

Development of a special CMM for dimensional metrology on microsystem components

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INTRODUCTION

Further miniaturization and modularization are current trends in microsystem technology, which require 3D-coordinate measurements to be performed with measurement uncertainties in the range of $0.1 \mu\text{m}$. With conventional coordinate measuring machines sub-centimeter structures usually can be measured only optically, i.e. in two dimensions with measurement uncertainties of about $1 \mu\text{m}$. Therefore activities were started to develop special measurement equipment which satisfies the described requirements. Moreover the equipment to be developed will also allow to perform measurements on other challenging objects, like e.g. small setting ring standards, small diameter wires etc.

The PTB started a project to develop a special CMM for dimensional metrology on microsystem components with an uncertainty of $< 0.1 \mu\text{m}$. The measurement range will be $25 \text{ mm} \times 40 \text{ mm} \times 25 \text{ mm}$. The instrument is based on a commercial CMM with improved capabilities through the use of high resolution scales and optimised air bearings. The instrument will consist of an optical measurement system and two tactile 3D-micro-sensing systems. To improve the measurement uncertainty of the instrument the translational displacement and the guiding deviations of the CMM are measured by laser interferometry.

At first an opto-tactile 3D-sensor with an optical fibre as a "probe pin" will be used. The sensor allows to use very small probing balls with diameters down to $25 \mu\text{m}$ and probing forces as low as $1 \mu\text{N}$. 2D probing uncertainties of $0.15 \mu\text{m}$ were already obtained with this system [1].

The second tactile sensor to be used is based on a silicon boss-membrane with piezo resistive transducers [2]. First probing experiments have been carried out showing its resolution and 1D-reproducibility of the contacting points to be better than 10 nm .

In parallel to the instrument development new precision diamond turned depth setting standards for topography measuring instruments with depths in the mm range have been developed [3]. The standards are made of OFHC copper and are covered with a wear-reducing nickel coating. The calibration uncertainty of the deepest grooves (currently $900 \mu\text{m}$) amounts to 54 nm . Under good conditions, these standards allow to perform traceable measurements of topography measuring instruments with a maximum uncertainty of 78 nm for the range of 1 mm .

THE SPECIAL CMM

The PTB develops a special CMM for dimensional metrology on microsystem components with an uncertainty of $< 0.1 \mu\text{m}$. The measurement range will be $25 \text{ mm} \times 40 \text{ mm} \times 25 \text{ mm}$. The instrument is based on a commercial CMM [4] with improved capabilities through the use of high resolution scales (10 nm resolution) and optimised air bearings. A stability of $< 20 \text{ nm}$ between ram and the basic setup in all axes was aimed at.

The instrument will consist of an optical coordinate measurement system and two tactile 3D-micro-sensing systems. Both tactile sensing systems will be mounted at different z-columns of the coordinate measuring machine (see Fig. 1). To improve the measurement uncertainty of the instrument the translational

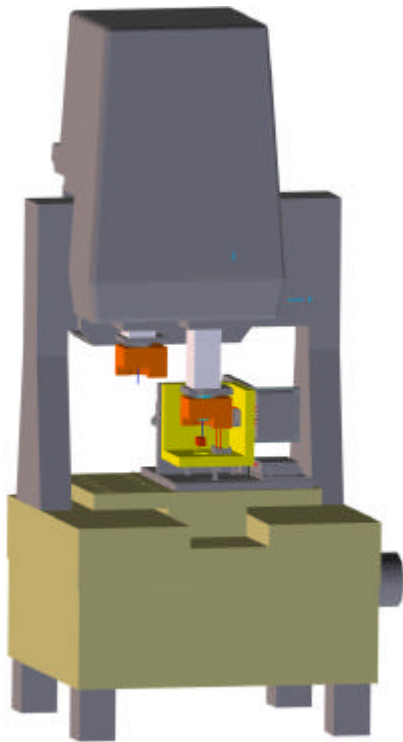


Fig. 1: The special CMM for dimensional measurements on microsystem components

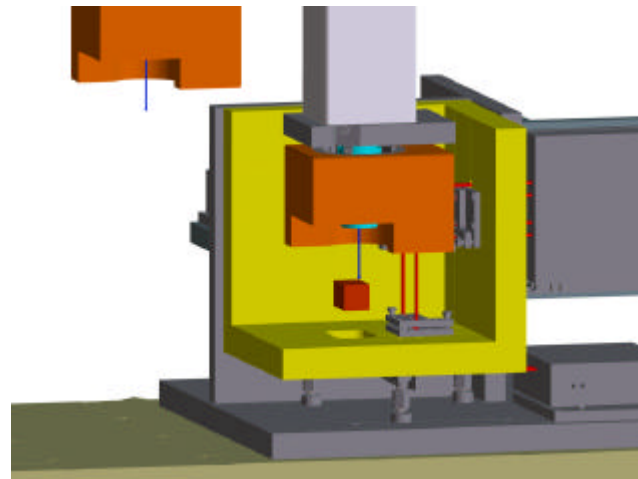


Fig. 2: Metrology-frame of the special CMM

displacement and the guiding deviations are measured by laser interferometry. A metrology frame including three minaturised plane mirror laser interferometers [5] for simultaneous measurement of displacement and angle is added to the CMM. Each of the two tactile sensors is enclosed by a zerodur cuboid that is mounted to one of the two CMM rams. The metrology frame consists of an outer aluminium frame, supporting the compact laser interferometers and an inner frame, made of invar, that supports the reference mirrors of the interferometers and the specimen to be measured (see Fig. 2).

The first tactile sensor to be used will be an opto-tactile 3D-sensor [6] with an optical fibre as a “probe pin”. The 2D version of this sensor [7] is commercially available with smallest probing ball diameters of 25 μm and probing forces down to 1 μN . The functional principle is based on the determination of the probing ball position by an optical imaging system and a CCD camera (Fig. 3). The “probe pin” used is an optical fibre whose tip is provided with a spherical probing element which is illuminated through the fibre.

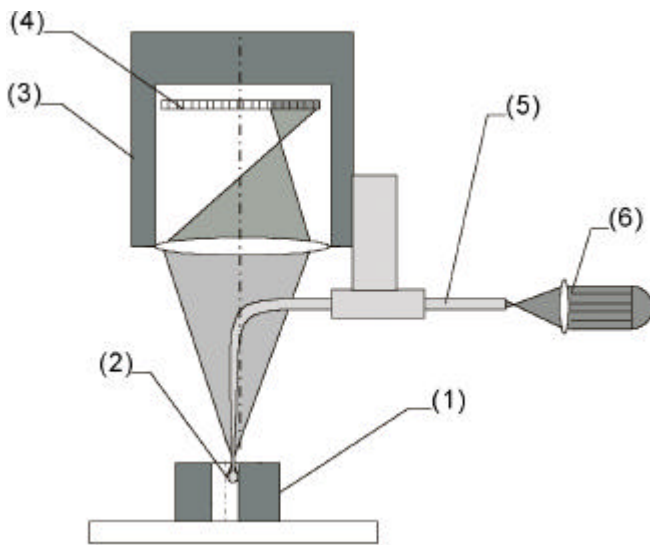


Fig. 3: Principle of the 2D opto-tactile micro-probe ((1) workpiece, (2) probing sphere, (3) measuring camera, (4) CCD-chip, (5) glass fibre, (6) light source)

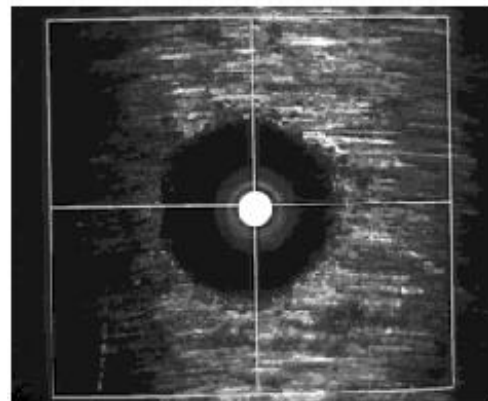


Fig. 4: CCD camera image of probing element and borehole with additional incident light for visual positioning

The optical fibre is mounted in the optical axis of the system such that the probing element is kept in the focussing plane of the optical system. The backscattered light of the ball is imaged on the CCD sensor as a bright light spot, whereas the rest of the fibre remains largely invisible to the camera as it is outside the focussing plane. When the probing element comes into contact with the workpiece surface (i.e. when shifting with respect to the camera), the light spot changes its position on the sensor. This change in position can be evaluated with subpixel accuracy. 2D probing uncertainties of $0.15 \mu\text{m}$ have already been obtained with this system [1]. Recently a modified 3D version has been realized and tested [6] that is planned to be used on the special CMM for first measurements. The 3D sensor (Fig. 5) uses a second imaging system that is mounted perpendicular to the probing fibre and images a second target mark (1).

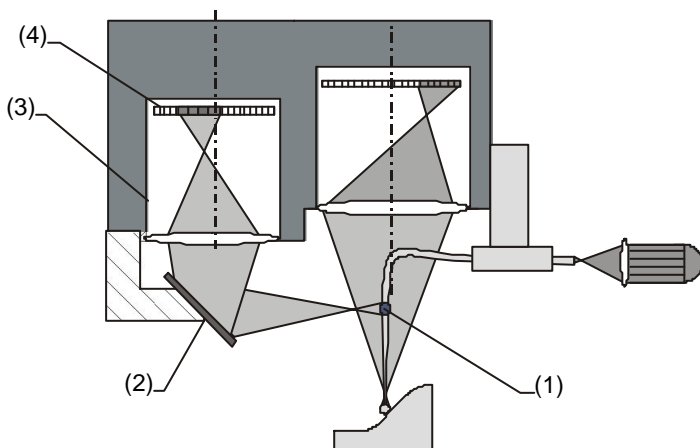


Fig 5: Principle of the 3 opto-tactile micro-probe: (1) second target mark (2) mirror, (3) second camera for measuring the z-deflection of the target mark, (4) CCD-chip

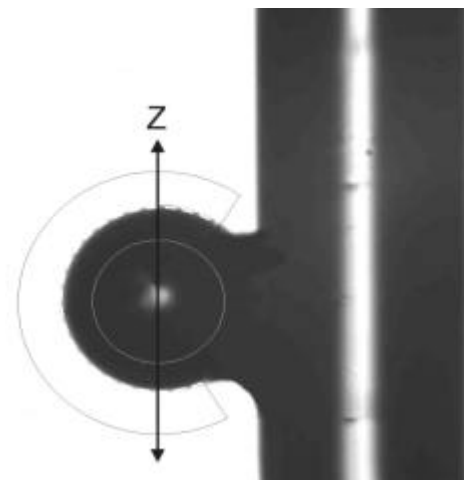


Fig 6: Second camera image of the second target mark for measuring the z-deflection

As a target mark for measuring the z-deflection a glass sphere was used. Illumination can be made optionally as vertical illumination or as transmitted light. Figure 6 shows the image of a target sphere glued to the stylus seen with the second camera in transmitted light.

The second tactile sensor to be used with the special CMM is a completely different type of tactile 3D-sensor. It is based on a silicon boss-membrane that acts as a membrane spring and a stylus in the center [2]. The probing element of the sensor consists in this early stage of

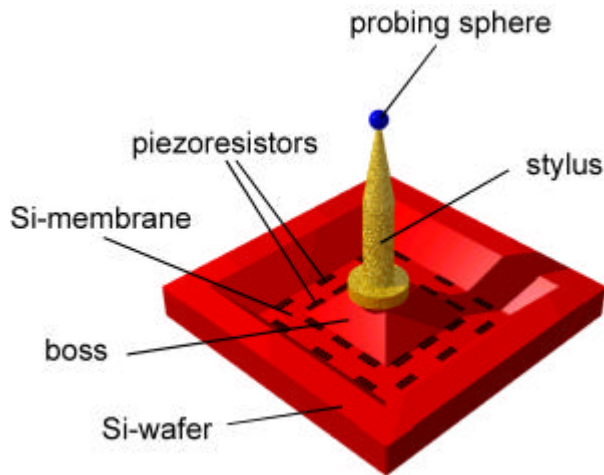


Fig. 7: 3D-Si-boss-membrane sensor with piezo resistive elements

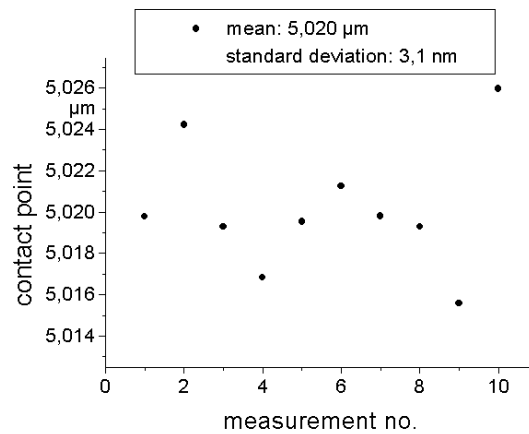


Fig. 8: 1D-repeatability of the probing point of the 3D-Si-boss-membrane sensor

development of a stiff stylus, 500 µm in diameter and 4 mm long. It is fixed to the boss by epoxy resin (Fig. 7). On the backside of the membrane there are piezo resistive elements that locally detect deformations of the membrane. Deflection of the stylus during probing of a workpiece deforms the membrane and causes local resistance changes of the piezo resistive elements. Connecting the piezo resistive elements to Wheatstone bridges allows to measure stylus deflections in x-,y- and z-direction. Probing experiments have been carried out showing a resolution of the sensor of a few nanometers and 1D-reproducibility of the probing points to be better than 10 nm (see Table 1 and Fig. 8).

	x-, y-probing direction	z-probing direction
resolution	3 nm	5 nm
repeatability of contact point position	< 10 nm	< 20 nm
stiffness	2.5 mN/µm	55 mN/µm
measuring range	20 µm	6 µm
crosstalk x-y-direction	< 15 nm _y /µm _x	< 120 nm _x /µm _z
crosstalk z-direction	< 15 nm _z /µm _x	-

Table 1: Specifications of the tactile 3D Si-boss-membrane sensor

For a maximum deflection of the probing sphere of 3 µm and a deflection velocity of 100 nm/s a high linearity ($R > 0.99997$) of the probing curves and no hysteresis deformation was found.

With deflections up to 20 μm in x-y-direction and a slow deflection velocity of 100 nm/min hysteresis due to the relaxation of the epoxy resin was observed. The maximum deflection in z-direction should not exceed 6 μm because of possible mechanical destruction of the boss-membrane.

In the following, measurement results with the 3D-Si-boss-membrane sensor will be described that were obtained at the PTB with a probing ball diameter of $\approx 160 \mu\text{m}$ and a shaft diameter of 500 μm . The maximum penetration depth into boreholes is only 200 μm according to the conical shaft. To demonstrate the capabilities of the system, 2D-measurements on a setting ring standard (1 mm diameter) were carried out. Probing direction was x-direction and it was analyzed the x-axis of the sensor. From the x-probing curves the probing points (probing force zero) were calculated. Fitting a circle to the measured probing points and calculating the deviations for each point gives the measured form errors (Fig. 7). These form errors are due to form errors of the ring, due to form errors of the probing sphere used, due to contributions of the 3D-Si-boss-membrane sensor and due to geometric errors of the x-,y-positioning table. The ring measurement was repeated several times in order to determine the measurement repeatability (see Fig. 8).

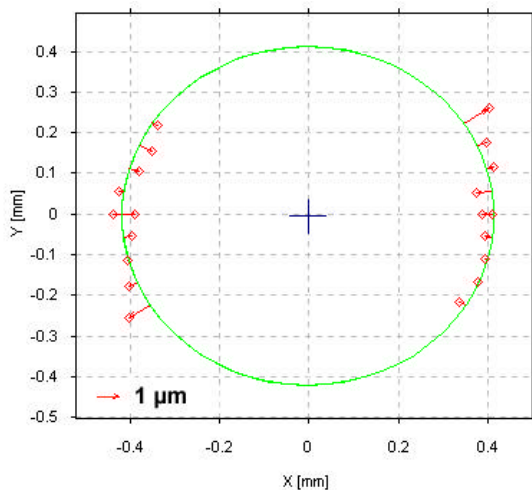


Fig. 7: Measured form errors of a setting ring standard with 1 mm diameter

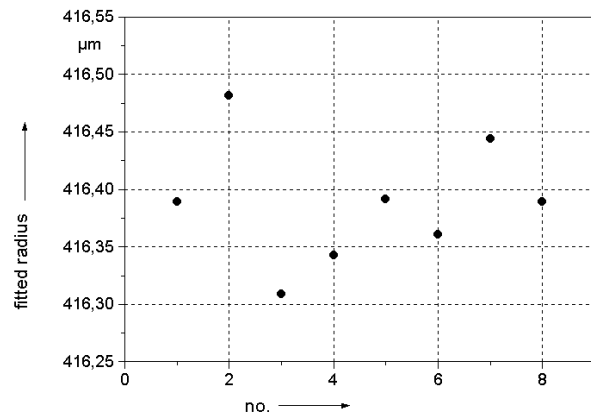


Fig. 8: Repeatability of the radius of a setting ring standard measured with the 3D-Si-boss-membrane sensor

The standard deviation reached for unidirectional probing at PTB is appr. 0.1 μm ; It is to be expected that for the two- and three-dimensional case comparable results can be achieved.

DEPTH SETTING STANDARDS FOR MEASUREMENT RANGES FROM 1 μm TO 1 MM

At PTB, ultraprecise surface figuring by diamond turning has proved its worth in the manufacture of superfine roughness standards. This technique not only allows synthetic roughness profiles [8] to be manufactured with great precision, but also surfaces of optical quality. Surfaces with arithmetical mean deviations of $R_a \approx 1 \text{ nm}$ and flatness errors smaller than 100 nm over ranges of a few millimeters are today the state of the art. Achieving this surface quality requires, however, a lot of time and effort. Special attention must, for example, be paid to the purity of the materials to be machined (for example, OFHC-Cu (oxygen-free copper) or highest grade aluminium), and the environmental conditions around the finishing machine must be very stable. Manufacture may take several days. For the manufacture of the

new depth setting standards, a commercial CNC diamond turning machine controlled by a laser interferometer (resolution: 10 nm) [9] was used. The material selected was very pure copper (OFHC-Cu), as the best surface qualities (arithmetical mean deviation $R_a = 1$ nm, waviness $W_t = 50$ nm, flatness 50 nm over a measuring length of 20 mm) have been obtained with this material. The copper disks used are 90 mm in diameter and 10 mm in thickness. A mono-crystalline natural diamond with a tip radius of 5 μm was used as a cutting tool. The feed rate was 0.1 mm/min on the plane surfaces and 0.03 mm/min on the flanks, with the spindle rotating at 1000 revolutions/min. Feed motion was 10 – 20 μm , only the final cut was carried out at a feed motion of 1 μm . After the rotationally symmetric grooves have been produced on the disk, the latter is cut into twelve parts of identical size using wire-EDM. To reduce wear the surface is covered with a nickel coating (thickness 5 μm). The surface hardness of the standards then is approx. 500 HV and corresponds to that of medium-hard steel. The surface is resistant to wear even if conventional contact stylus instruments are used whose measuring force is relatively great (in the mN range). As a result of the nickel coating the roughness of the surface increases, however, so that the arithmetical mean deviations then are $R_a = 9$ nm. Limited by the layer thicknesses which can be produced in practice, profiles with a depth down to 100 μm can be cut into the Ni layer also directly and used as standards without additional coating. This allows the roughness originally produced in the turning process (which is a little lower) to be maintained. For the grooves deeper than 100 μm it is planned to apply an additional cut after coating the disk with the wear reducing Ni layer in order to achieve a better surface quality.

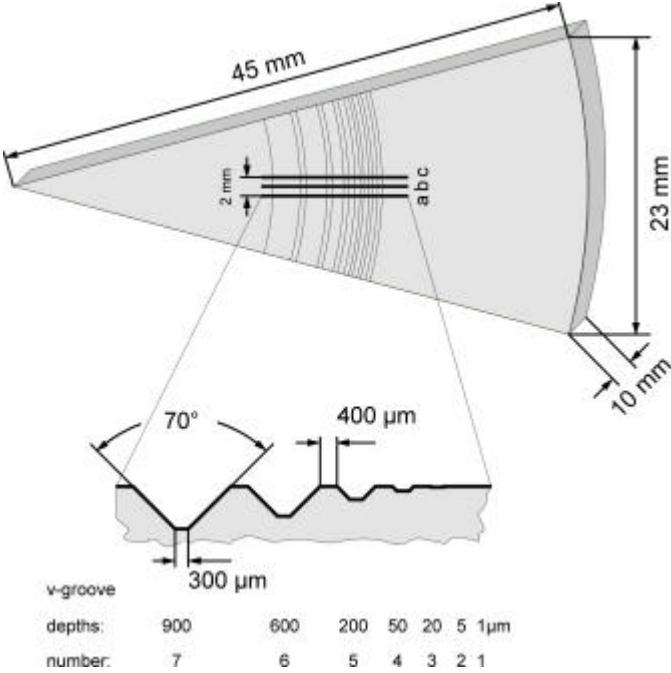


Figure 10: Photo of the new diamond-turned depth setting standard

Fig. 9: Details of the new diamond-turned depth setting standard

The aperture angle of the grooves is $(70 \pm 1)^\circ$, the width of the grooves at the root 0.3 mm, and the range between the v-grooves 0.4 mm in length. As an example, Figure 9 shows a selection of groove depths. As the grooves can be manufactured with any depth desired, grading of their depths can be adapted to specific measuring instruments. It is moreover possible to manufacture any aperture angle greater than 70° and, thus, edges with flatter slope. Even

optical measuring instruments such as, for example, fringe projection measuring instruments for which continuous tracing of the fringes is essential for evaluation, can be calibrated with such grooves.

Calibration can be carried out very efficiently, as all calibration grooves can be measured in a single measurement. The length of the profile to be measured amounts to only 8 mm for seven grooves between 1 μm and 1 mm in depth. The groove depths (d) have been calibrated using a Form Talysurf stylus instrument [10]. The expanded uncertainty for the deepest groove (900 μm in depth) is $U = 54 \text{ nm}$. The main contributions to the uncertainty follow from the repeatability of the FTS calibration ($u = 2.5 \cdot 10^{-5} \cdot d$), from the uncertainty of the step heights of the standard used to calibrate the FTS (7.5 nm) and from the deviation of the feed unit from the level plane and the drift of the FTS during the measurement (6.1 nm).

The uncertainties obtained here are typical of the diamond-turned depth setting standards presented. Deviations are within the range of a few per cent.

Which uncertainties of measurement can be obtained in the calibration of a measuring instrument when the new diamond-turned depth setting standards are used? To answer this question it is assumed that the properties of the measuring instrument to be calibrated are similar to those of a Form Talysurf stylus instrument [11]. The uncertainty of measurement of the measuring instrument to be calibrated can then be calculated, assuming a standard uncertainty of the calibration standard of 54/2 nm. From this follows an uncertainty value of the calibrated topography values 38.4 nm when a groove 1 mm in depth is to be measured. When an uncertainty contribution caused by the alignment of the profile is taken into account, and on the assumption that four repeat measurements are performed, an expanded uncertainty of measurement of $U = 78 \text{ nm}$ results. Thus under good conditions, allows link-up of topography measuring instruments to a material standard with a maximum uncertainty of measurement of 78 nm in the measurement range of 1 mm.

In the case described here, the grading of the groove depths has been adapted to the measurement ranges of a contact stylus instrument; however, the manufacturing process allows any grading desired. Nominal values can be complied with with tolerances of a few thousandths.

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