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A novel approach to positioning- and measuring technique for nanometrology

Publikation entstand im Rahmen von :
International Conference Sensors and Systems, 24.-27. Juni 2002, St. Petersburg, Russland

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A NOVEL APPROACH TO POSITIONING- AND MEASURING TECHNIQUE FOR NANOMETROLOGY

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Abstract
At the Institute of Process Measurement and Sensor Technology of the TU Ilmenau, a scanning force microscope (measuring range 15 µm x 75 µm x 15 µm) having a laser-interferometric 3D-nanomeasuring system free from Abbe errors has been developed in cooperation with the PTB Braunschweig. The extended measuring uncertainty (K = 2) is only 0.2 nm and was obtained with a structure standard. To achieve a considerable extension of the measuring range up to 25 mm x 25 mm x 5 mm, a nanopositioning and –measuring machine was developed. The resolution of the measuring axes is 1.24 nm. The laser-interferometric measurement is free from Abbe errors of 1st order in all measuring axes. The deviations of the guides used are compensated by means of a precision mirror corner.

1. Introduction

The big advances made in the fields of microelectronics, microtechnology, nanotechnology and precision engineering require the exact measurement of ever smaller structures, with those structures being localized in increasingly large spatial areas. According to the International Technology Roadmap for Semiconductors of 1999, the positioning ranges to be realized already in the years from 2010 to 2014 will cover an area of 450 mm x 450 mm. Furthermore, it will be necessary to measure and also to manufacture structure widths as small as about 35 nm with nanometer accuracy. Such extreme requirements are closely linked with technologies such as electron ray or X-ray lithography. However, also Nanoimprinting Lithography, which is a very promising new approach to the creation of nanostructures /1/ , will place great demands on measurement and positioning technology. Also, the following techniques and technologies are highly dependent on efficient measuring and positioning systems: mask and wafer inspection, circuit testing, scanning probe microscopy, genetic engineering, precision treatment and assembly, development and analysis of new materials, free-form surface characterization, and 3D-precision measurement of small parts (microlenses, microbenches, precision moulds and mechanical precision parts).

For a great number of scientific disciplines, mastering these new technologies and techniques means to respond to enormous challenges. Included are particularly also the 3D-techniques for measuring and positioning objects and for sensing them. Only when these three components can meet highest demands and when they are optimally adapted to the positioning and measuring tasks, the required new quality of measurement can be achieved. Although very promising approaches are available in the scientific and technical spheres nowadays, the aims cited above can only be reached through intensive research work.

There is not only a lack of nanomeasuring and positioning systems but also of 1D- to 3D-mechanically tactile and optical sensing systems to within a nanometre which are primarily necessary for measuring small parts having a sophisticated geometry. The challenges placed on the nanomeasuring and positioning techniques are additionally tightened up by the requirement to be in full working order also under vacuum conditions.

In the following, some developments made at the Institute of Process Measurement and Sensor Technology of the TU Ilmenau in the fields of nanomeasuring and positioning technology will be described.

2. 3D-nanomeasuring system free from Abbe errors for the scanning force microscope type VERITEKT

Figure 1 represents schematically the main component parts of nanomeasuring and positioning technology, as described in the introductory paragraph.

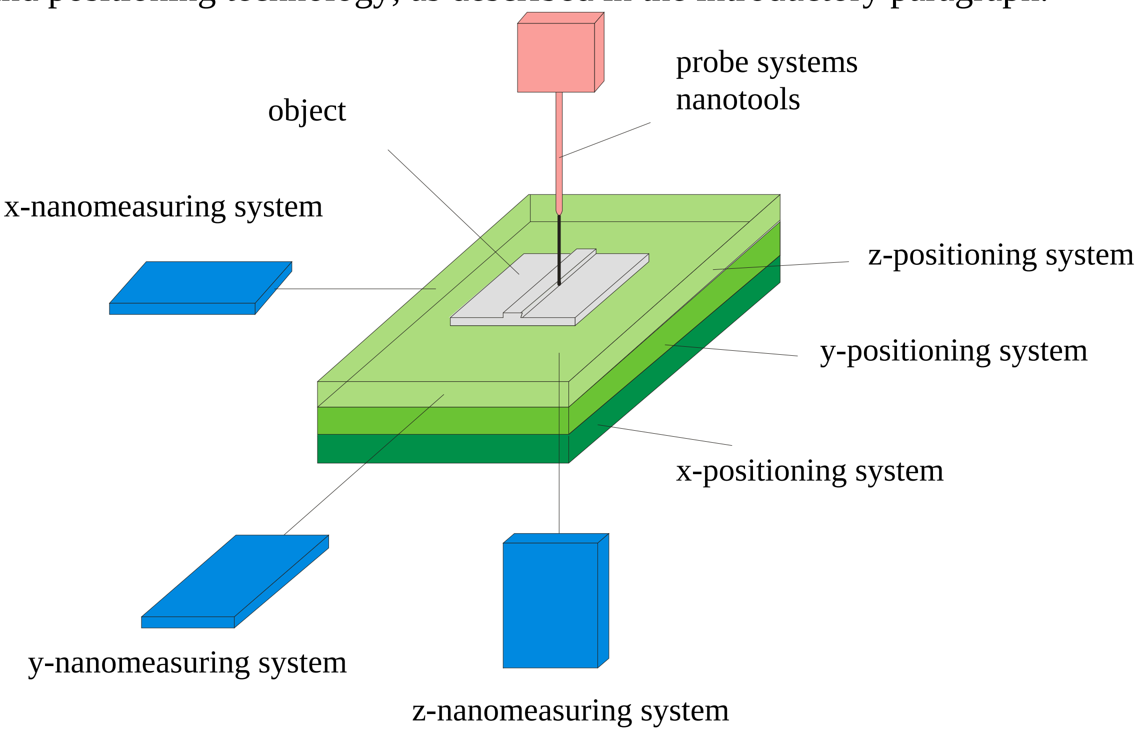


Fig. 1: Main component parts of nanomeasuring and positioning technology

The measuring, positioning and probe systems should be arranged in such a ways so as to make sure that only minimum measuring deviations occur. Minimum measuring errors require the Abbe comparator principle to be realized in all three measuring axes, measuring and positioning systems to within a nanometre, as well as probe systems of high resolution and stability. These principles have been realized for the first time in the scanning force microscope type VERITEKT.

Due to its special specimen guiding mechanism, this scanning force microscope, manufactured and distributed by the CZ Jena GmbH company until 1997, offers the best prerequisites for being further developed to a precision three-coordinate measuring system in the micrometre measuring range (15 µm x 75 µm x 15 µm). Figure 2 shows the simplified principle of the VERITEKT microscope. A 3D-monolithic scanner carries the x-, y- and z-drive and measuring systems. The three drive and measuring systems function nearly separately. Each axis is driven by piezoactuators combined with capacitive sensors for position measurement. In the x- and y-axes, the infringement of the Abbe comparator principle results in considerable measuring errors when tilts occur during movement:

$$f_x = L_x \,.\, \sin\beta \tag{1}$$

$$f_y = L_y \,.\, \sin\beta \tag{2}$$

In the z-axis, errors of 2^{nd} order occur:

$$f_z = L_z \,.\, (1 - \cos\beta) \tag{3}$$

L_x, L_y, L_z - distances between the measuring systems and the probe tip

β - angles of tilt of the axes

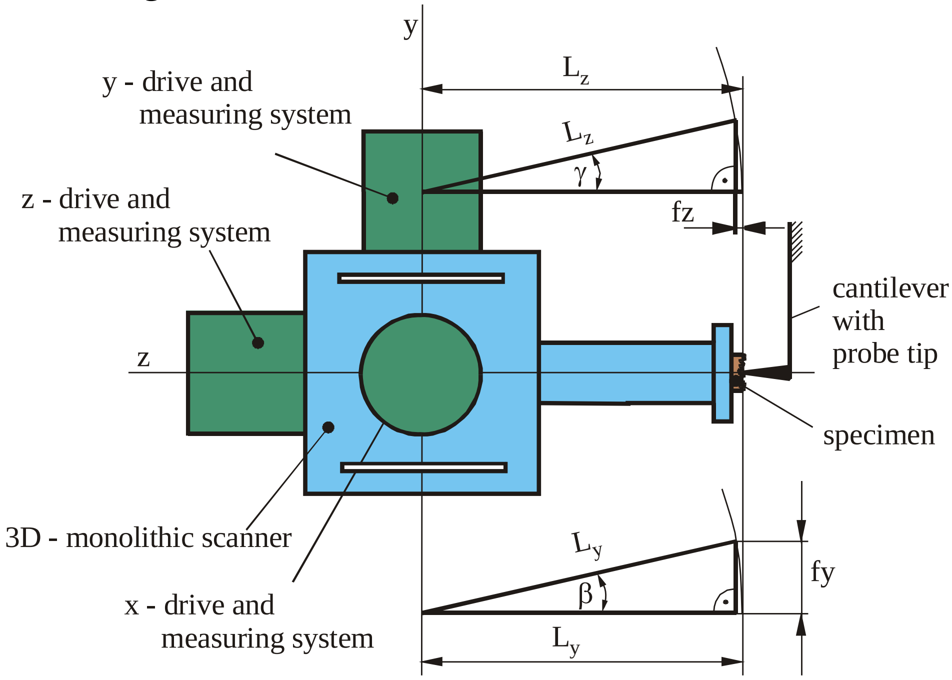


Fig. 2: Abbe error at the 3D-monolithic scanner of the VERITEKT microscope

As in case of the VERITEKT microscope the distances L_x, L_y and L_z are approximately 60 mm, considerable errors result even if the angle of tilt is small. Those errors can distinctly be reduced only if the distances L_x, L_y and L_z are short. From this, it follows that the measuring systems must be positioned as close to the measuring object (specimen) as possible. Ideally, the measuring axes should intersect in the point of contact of the probe tip.
At the Institute of Process Measurement and Sensor Technology of the TU Ilmenau, a suitable laser-interferometric three-coordinate measuring system was developed and manufactured by the SIOS Meßtechnik GmbH Ilmenau company /2, 3, 4/. The fundamental mode of action of the 3D-nanomeasuring system free from Abbe errors of the VERITEKT microscope is shown in Fig. 3.

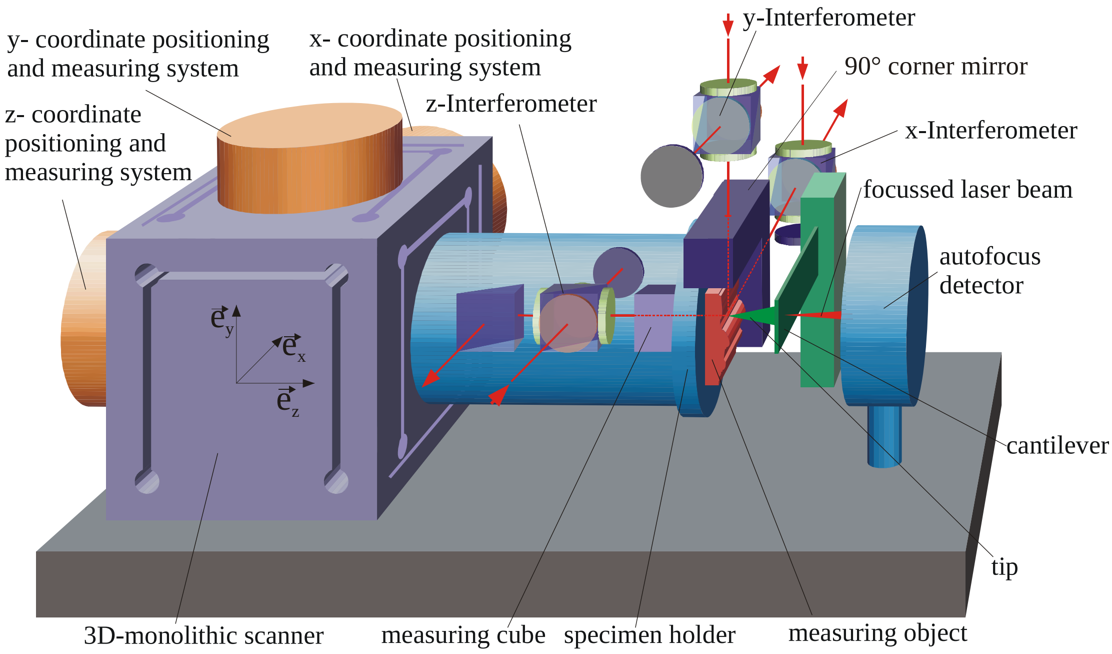


Fig. 3: VERITEKT microscope with laser-interferometric 3D-measuring system free from Abbe errors

A measuring cube (8 mm x 8 mm x 8 mm) is firmly positioned in the moving specimen holder as close to the measuring object as possible. The measuring cube has three precision faces which are perpendicular to one another and follows the three-dimensional movement of the measuring object (specimen). The measuring beam of the z-miniature interferometer is directed perpendicularly to the silvered z-face of the measuring cube, with its virtual extension hitting the tip of the sensing needle. In this case the measurement is free from Abbe errors of 1st order.

In order to be able to make measurements free from Abbe errors also in the x-y plane, i.e., to avoid errors of 1st order, a 90^o-corner mirror with silvered external faces is firmly attached to the specimen holder. The 90^o-corner mirror as well as the miniature interferometers are to be adjusted to the specimen holder in such a way that the measuring beams of the miniature y-interferometer and of the miniature x-interferometer hit the mirror surfaces at an angle of 90^{o} and the virtual extensions of both measuring beams intersect in the tip of the sensing needle.

In cooperation with the PTB Braunschweig, Abteilung 5 (Fertigungsmess-technik), two VERITEKT microscopes were equipped with the Abbe error-free measuring systems and tested successfully. By means of suitable structure standards, scientists of the PTB achieved an extended measuring uncertainty (K = 2) of only 0.2 nm using the laser-interferometric 3D-measuring system /5/. The measurements made at the PTB clearly show that a scanning force microscope which performs exact measurements in a metrological sense was developed.

3. Nanomeasuring machine

3.1. Structure and functioning /6, 7/

As reported above, it was possible to achieve extremely little measuring uncertainties by means of the metrological VERITEKT microscope. However, its measuring range is only 15 µm x 75 µm x 15 µm. As it is said in the introductory paragraph, considerably larger measuring ranges to be realized at the same metrological certainty are required today. Larger measuring ranges of, for example, several centimetres can no longer be realized by means of spring guides. Air guides cannot be used either as they do not make it possible to achieve path accuracies of <10 nm. Therefore, precision ball guides have been used with the nanomeasuring machine. However, such guiding systems present systematic deviations. With the functional principle we have chosen to realize a nanomeasuring machine, we have been able to largely compensate these deviations. The basic principle of this machine is illustrated in Fig. 4.

The standard of the nanomeasuring machine is constituted by a mirror corner consisting of three plates arranged perpendicularly to one another. The external faces of the plates are mirrored. The mirror corner was measured against standard. From the data obtained, functions were derived to correct the measuring values by way of calculation.

The object is positioned on the base plate of the mirror corner and sensed or treated by a stationary system (AFM, STM, autofocus, tactile probes, nanotools). The probes are employed as zero systems only. As the point of contact of the probe with the surface of the measuring object is stationary, a measurement free from Abbe errors can be achieved in all three axes. For this, three plane mirror interferometers type SP 500 made by the SIOS Meßtechnik GmbH company are fixed to a Zerodur base. The measuring beams sent out by the interferometers are reflected by the external faces of the mirror corner. The virtual extensions of the measuring beams hit the surface of the measuring object in the point of contact of the probe. As a result, any Abbe errors of 1st order will be avoided in all measuring axes.

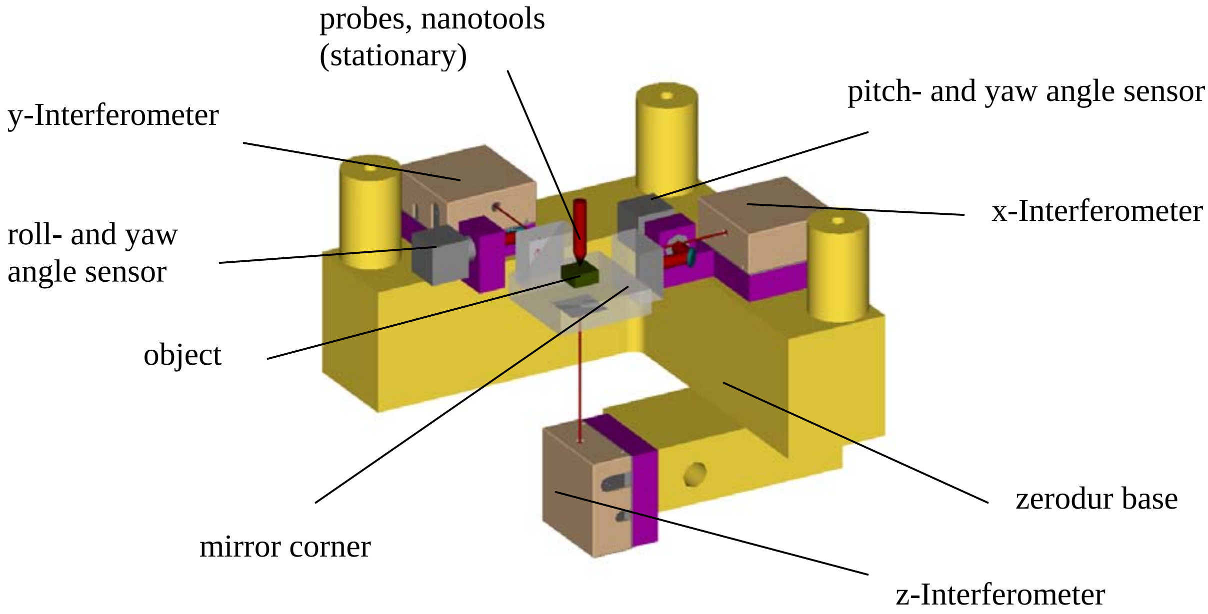


Fig. 4: Basic set-up of the nanomeasuring machine

In the measuring axes following cosine errors result:

$$f_x = -L_x \left(\frac{1}{\cos\alpha} + \frac{1}{\cos\gamma} - 2 \right) \tag{4}$$

$$f_y = -L_y \left(\frac{1}{\cos\beta} + \frac{1}{\cos\gamma} - 2 \right) \tag{5}$$

$$f_z = -L_z \left(\frac{1}{\cos\alpha} + \frac{1}{\cos\beta} - 2 \right) \tag{6}$$

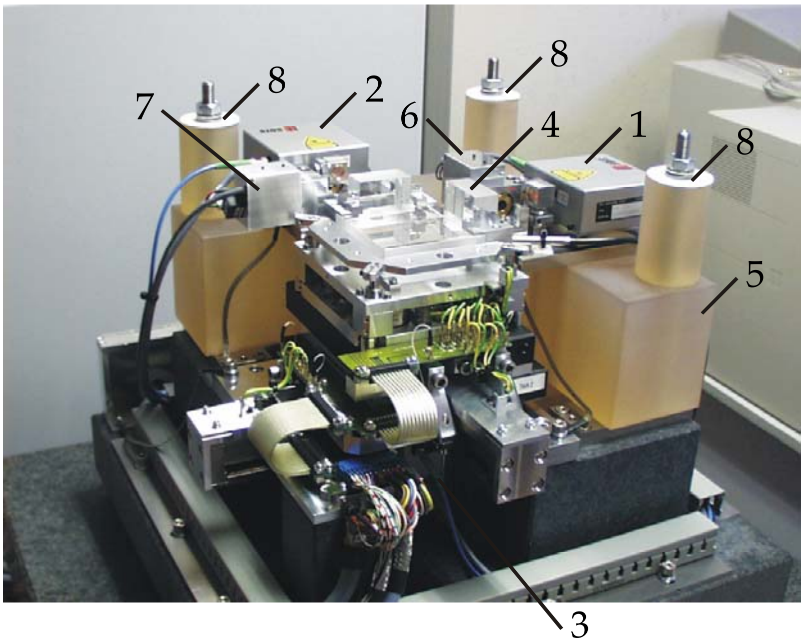
where

L_x, L_y, L_z are the distances between the external faces of the mirror corner and the point of contact of the probe with the surface of the measuring object.

α, β, γ are the pitch-, roll- and yaw angles of tilt of the mirror corner.

To measure the measuring object, the mirror corner with the object must be guided parallel with great attention being paid to the fact that the contact of the probe is maintained at any time. If this is the case, possible systematic errors of the guides will not have any influence on the result of measurement. For compensating the tilt errors of the guides, pitch, yaw and roll angle sensors are attached to the zerodur base.

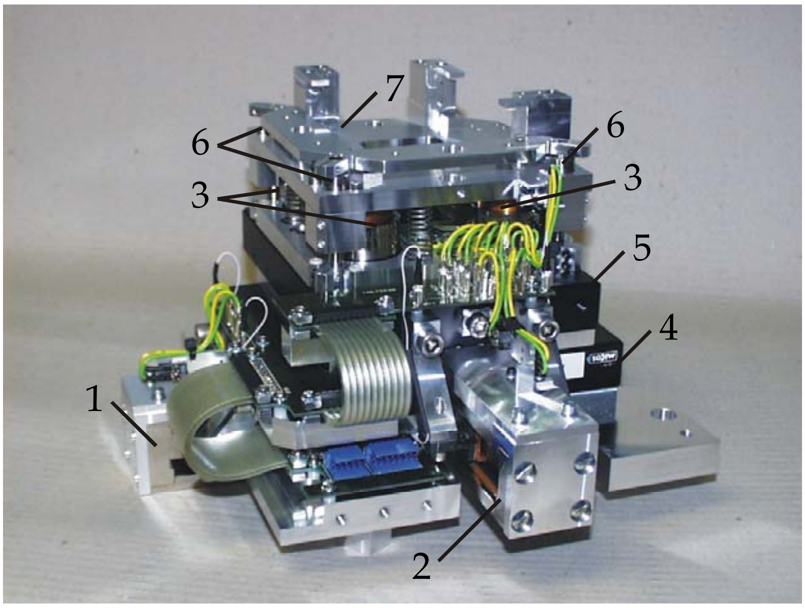
The nanomeasuring machine is equipped with ball guides for all three axes serving as linear guiding elements (Fig. 5). The drives for the guides are all of an electrodynamic type. Each of the x- and y-axes is provided with a separate drive system. The drive system of the z-axis consists of four individual drives. This makes it possible to adjust the roll and pitch angles of the guides by means of the angle sensors.



1 x-Interferometer
2 y-Interferometer
3 z-Interferometer
4 mirror corner
5 Zerodur base
6 pitch- and yaw angle sensor
7 roll- and yaw angle sensor
8 fixing points for probe system

Fig. 5: Drive and guide system of the nanomeasuring machine

The complete nanomeasuring machine is represented in Fig. 6. A zerodur plate for holding the probe systems is fixed to the zerodur columns 8.



1 x-drive
2 y-drive
3 z-drive
4 x-guide
5 y-guide
6 z-guide
7 moving mirror platform

Fig. 6: Nanomeasuring machine

3.2 Metrological properties

The nanomeasuring machine has a measuring range of 25 mm x 25 mm x 5 mm and a resolution of 1.24 nm in all measuring axes. The laser-interferometric measurement is free from Abbe errors of 1st order in all three coordinates. When the machine was tested, also the other axes were driven within the digital uncertainty of 1.24 nm, with the measuring table being moved linearly. Thus, within its measuring range, the nanomeasuring machine is able to meet the requirements of microelectronics, microtechnology, nanotechnology, and precision engineering at highest possible measuring uncertainty.

4. Acknowledgements

The authors wish to thank all those colleagues from the TU Ilmenau who have contributed to the developments presented here. Our special thanks are due to the Thüringer Ministerium für Wissenschaft, Forschung und Kultur for promoting the nanocoordinate metrology in the framework of joint projects.

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