High-Accuracy CMM Metrology for Micro Systems.

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Abstract
The increasing use of micro systems in industry combined with an ever-increasing demand for higher measurement accuracy has led to ongoing developments in the field of dimensional metrology. Recently, several measuring machines suitable for measuring micro mechanical products have been introduced to the market. This article aims to give an overview of the state-of-the-art methods for these measurement tasks.

Introduction

Conventional measuring methods restrict the possibilities for three-dimensional measurements on micro products. Conventional Coordinate Measuring Machines (CMMs) lack the required level of uncertainty, Atomic Force Microscopes (AFM) lack the required range and optical methods are often not suitable for true three-dimensional measurements. Examples include the measurements of small holes (e.g. fuel injection nozzles), LIGA products, Micro Electromechanical Systems (MEMS), etc. Some available products that are currently available are given in Fig. 1.

Fig. 1 Example products, from left to right: microturbine (MIT), array of needles (IMM Mainz), Pennymotor within bearing (Micromotion) and piezo-motor (Miniswys)

The first section of this paper covers some of the available measuring machines suitable for measuring MEMS. Then some important issues with respect to probe design are discussed and some examples of available probe systems are given. Finally the calibration results and recent developments of the probe system, developed at the Eindhoven University of Technology, will be discussed.

Coordinate Measuring Machines for Micro Products

Generally speaking there are two ways to approach the measuring of micro products: bottom-up and top down. The top-down approach is done by improving conventional CMMs. These have excellent range, but lack the needed uncertainty for measuring micro products. The bottom-up approach aims at increasing the measurement range of nano-metrology devices, like the Atomic Force Microscope (AFM) and Scanning Probe Microscope (SPM).

AFM and SPM measuring techniques are typically used for surface characterisation. For True 3D measurements it is often more advantageous to use a CMM. Several CMMs have been recently introduced achieving an uncertainty of 100 nm or better and enabling three-dimensional scanning of micro products. Most notable are the designs by Ruijl [1], Vermeulen [2], van Seggelen [3], Peggs [4] and Oiwa [5], which will be discussed briefly.

The design by Ruijl [1] is composed of a metrology frame with thermal shielding on which three laser sources are mounted, as seen in Fig. 2. The laser beams point straight at the tip of the probe used, thus minimising Abbe errors. The workpiece table is made from zerodur to minimize thermo-mechanical effects and can be translated using Lorentz-actuators. A mechanism is used to compensate for the weight of the workpiece, thus decreasing the power dissipation in the actuators.

Range:	100 x 100 x 40 mm	3D Uncertainty:	30 nm

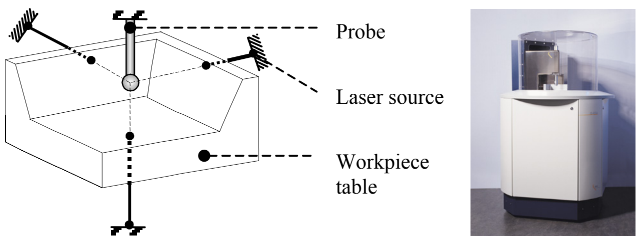

Fig. 2 Operating principle and picture of the ‘Isara’ CMM by Ruijl

Vermeulen [2] uses linear scales to measure the position of the probe tip. The measuring heads for the scales in the horizontal plane are mounted on two intermediate bodies, as shown in Fig. 3. When the probe tip is in the horizontal plane of the slides the probe tip position is measured in Abbe. The design also features air bearings for high repeatability and small power dissipation in the slides and a frame based on closed boxes to obtain a light and stiff construction.

Range:	100 x 100 x 50 mm	3D Uncertainty:	100 nm

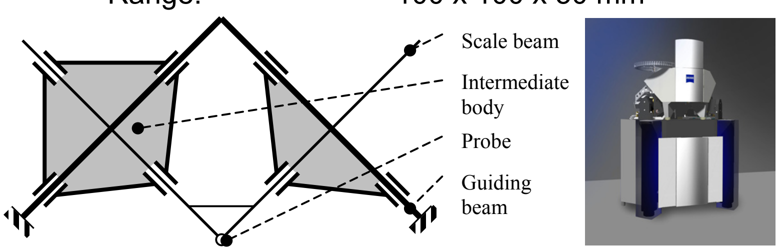

Fig. 3 Operating principle and ‘artist impression’ of the ‘F25’ CMM by Vermeulen

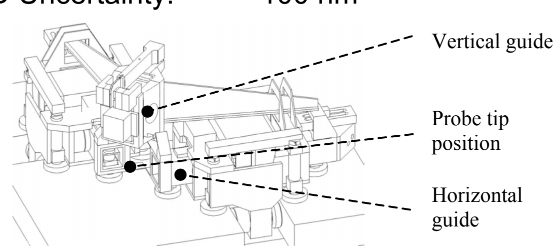

Fig. 4 Schematic of the CMM by van Seggelen

Van Seggelen [3] designed a CMM based on the design by Vermeulen, as shown in Fig. 4. His design is intended for measuring micro products in an array setup. The vertical stroke is thus limited to 4 mm. This assures the Abbe offset is less than 2 mm and enables the use of elastical guides. As a result the dynamic mass is kept low (approximately 8,5 kg), enabling high-speed measurements and decreasing heat generation in the linear DC motors.

Range:	50 x 50 x 4 mm	3D Uncertainty:	25 nm

Peggs [4] build a high-accuracy CMM using a conventional CMM as a moving table. The workpiece is fixed on an Invar® table and the position of the probe tip is measured using three laser interferometer systems, as seen in Fig. 5. To compensate for Abbe errors angular deviations of the mirrors are measured via an autocollimator. Each autocollimator uses a laser beam that reflects from the measurement mirror. The position of this beam onto a 4-quadrant photo-detector is used to calculate the angular variations.

Range:	50 x 50 x 50 mm	3D Uncertainty:	50 nm

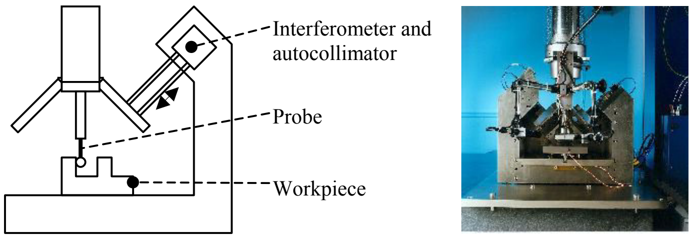

Fig. 5 Operating principle and picture of NPL's 'Small CMM'

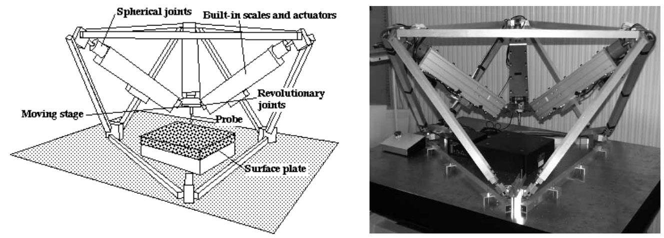

Fig. 6 Operating principle and picture of the CMM by Oiwa.

A more exotic CMM is designed by Oiwa [5]. The design is based on an octahedral frame in which the probe stage is supported by three struts, as seen in Fig. 6. The struts can be expanded or contracted using three AC servomotors and ball screws. A linear scale is integrated into each strut, thus measuring its length variations.

Range:	120 x 120 x 120 mm	3D Uncertainty:	250 nm

Other designs worth mentioning here are the designs by Jansen [6], Takamasu [7], Dai [8], Mitutoyo [9], Panasonic [10], Kramer [11], Shiozawa [12] and Jäger [13].

Limitations of the measuring instrument

The uncertainty of these CMMs is often limited by the uncertainty of the measuring instrument. As described by Franks [14] no instrument measures topography alone. A mechanical probe will also respond to changes in the mechanical properties of the surface (Young's modulus, hardness, etc.), an optical probe will respond to reflectivity and optical constants, a scanning tunnelling microscope (STM) responds to electrical properties of the surface, etc. The influence of surface properties on a measurement becomes increasingly apparent in the micro- and nanometer region.

Several optical measurement methods are available offering low uncertainty in the plane of the measurement. However for true 3D measurements these systems often do not suffice, as shown in Fig. 7.

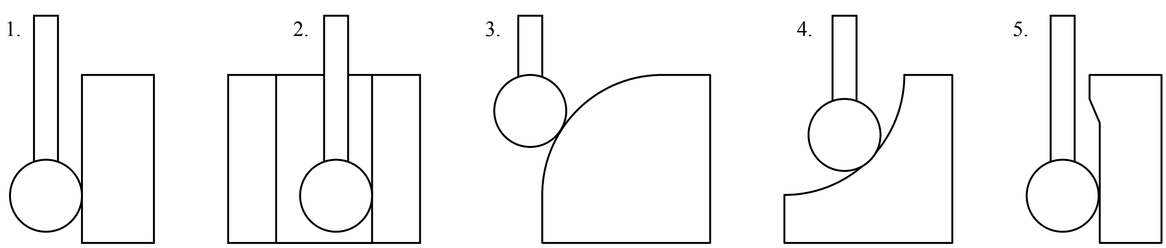

Fig. 7 Limitations of optical measurement techniques: (1,2): shape, diameter and cilindricity on varying heights, (3,4): radius of edge and (5): measurement under burr

For these tasks mechanical probes are better suited. Generally mechanical probes can be divided into touch-trigger probes and measuring probes. For achieving nanometer uncertainty touch-trigger probes are at present not suitable. Therefore the remainder of the article will focus on mechanical measuring probes.

One of the critical aspects when using mechanical probes is the surface-probe interaction. In order to avoid plastic deformation to the workpiece the static and dynamic forces during a measurement should remain small. This is especially true for probe tip diameters of 1 mm or less. This will be discussed in the next section.

Static forces

Static probing forces result from CMM over-travel. At a measurement speed of 1 mm/s the over-travel is typically 7 μm. The resulting force between a workpiece and probe tip can be calculated by multiplying the over travel distance Δx_o by the stiffness of the probe suspension c_{probe}. To avoid plastic deformation between a planar workpiece and a spherical tip equation 1 should hold:

$$\Delta x_o \, c_{probe} \leq \frac{\pi^3 \, p_o^3 \, r_{red}^2}{6 \, E_{red}^2} \qquad [1]$$

Where:

p_o Maximum occurring Von Mises stress in the plane, material dependent
r_{red} Reduced radius, for a planar workpiece this equals the probe tip radius
E_{red} Reduced E-modulus, for an infinitely stiff probe tip this equals the E-modulus of the workpiece material.

It should be clear that when using small probe tips (< 1 mm in diameter) one should either decrease the approach speed or decrease the stiffness of the suspension. It is calculated that for a 300 μm probe tip the suspension stiffness should be 200 N/m or less to avoid plastic workpiece deformation [15].

Another issue with respect to the stiffness of the probe suspension is the virtual play during a measurement. Due to surface forces and forces due to CMM over travel during scanning, the probe tip exerts a force *F* on the workpiece surface. During scanning of the workpiece friction as a result of these forces results in a stick-slip effect of the probe tip across the surface. This virtual play is approximated by:

$$\Delta x_{play} = \frac{\mu F}{c_{probe}} \qquad [2]$$

Where:

Δx_{play} Virtual play
μ Coefficient of friction

The suspension stiffness c_{probe} should therefore be small enough to avoid plastic deformation, but high enough to decrease the virtual play to an acceptable level.

Dynamic forces
The critical parameter with respect to the dynamic forces during probing is the dynamic probe mass. This is the equivalent mass of all components rigidly connected to the probe tip, i.e. the mass that is felt when trying to accelerate the probe tip. In most any probe the dynamic mass is highest when probing in the direction of the stylus.

During a collision between probe tip and workpiece the kinetic energy will be transformed into deformation energy. In order to prevent plastic deformation from occurring the kinetic energy should be less than the maximum energy which can be absorbed elastically by the material, as given by equation 3.

$$\tfrac{1}{2} m v^2 \leq \frac{\pi^5 r^3 p_0{}^5}{60 E_{red}^4} \qquad [3]$$

Where:
m Dynamic probe mass
v Relative speed between probe and workpiece

In order to avoid plastic deformation it is thus needed to decrease the approach speed or decrease the dynamic mass. It is calculated that for a probe tip with a diameter of 300 μm the dynamic mass should be 20 mg or less in order to avoid plastic deformation [15].

Developments in Probes for Micro Products
Several probes have been designed achieving an uncertainty of 100 nm or better. Most notable are the designs by Pril [15], Brand [16], Peggs [4], Guijun [17], Meli [18] and Mitutoyo [9].

Pril [15] designed a probe based on silicon technology, as shown in Fig. 8. The probe tip, stylus and intermediate body are suspended statically determinate using three slender rods, which enable motion in the vertical direction and pseudo translations in the horizontal plane. The probe features a mean thermal drift of 2 nm/hour, a dynamic mass of 20 mg, thus enabling high-speed measurements, and controllable suspension stiffness, thus preventing plastic workpiece deformation and minimizing virtual slip.
3D Uncertainty: 20 nm Measuring range: 20 μm

Fig. 8 ‘Nano probe’ by Pril

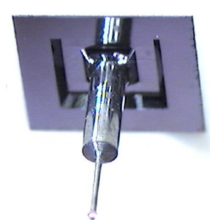

Fig. 9 ‘Boss micro sensor’ developed at the PTB.

Fig. 10 Picture of ‘NPL probe’ by Peggs.

Brand [16] et al. also developed a probe based on silicon technology, as shown in Fig. 9. A commercial stylus is used which is shortened to 5 mm and attached to the membrane using epoxy adhesive. Piezo resistive strain gauges on the backside of the membrane measure the 3D displacement of the probe tip.
3D Uncertainty: 50 nm Measuring range: 20 μm

Peggs [4] developed a probe based on capacitive sensors. The flexture stucture is made from tungsten carbide tubing and berylliumcopper strips, as seen in Fig. 10. Thus a stiff and lightweight constructions is obtained (dynamic mass approximately 370 mg). The suspension is isotropic and its stiffness is 10 N/m.

3D Uncertainty: 40 nm Measuring range: 20 μm

Guijun [17] developed a 2D opto-tactile micro probe. The stylus is composed of a thin fiber with a probe tip melted at the end of it. It is thus possible to create probe tip diameters as small as 25 μm and static measuring forces in the μN range. Schwenke [19] developed a 3D-probe with similar characteristics, as shown in Fig. 11. The probe tip is illuminated through the fiber and its position is detected by an optical imaging system and a CCD camera. For measuring z-displacements a second sphere is attached to the fiber.

3D Uncertainty: 500 nm Measuring range: > 1 mm

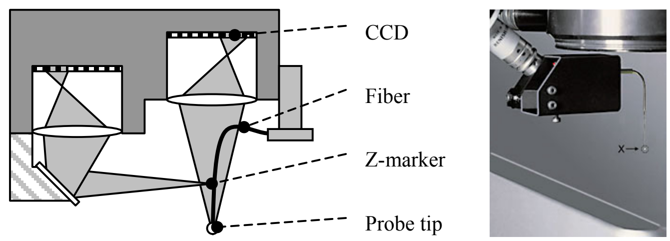

Fig. 11 Operating principle and picture of probe developed by Schwenke.

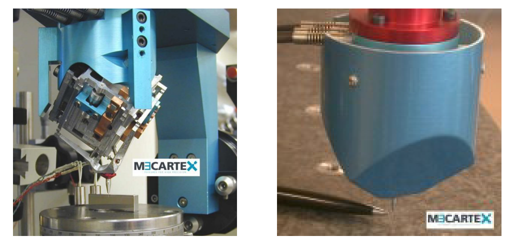

Fig. 12 Picture of probe designed by Meli.

Meli [18] designed a 3D probe based on parallel kinematics with flexure hinges, as seen in Fig. 12. The probe is manufactured from a single block of aluminium and is thus free of internal stress. Probe tip translations are measured using inductive sensors. The suspension is isotropic with a stiffness of 20 N/m. The dynamic mass is approximately 8 grams.

3D Uncertainty: 30 nm Measuring range: 200 μm

The probe by Mitutoyo [9] consists of a fiber on which a probe sphere is melted, thus enabling probe tips of 30 μm in diameter or bigger. The stylus is vibrated during the measurement and contact is detected by variations in the stylus's amplitude, as shown in Fig. 13.

3D Uncertainty: 200 nm Measuring range: 200 μm

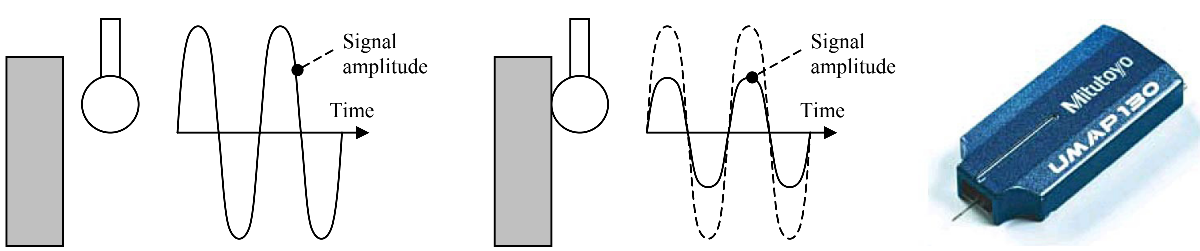

Fig. 13 Operation and picture of 'UMAP' probe by Mitutoyo.

Recent developments at the Eindhoven University

The Eindhoven University of Technology is working on improving the ‘nano probe’ designed by Pril. The research focuses on making the probe system cheaper, more accurate and suitable for ever-smaller probe tips. Commercial sapphire probe tips mounted on a stylus are available down to 300 micrometers in diameter. The smallest sapphire probe tip currently available is 125 micrometer in diameter and has been implemented by Meli on the probe system he developed. As discussed earlier these small tip diameters result in severe limitations with respect to the dynamic mass and suspension stiffness of the probe systems.

The anisotropy of the suspension as a result of silicon material properties can be counterweighted by adjusting the chip design. Thus, for a 4 mm stylus an isotropic behaviour can be obtained. Also work is being done on improving the design to facilitate its assembly and thus making the system even cheaper. Finally, calibrations are preformed in which the probe is measured against a laser interferometer on the setup shown in Fig. 14.

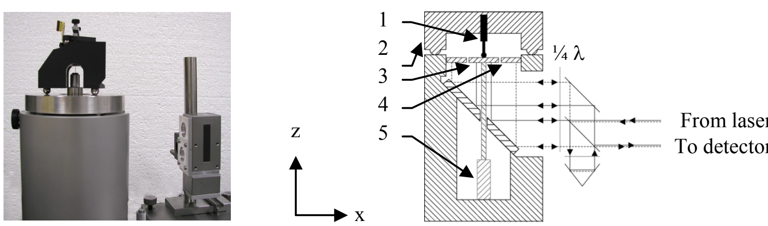

Fig. 14 Schematic and picture of the calibration setup of the ‘nano probe’

The probe (1) is placed in a bracket (2) using a kinematic coupling (Kelvin clamp). The probe tip measures the displacement of a measuring mirror (3). The measuring mirror can be displaced relative to a reference mirror (4) using a piezo actuator (5). This displacement is measured using a laser interferometer. Thus the displacement of the mirror as measured by the probe can be compared to the laser interferometer signal.

Results for a typical measurement are given in Fig. 15. The results for x and y in this figure are shifted 40 and 20 nm respectively. It can be seen that for a 4 μm displacement the 1D standard deviation is approximately 1,9 nm. The 3D standard deviation in this range is approximately 3,2 nm. The mean drift in the electronics and chip during a 65-hour measurement is less than 2 nm per hour, as seen in Fig. 15.

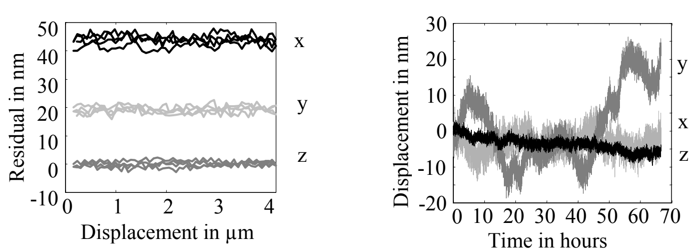

Fig. 15 Residuals for a 4 μm displacement and thermal drift in the electronics and chip

Conclusion

Several CMMs have been introduced, capable of measuring micro products. These CMMs are available with 3D measurement uncertainties of 25 - 250 nm. For 1D measurements the expected uncertainty is even better. As shown, the limiting factor is often the probe system used. For true 3D measurements a tactile measuring probe is in most cases best suited. It is shown that in order to avoid plastic deformation at approach speeds of 1 mm/s and using a spherical probe tip with a diameter of 300 μm the dynamic mass should be 20 mg or less and the stiffness of the probe suspension should be 200 N/m or lower. Also the uncertainty of the probe system used should be better than the uncertainty of the CMM. Several probe systems have been introduced, with probe tips down to 25 μm diameters and with 3D uncertainties of 20 - 500 nm.

References

[1] Ruijl, T.A.M., 2001, *Ultra Precision Coordinate Measuring Machine; Design, Calibration and Error Compensation*, ISBN 90-6464-287-7, PhD. Thesis, TUD

[2] Vermeulen, M.M.P.A., Rosielle, P.C.J.N., Schellekens, P.H.J., 1998, *Design of a high-precision 3D-coordinate measuring machine*, Annals of the CIRP, **47** (1), pp. 447-450

[3] van Seggelen, J.K., Rosielle, P.C.J.N., Schellekens, P.H.J., 2002, *Design of a 3-D CMM with elastically guided z-axis and x,y axis with less than 2 mm ABBE offset*, Proc. of EUSPEN, Eindhoven, The Netherlands, pp. 29-32

[4] Peggs, G.N., Lewis, A.J., Oldfield, S., 1999, *Design for a compact high-accuracy CMM*, Annals of the CIRP, **48**, pp. 417-420

[5] Oiwa, T., 1997, *New coordinate measuring machine featuring a parallel mechanism*, J. Japan Soc. Prec. Eng., **31** (3), pp. 232-233

[6] Jansen A.. Rosielle P.C.J.N Schellekens P.H.J., 1999, *A fully Elastically Guided Three-dimensional CMM with a measurement Volume of 1 cm^3*, ASPE, pp. 453-456

[7] Takamasu, K., Furutani, R., Ozono, S., 1997, *Development of Nano-CMM (Coordinate Measuring Machine with Nanometer Resolution)*, Proc. of IMEKO, **14**, p. 34-39

[8] Dai, G., Pohlenz, F., Danzebrink, H.U., Xu, M., Hasche, K., Wilkening, G., 2004, *A novel metrological large range scanning probe microscope applicable for versatile traceable topography measurements*, Proc. of EUSPEN, Glasgow, Scotland, pp. 228-229.

[9] Mitutoyo, *UMAP Vision System*, Bulletin No. 1631

[10] Panasonic, 2003, *Ultrahigh Accurate 3-D Profilometer*, Catalog

[11] Kramar, J.A., Jun, J.S., Penzes, W.B., Scire, F.E, Teague, E.C., Villarrubia, J.S., 1999, *Molecular Measuring Machine Design and Measurements*, Proc. of EUSPEN, Denmark, May 28-30, 2000, pp. 34-44

[12] Shiozawa, H., Fukutomi, Y., Ushioda, T., Yoshimura, S., 1998, *Development op ultra-precision 3D-CMM based on 3-D metrology frame*, proc. ASPE, **18**, pp. 15-18

[13] Jäger, G., Manske, E., Hausotte, T, Büchner, H.J., 2000, *Laserinterferometrische Nanomessmachinen*, VDI Berichte 1530, Sensoren und Messsysteme 2000, pp. 271-278

[14] Franks, A., 1991, *Nanometric surface metrology at the National Physical Laboratory*, Nanotechnology, **2**, pp. 11-18

[15] Pril, W.O., 2002, *Development of High Precision Mechanincal Probes for Coordinate Measuring Machines*, ISBN 90-386-2654-1, PhD. Thesis, TU/e sectie Precision Engineering

[16] Brand, U., Kleine-Besten, T., Schwenke, H, 2000, *Development of a special CMM for dimensional metrology on microsystem components*, ASPE, **15**

[17] Guijun, J.I., Schwenke, H, Trapet, E., 1998, *Opto-tactile sensor*, Quality Eng, **7-8**, pp 40-43 (in German)

[18] Meli, F., Fracheboud, M., Bottinelli, S., Bieri, M., Thalmann, R., Breguet, J.M., Clavel, R., 2003, *High precision, low force 3D touch probe for measurements on small objects*, Proc. of EUSPEN, Aachen, Germany.

[19] Schwenke, H., 1999, *Messkopf für Mikrostrukturen*, PTB-News, Vol. 5 (in German)