table, which moves only

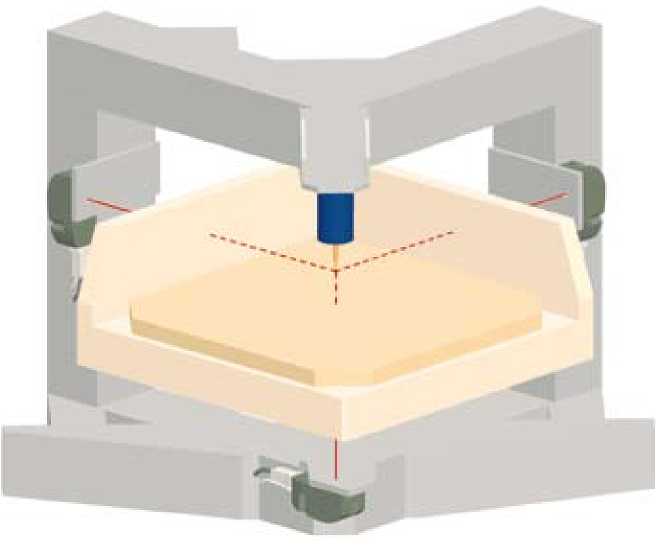


Figure 2. The 3D Abbe principle of the Isara 400 CMM.

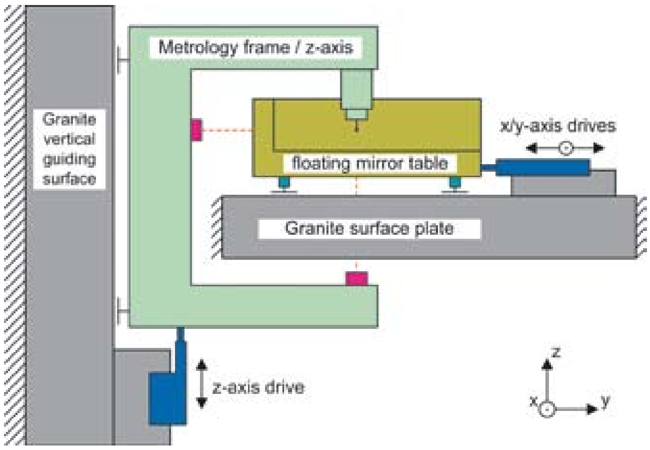


Figure 3. Concept of the Isara 400 CMM.

in X- and Y-direction over a granite plate, guided by air bearings. The complete metrology frame moves in Z-direction, with guiding provided by air bearings against a vertical granite surface. This metrology frame contains the three laser interferometers and the probe, thus maintaining the Abbe alignment.
The Isara 400 CMM features several design principles that are required for precision measurement machines [5]. The design of several key components is described in the next sections.

Mirror table

The mirror table of the Isara 400 is a monolithic Zerodur part with three reflective sides; see Figure 4. An additional product table is used as an interface between product and mirror table. This Silicon Carbide (SiC) product table was designed to be both light and stiff. The three supports of the product table are placed directly above the three supports of the mirror table, so that the weight of the product and product table does not cause additional deformation of the mirrors. The mirror table is supported by three flat air bearings, whose preload is provided by the weight of the mirror table assembly with product.
The coupling between the floating mirror table and the X-carriage, see Figure 4, must define three degrees of freedom (X, Y and Rz) and allow for differences in thermal expansion. As the coupling is directly connected to the

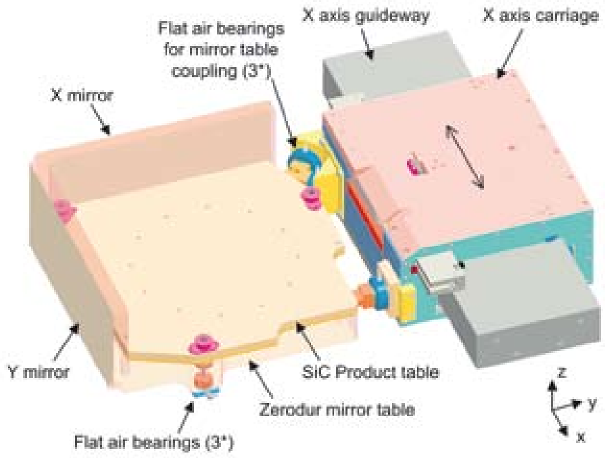
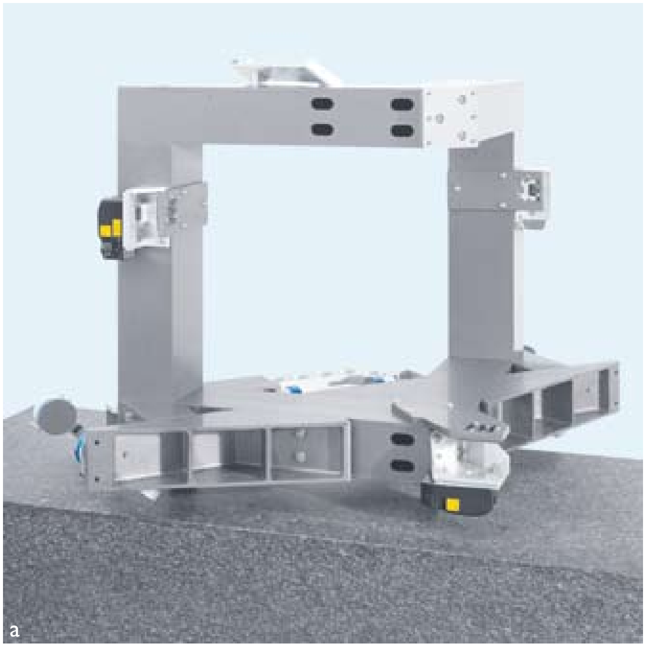


Figure 4. Floating mirror table and X-axis drive.

mirror table, it must be very compliant for parasitic motions between the mirror table and the X-carriage (Z, Rx and Ry); such parasitic motions should not cause deformations of the mirrors. Especially the flatness of the Z-mirror is sensitive to forces exerted by the coupling due to such motions. Parasitic motions may result from non-flatness and non-parallelism of the X-Y guideways and sagging of the guideways because of the moving parts. Furthermore, the coupling must deal with different fly heights of the floating table resulting from different product loads.
The selected coupling concept consists of three air bearings which are mounted onto the side of the mirror table. One bearing is placed normal to the X-axis carriage, while the other two are placed under a 45° angle, thus fixing the X, Y and Rz degrees of freedom. Influences from vertical motions and also thermal effects will not lead to forces acting on the mirrors, because the frictionless coupling of the bearings cannot transmit any forces in Z direction. The parasitic Ry motions will only act on the two bearings at the back side, Rx motions will act on all three bearings. An error budget was made of all possible parasitic rotations and the worst case situation was used as input for a finite element method analysis. With this design, the effect on the flatness of the three mirrors was found to be < 1 nm. As the three bearings are only required to move over a few micrometers, the preloading can be achieved by adding extension springs directly to the bearings. These compliant springs will cause a force-closed preload for the bearings. The influence of those springs on the mirrors was also calculated and found to be negligible.

Metrology frame

The metrology frame, shown in Figure 5a, has to maintain the mutual position and alignment of the probe and the three laser interferometers with high stability. This means that it should be very stiff, so that deformations due to acceleration forces are small, but also that its thermal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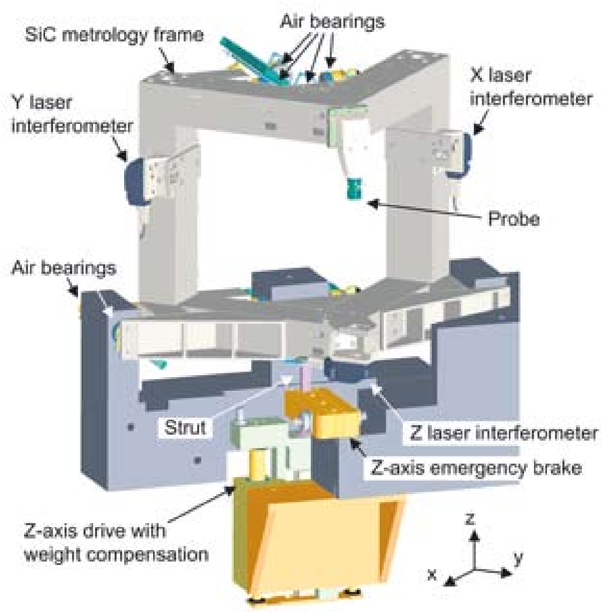

b

Figure 5. The metrology frame.
(a) Actual construction.
(b) Schematic, also showing the Z-axis drive. Granite guiding surfaces are shown only partially.

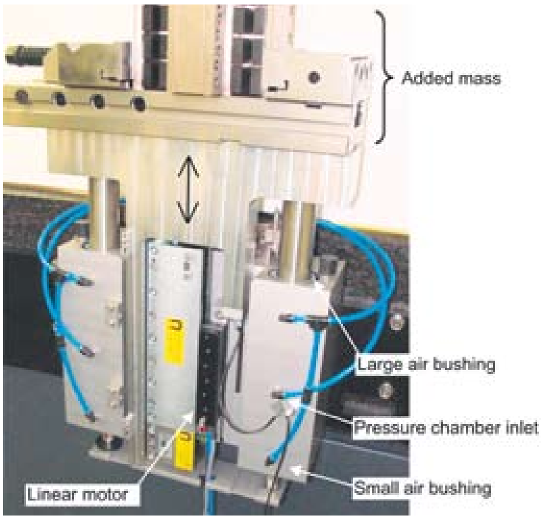

Figure 6. The Z-axis drive with weight compensation system.

expansion needs to be very low. In addition, as the metrology frame in this design is translated vertically, it is preferable that its mass be as low as possible. The metrology frame is an assembly of SiC beams. Although this material has a larger thermal expansion than for example Invar, it has a much better specific stiffness (ratio of elasticity modulus vs density) and better thermal conductivity. The metrology frame is statically determined in six degrees of freedom by means of five flat air bearings and a strut joint to the Z-drive. All bearings are preloaded with flat air bearings on the opposite side. As the machine is a multi- probe machine, it contains a kinematic probe mount for a quick and reproducible exchange of probes. The Z-drive moves the metrology frame in the vertical direction. It is placed below the metrology frame and connects with a strut directly through the centre of mass. Around the coupling strut an emergency brake is placed which can hold the metrology frame in place by clamping the strut, for example when no electric or pneumatic supply is present, see Figure 5b.

The Z-drive contains an air bearing guide for the linear motor, with an integrated weight compensation system, see Figure 6. This bearing system consists of two shafts; each shaft is guided in two cylindrical air bearings (bushings) with different diameters. The space inbetween is sealed by the two bushings, thus serving as a pressure chamber. By supplying exactly the right air pressure, the weight of the metrology frame can be compensated and equilibrium is achieved. As a result, the required force from the linear motor to hold the metrology frame in place is minimized. The heat generation of this drive is therefore very low. The Z-drive shown in Figure 6 is currently being tested.

Ultra-precision probe

Conventional touch probes are generally not suitable for ultra-precision coordinate metrology, due to their relatively high measuring uncertainty and large probing forces, and their ability to measure small features is limited, due to the relatively large probe tips that are applied. Several different ultra-precision touch probes developed over the past years [6] [7] [8] [9] share a common design feature: the stylus is elastically suspended, allowing deflection of the probe tip and thus reducing probing forces. This deflection is measured by means of an integrated measurement system within the probe. Building on these previous efforts in the development of ultra-precision touch probes, the new Triskelion probe system was developed; see Figure 7.

Figure 7. Triskelion ultra-precision probe.

The stylus, which consists of a stiff tungsten carbide shaft with a small ruby sphere (Ø 0.5 mm) at the end, is elastically suspended, thus allowing deflection of the tip during probing measurements. The flexure part is a monolithic foil. Three targets for the capacitive probes are integrated in the leaf-spring design. The displacements of these targets are measured with capacitive sensors and can be used to determine the X, Y and Z deflections of the probe tip. Except for the sensors, the stylus and the probe tip, the complete probe is made from invar to ensure good thermal stability.

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. The table is then displaced and the output signals of the probe are measured simultaneously with the table displacement, which is measured by laser interferometer systems. By repeating this measurement for multiple probing directions, a full 3D calibration model of the sensitivity is obtained. This sensitivity calibration is validated by performing additional probing measurements. For all measurements, the absolute measurement errors are < 10 nm per axis of the coordinate system and < 15 nm in 3D. Several product measurements have been performed, using the new probe system integrated into an ultra-precision CMM. Figure 8 shows the measurement of an aspherical mould insert and the corresponding form error of the profile measurement across the center, which is obtained after subtraction of the theoretical asphere.

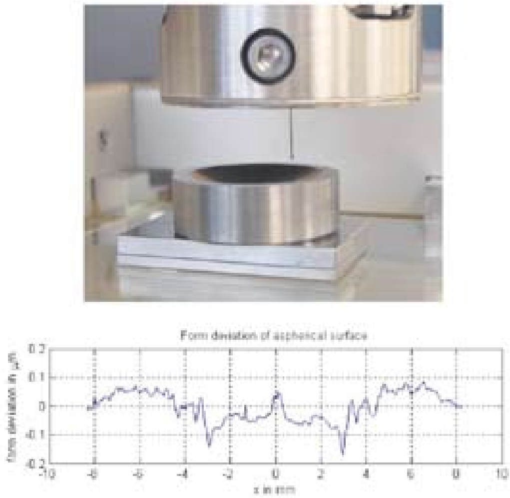

Figure 8. Aspheric mould measurement using the Triskelion probe.

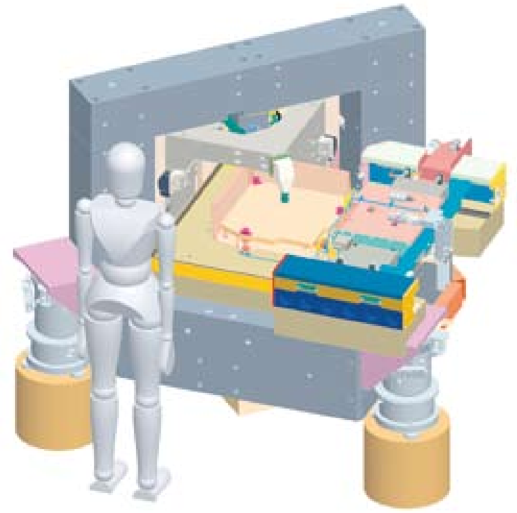

Figure 9. Overview of the Isara 400 CMM.

Measuring uncertainty

An extensive uncertainty analysis was performed to make an accurate estimation of the expected measuring uncertainty of the Isara 400 CMM. Some of the most important contributing factors are the uncertainty of the laser interferometers, the calibration uncertainty of the mirror table (flatness and perpendicularity), the stability of the metrology frame and the measurement uncertainty of the probe. For all axes, the expected 1D measuring uncertainty is 45 nm (2σ), whereas the full-stroke 3D measuring uncertainty totals 100 nm (2σ). Both values include contributions from the described probe system and are valid within the complete measuring volume of the machine.

Conclusion

The new Isara 400 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 within the complete measuring volume of 400 x 400 x 100 mm. Tactile probes, such as the presented Triskelion ultra-precision touch probe, as well as other possible (optical) probe systems can be used to perform scanning or point measurements. The machine, see Figure 9, provides a technology basis which can be adapted and optimized for specific user requirements. It will be operational by the end of 2009.

Authors' note

The authors work at IBS Precision Engineering, headquartered in Eindhoven, the Netherlands, Rilpho Donker as a senior mechanical designer, Ivo Widdershoven as a metrology expert, and Henny Spaan is the managing director.
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