Calibration of a Micro Probe Array

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KEYWORDS : Coordinate measuring machine, Micro CMM, Probe Array, Calibration

Conventional coordinate measurement machines are not well adapted to the specific needs for the measurement of mechanical micro structures that are made in a highly parallel production process. Especially the increase of the measurement speed is addressed by using an array of micro probes and by measuring multiple objects parallel. This paper describes the calibration procedure of the probe array. It consists of multiple micro probes that are etched into the same silicon substrate. The styli are glued on to a boss structure in the middle of a silicon membrane. To facilitate the alignment of array and the underlying wafer, the array is mounted on three stacked rotational stages. Due to the production tolerances, the effective distances of the probes to the rotational axes have to be calibrated. The probe sensitivity is the third field of calibration.

Manuscript received: January XX, 2011 / Accepted: January XX, 2011

NOMENCLATURE

$\mathbf{p}_c$	=	contact point, position of array at the moment of beginning surface contact of touching ball and reference ball
$\mathbf{p}_s$	=	center point of adjustment sphere fitted into contact points
$\mathbf{p}_{p,0}$	=	probe positions points of not rotated array
$\mathbf{p}_a$	=	array position
$\mathbf{p}_{p,0,x}$	=	expected probe positions of array after X-rotation
$\mathbf{p}_{p,0,y}$	=	expected probe positions of array after Y-rotation
$\mathbf{p}_{p,0,z}$	=	expected probe positions of array after Z-rotation
$\mathbf{p}_{p,x}$	=	measured probe positions of array after X-rotation
$\mathbf{p}_{p,y}$	=	measured probe positions of array after Y-rotation
$\mathbf{p}_{p,z}$	=	measured probe positions of array after Z-rotation
$\mathbf{p}_{ref}$	=	positions of reference balls
h_B	=	height of ball equator above ground plate
$\mathbf{u}$	=	output voltage of sensor
$\mathbf{A}$	=	transfer matrix of single probe
i	=	probe index

1. Introduction

The measurement speed of conventional coordinate measurement machines (CMM) with a single probe is only sufficient for spot checks of microstructures on a wafer. In [1] a µCMM was presented (Fig. 1) that tackles this problem by using an array of 3D microprobes to measure multiple objects on a wafer simultaneously. The probe array consists of 3x3 micro probes with a nominal distance of 6.5 mm. The probe length is 5 mm and the diameter of the touching balls is 300 µm. The microprobes are etched into the same silicon substrate and the styli are glued on to a boss structure in the middle of a silicon membrane. The deformation of the membrane is measured by piezoresistors at the reverse side. Detailed information is given in [2].

Different to CMMs with only one probe it is required to align the array to the underlying wafer and its microstructures in order to measure the corresponding point at each structure. To facilitate this, the µCMM has three rotational degrees of freedom (DOF) featured by two goniometers and one rotational stage whose axes cross in one point near the middle touching ball.

Despite of great effort in connecting the styli to the membrane, the exact positions of the touching balls are unknown and have to be determined by calibration. To be able to measure with a probe array it is sufficient to keep the deviations from the nominal positions below ±5 µm in each direction. These deviations superpose to the relative dislocation of each surface to measure. With respect to the maximum probe deflections of about 100 µm in X- and Y-direction and 25 µm in Z-direction the deviations from the nominal probe positions have to be that small to get into contact with every probe at the same time. A large deviation would also lead to a large difference in the contact forces and the resulting deformation of the object under test.

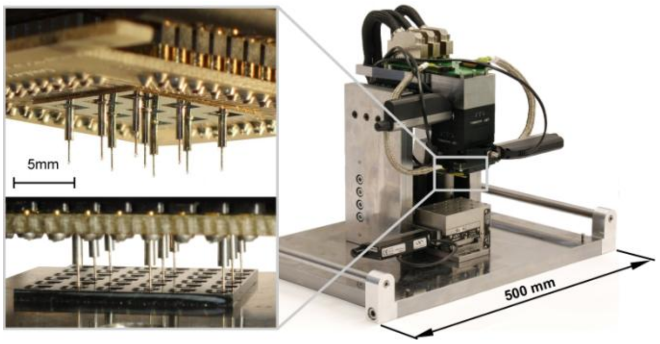


Fig. 1 µCMM with probe array

The second subject of the calibration is the sensitivity of each probe. In a more general approach this means not only a linear factor for the relation of output voltage and applied deflection but a transfer matrix which covers the orientation and crosstalk between the axes of a single probe. Even though in this project the arrays are built out of a single silicon structure it was a goal to keep the calibration procedure independent of specific array properties as much as possible. This way the calibration strategies will be applicable for future array versions, e.g. arrays made out of single probes or with different probe arrangements. The needed time for the calibration should maximally grow linear with the number of probes. Beside that there should be only little manual interaction for the user.

2. Calibration normal

The calibration of the probe array is done by using the ball plate shown in Fig. 2 as calibration normal. The precision ruby balls are glued into pyramids on a silicon substrate which have the same nominal spacing as the probes. These pyramids are made by photolithography and anisotropic etching. So their relative positions and sizes have only small deviations from their nominal values (less than ±2.5µm). For reasons of thermal stability the silicon plate itself is glued onto a larger plate of silicon carbide (SiC) which has the same coefficient of thermal expansion. This SiC plate is mounted on the CMM's translational stage by means of an optical slide system with good reproducibility of the orientation. The relative ball position and the orientation of the silicon plate in respect to the slide system are calibrated.

Fig. 2 Calibration normal

3. General calibration procedure

Before the automatic calibration sequence can start the array has to be positioned manually about 1 mm above the reference structure. The calibration itself is done by the following steps:

1. Alignment to calibration normal
2. 5-point probing to estimate position of reference balls
3. Probing of points on upper hemisphere
4. Calculation of contact points
5. Fitting adjustment spheres into contact points of each probe to calculate relative distance of probing balls
6. 3 additional probings (like step 3-5) with rotated array around X-, Y- and Z-axis with known rotation angle. Calculate position of pivot point from shifted probe positions.
7. Calculation of transfer matrix

These steps will be explained in more detail in the following sections.

3.1 Alignment to calibration normal

The first step of each calibration or measurement is the alignment of the probe array to the object under test. In principle this is done by aligning the array onto two nonparallel planes with partially restricted degrees of freedom. In case of calibration the first alignment is onto the silicon plate (Fig. 3 top). Here only the rotation around the normal vector of the plate is locked and rotations around X- and Y-axis are allowed. In the second stage the only the rotation around Z-Axis is allowed (Fig. 3 bottom). After this the complete orientation of the array is determined. The second plane is approximated by the reference balls on the plane that were touched at the height of their equator. The error caused by the superposition of the round surface of the balls and the position error of the touching balls is negligible because the accuracy has only to be good enough to get into contact with each probe. The exact orientation gets calculated later on.

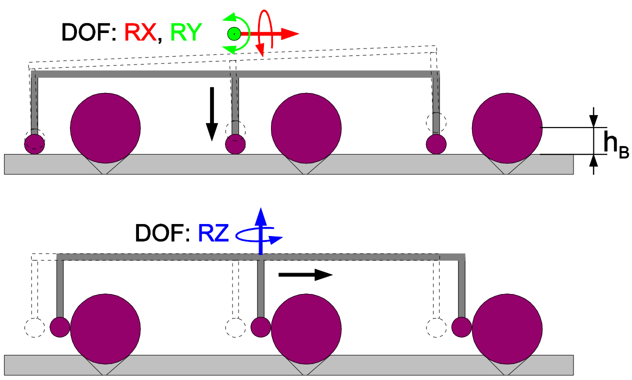


Fig. 3 Array alignment

The Best-Fit-plane through the touching balls usually is tilted against the rotation stage. For the usage of an array it is convenient to subtract this value from the positions sent to the rotary stages to ensure that an array in 0-degree-position of all axes is parallel to the machines XY-plane. Therefore these offset angles which are given by the difference of the current rotation angles to the known orientation of the reference structure are stored as an additional configuration parameter of the array.

In case of calibration one challenge is the fact that the array properties are still unknown and therefore the sensor signals cannot be used as a value for the deflection of each probe. Furthermore the arrays are very sensitive and allow only small deflections. The solution is to use only the value of the sensor signal, not the direction of the deflection vector. Instead of this the negative surface normal vector is used for the calculations. For the probing of the calibration normal it can be assumed to be known and to be a reasonable approximation of the deflection vector.

3.2 Estimation of position of ball plate

After the alignment the Z-position of the equator of the reference balls is known because the height h_B as the distance between silicon plate's surface and equator is determined by the normal's calibration (Fig. 3). Therefore a 5-point probing with large approaching distances can be performed with four points on the equator and one on top. The probes are only used in switching mode, which means that the exceeding of a threshold voltage triggers the stop of the array's motion. Because of deviations of the positions of the touching balls and reference balls another probe usually triggers this stop for each of the five probings. Therefore the fitted adjustment sphere through these points is a little larger than the sum of the diameters of reference and touching ball. The center of this virtual sphere is the target of the probing motions of the next steps.

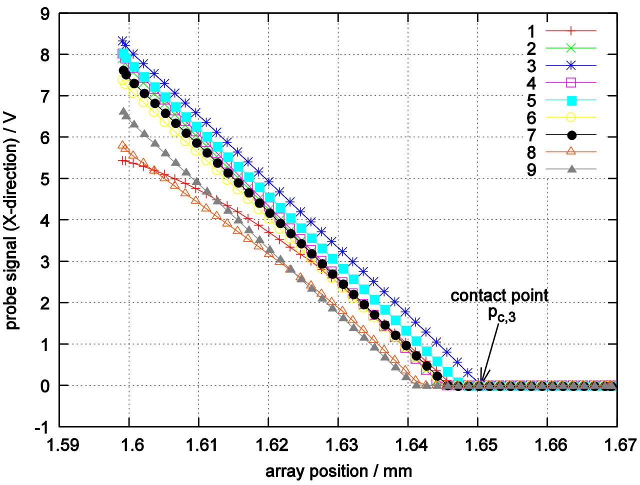
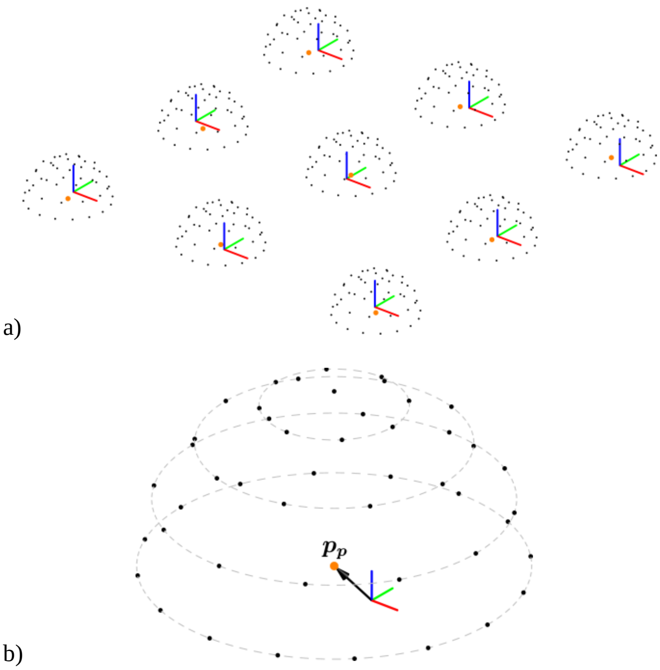


Fig. 4 Probe output voltage during probing

3.3 Relative probe distance

The raw data for the calibration is gathered by probing the upper hemisphere of the reference balls with an evenly spaced pattern. So the current pattern leads to 47 points. During each probing the current array position $\mathbf{p}_a$ and the output voltages $\mathbf{u}$ of all probes are gathered with a rate of 100 Hz. With a motion speed of max. 50 µm/s this gives a local resolution below 0.5 µm which is sufficient for this calibration, but could be increased if necessary. Fig. 4 shows as an example the X-component of this data for one probing in negative X-direction (the motion starts at the right end). It can be seen that all probes get into contact with the ball surface within a distance of 10 µm (1.65 mm-1.64 mm). The individual contact points $\mathbf{p}_c$ are calculated by linear extrapolation of the lowest ten points to zero deflection. This extrapolation is done with all three



a)

b)

Fig. 5 Contact points , a) whole array b) single probe

vector components together, not independently, to get reliable 3D results for single axis movements.

These contact points are gathered for all probes (Fig. 5 a, shifted to nominal position) and an adjustment sphere is fitted into every point set. The difference of the relative position of the corresponding reference ball ($\mathbf{p}_{ref}$) and the center point of this sphere ($\mathbf{p}_s$) (Fig. 5 b) gives the probe position $\mathbf{p}_p$ relative to the nominal position:

$$\mathbf{p}_\mathrm{P} = \mathbf{p}_\mathrm{ref} - \mathbf{p}_\mathrm{S}$$

With this the relative positions of the probes $\mathbf{p}_{p,0}$ are determined. Fig. 6 shows an example of measured positions. The Best-Fit-plane through these points is still slightly tilted against the XY-plane but these angles can be added to the already stored offset angles of the array (see 3.1).

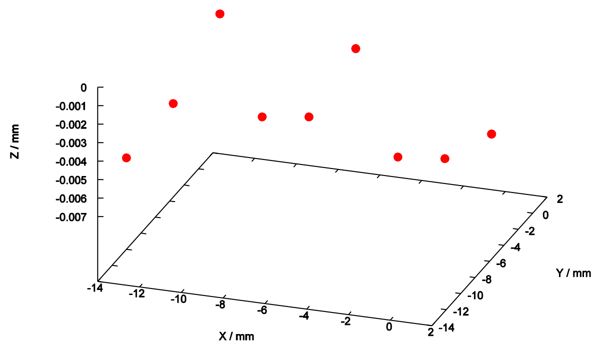


Fig. 6 Calculated positions of probes

3.4 Center of rotation

The next step of the calibration is the determination of the coordinates of the array's pivot. For this the same probing sequence as

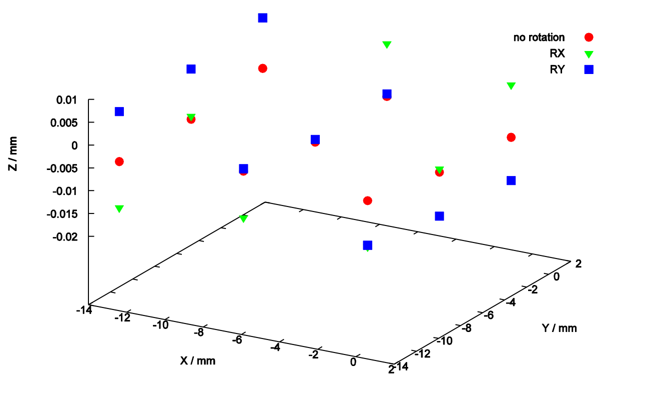


Fig. 7 Center points of rotated arrays

for the calibration of the probe position is executed three times with the array rotated around X-, Y- and Z-axis by a known angle. This angle is calculated in a way that the outermost probes (nominal position) will move about 10-30 µm, which is limited by the maximum probe deflections. The calculation of the contact points $\mathbf{p}_c$ and the resulting probe positions $\mathbf{p}_{p,x...z}$ is done in the same way as explained before. From this three sets of probe positions can be obtained, which are used to calculate the position of the pivot. Fig. 7 shows these positions for X- and Y-rotation in comparison to those of the unrotated array (cf. Fig. 6).

For the determination of the pivot the assumption is made that the axes meet in one point and are rectangular to each other. This is reasonable because these errors would be caused by properties of the CMM and not the array itself and therefore should be calibrated and compensated separately.

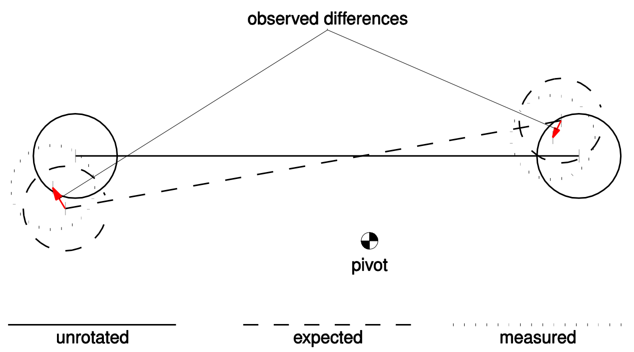


Fig. 8 Calculation of pivot point

The calculation of the pivot point is done by rotating the calculated probe positions without applied rotation $\mathbf{p}_{p,0}$ around an estimated pivot point. Fig. 8 shows the principle for one axis and two probes. The optimal pivot position is determined by minimizing the sum of the differences between these expected probe positions and the measured ones:

$$\sum_i |p_{p,0,x} - p_{p,0}| + \sum_i |p_{p,0,y} - p_{p,0}| + \sum_i |p_{p,0,z} - p_{p,0}| \overset{!}{=} \min$$

It is important to rotate the array at once as a "solid body" to keep the probe distances constant during this optimization. Other methods would lead to additional uncertainties caused by the relatively high positioning uncertainties in comparison to the measured probe shifts.

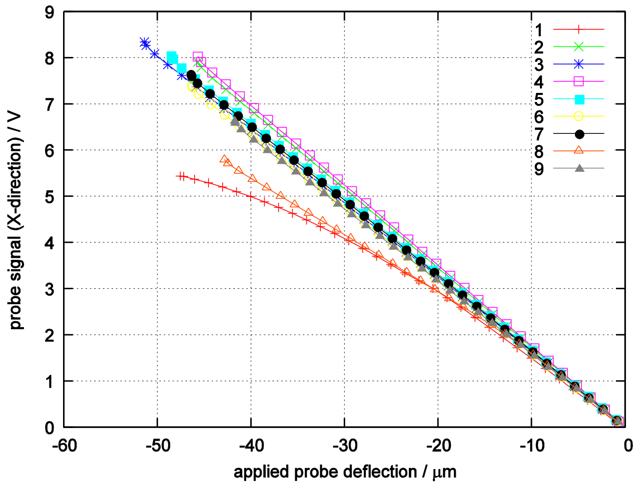


Fig. 9 Probe output voltage as a function of applied deflection

3.5 Transfer matrix

In the last calibration step the contact points calculated before are used to shift the deflection part of the data from $\mathbf{p}_a$ to $\mathbf{p}_a$-$\mathbf{p}_c$. The result is the sensor output voltage over the actual applied deflection (Fig. 9). From this data the elements of a transfer matrix **A** can be calculated. The deflection vector **d** as a function of the voltage **u** is given by

$$\mathbf{d} = \mathbf{A}\mathbf{u}$$

$$\begin{pmatrix} d_x \\ d_y \\ d_z \end{pmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \cdot \begin{pmatrix} u_x \\ u_y \\ u_z \end{pmatrix}$$

which can be transformed into

$$\begin{pmatrix} d_x \\ d_y \\ d_z \end{pmatrix} = \begin{bmatrix} u_x & u_y & u_z & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & u_x & u_y & u_z & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & u_x & u_y & u_z \end{bmatrix} \cdot \begin{pmatrix} a_{11} \\ a_{12} \\ \vdots \\ a_{32} \\ a_{33} \end{pmatrix}$$

$$\mathbf{d} = \mathbf{U}\mathbf{a}$$

With this we can build an overdetermined equation system by expanding the equation above with the observed values of every measured data point of all probings:

$$\mathbf{d}^* = \mathbf{U}^*\mathbf{a}$$

Then the best fitting coefficient vector **a** is obtained by solving the linear equation system

$$\mathbf{a} = \mathbf{U}^{+}\mathbf{d}$$

where $\mathbf{U}^{+}$ is pseudoinverse of $\mathbf{U}^{*}$. Now the transfer matrix **A** is determined.

4. Conclusions

In this paper an automatic calibration procedure for a micro probe array has been demonstrated that does not rely on specific probe arrangements and other array properties. The calibration time is independent of the number of probes which will be important for the calibration of larger arrays. The positions of the touching balls were determined. These positions are expressed as their relative distances, the distance of the probe grid to the pivot point and an angular offset for the orientation. The second calibration goal was the determination of a transfer matrix for each sensor as a generalized sensitivity factor. The general procedure for the required alignment was shown.

ACKNOWLEDGEMENT

The authors gratefully acknowledge funding of the project by Deutsche Forschungsgemeinschaft (DFG) within the Priority Programme SPP1159 "New Strategies for Measurement and Test Techniques for Production of Microsystems and Nanostructures". Christian Schrader is a member of the International Graduate School of Metrology (IGSM) Braunschweig.

REFERENCES

1. Schrader, Ch.; Tutsch, R.; Herbst, Ch.; Büttgenbach, S.; Krah, T.: Micro Coordinate Measuring Machine for Parallel Measurement of Microstructures. Key Engineering Materials, Vol. 437, 2010, pp. 136-140, ISBN 0-87849-273-9
2. Krah, T.: Mikrotasterarrays zur parallelisierten Messung von Mikrostrukturen. PhD thesis, Braunschweig, Technische Universität Braunschweig, 2011