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Nanopositioning and Nanomeasuring Machine NPMM-200 – sub-nanometre resolution and highest accuracy in extended macroscopic working areas

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Abstract
At the Technische Universität Ilmenau, a new Nanopositioning and Nanomeasuring Machine NPMM 200 with a measuring range of 200 mm × 200 mm × 25 mm and a resolution of 0.02 nm has been developed. In order to achieve both highest nanometre accuracy and largest three-dimensional working space, an extended three-dimensional Abbe comparator principle is applied. The object to be measured is placed on a special mirror plate whose position in all six degrees of freedom is measured by high-precision multi-axis fibre-coupled laser interferometers. By means of an advanced closed-loop control tilt errors induced by the guiding systems can be minimized up to interferometric level. This paper presents the metrological concept, the realized design, the conditioning of environmental parameters as well as some first measuring results.

Keywords: Nanopositioning and Nanomeasuring Machine; Abbe comparator principle; closed-loop controll

1. Introduction

Precision is one of the enabler of modern technologies. To keep on with scaling down nanoelectronic components alternative solutions to EUV lithography are more and more under consideration. Therefore, the development of new nanofabrication approaches is pushed. But master ever smaller structures in increasingly big volumes represent an important motivation for the development of high-precision metrology equipment. On the other side, high precision optics and freeform surfaces require new challenging 3 D instrumentation over long measuring intervals with nanometre precision. Nanopositioning and nanomeasuring machines are such a metrological equipment that allows measurements with nanometre accuracy in large measurement regions of several millimetres in all directions. Thus, at the Technische Universität Ilmenau, the nanopositioning and nanomeasuring machine NPMM 200 was developed and analysed. This device has a measuring and positioning range of 200 mm × 200 mm × 25 mm, a resolution of 0.02 nm and an outstanding measurement performance.

2. Measurement principle and setup

To achieve highest accuracy the Abbe comparator principle has to be applied in all three coordinate axis. Additional, all angular deviations are permanently measured and are minimized by an advanced closed-loop control. Therefore, comparable to the nanomeasuring machine NMM-1 [1,2] and in contrast to state-of-the-art coordinate measuring machines the measuring probe is fixed and the object to be measured is moved (see fig.1).

The three-axis guiding system presents unavoidable angular deviations in the order of some arc seconds. Nevertheless, these deviations are measured with a resolution of less than 0.001" and can be controlled better than 0.1" permanently by a closed loop control. Therefore, the residual Abbe error can be minimised even when the Abbe offset is not zero. With this approach, the Abbe principle is fulfilled in 3 D in an extended manner within the complete measuring volume.

The mechanical and optical structure is shown in Figure 2. Six fiber coupled laser interferometers (1-5) measure all motions in all six degrees of freedom with a resolution of 20 pm.

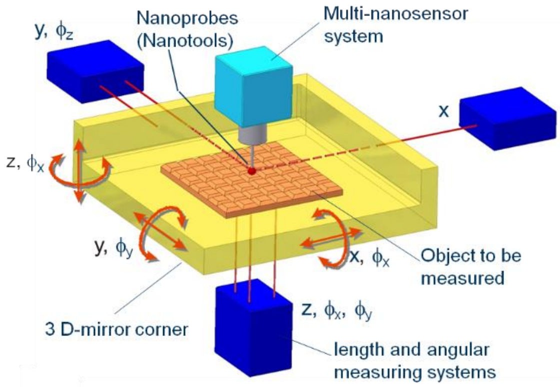

Figure 1. Basic principle of a nanopositioning and nanomeasuring machine [2].

Three laser measurement axes intersect in one point. This point is in the same time the touch point of the probe (6), which on the other hand is working as a zero point sensor. The other three laser axes are almost parallel to the former axes and measure the angular tilt (4,5).

The mirror plate (9) which carries the object to be measured (8) is applied with reflective coatings on the three measuring surfaces. The flatness and the orthogonality of these surfaces determine the accuracy of measuring machine. The metrological frame (10) is made of Zerodur (expansion class 0) to avoid unwanted thermal length changes. It carries the three length and three angle measuring systems, additional reference sensors (11), and the probe system (6). The measurement stage carrying the mirror plate is realized by three guiding systems (13-15) and driven by electrodynamic drive systems (16-18) outside the measuring space of the machine to avoid thermal influence of the voice coil systems onto the measuring table.

The three-axis guidance system of NPMM 200 is a serial kinematic configuration with linear roller guides.

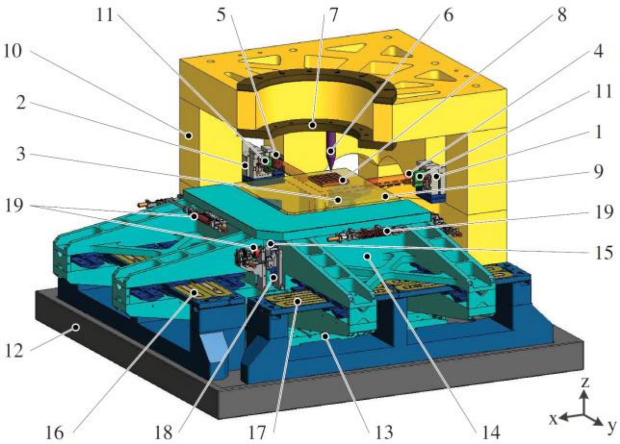

Figure 2. Mechanical and optical basic structure of NPMM 200 (1 x-, 2 y- and 3 z-interferometer, 4 pitch and yaw angle sensor (ϕy and ϕz), 5 roll and yaw angle sensor (ϕx and ϕz), 6 probe system (fixed in space), 7 mounting points for the probe system, 8 measuring object, 9 mirror plate, 10 metrology frame, 11 reference sensors, 12 base plate, guiding system of the 13 x-, 14 y-, and 15 z-axis, drive systems of the 16 x-, 17 y-, and 18 z-axis, 19 weight force compensation.

Four gravity compensation units (19) complete the mechanical system. The mechanical setup can be seen in Figure 3.

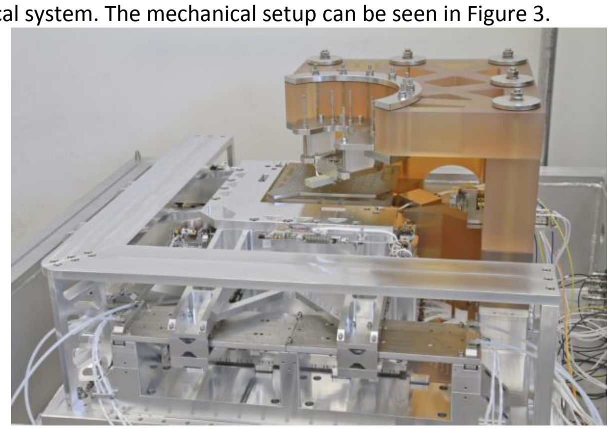

Figure 3. Setup of the NPMM-200.

A heterogeneous modular multiprocessor system is used as signal and information processing system. With commercially available PXI components and specifically developed hardware and software, a complete infrastructure was created, for example for data processing, control and regulation processes.

The base of the controller is a multivariable state controller which serves as subordinate control system. An extended Kalman filter is used as a disturbance observer for each axis of motion. An algebraic derivative estimator is used for state reconstruction. For feedforward control an adaptive friction model is applied.

3. Positioning and measuring properties

The positioning properties are largely determined by the control system. Therefore, the permanent position and angle noise was investigated. The permanent position noise is less than 0.3 nm for all three axes [3]. With activated drives and thus, in closed loop, it increases up to 2 nm on average.

In Figure 4, the measurement steps of 1 nm in all three axes, are shown. All three axes were moved simultaneously, and then stopped for 5 s. Although the primary measurement values show a positioning noise of 1 nm (peak to peak) the steps can be visualized clearly by a subsequent filtering of the measured data. Measurements for positioning repeatability showed that arbitrary positions in the measuring volume can be approached with a standard deviation of the target position of < 2 nm.

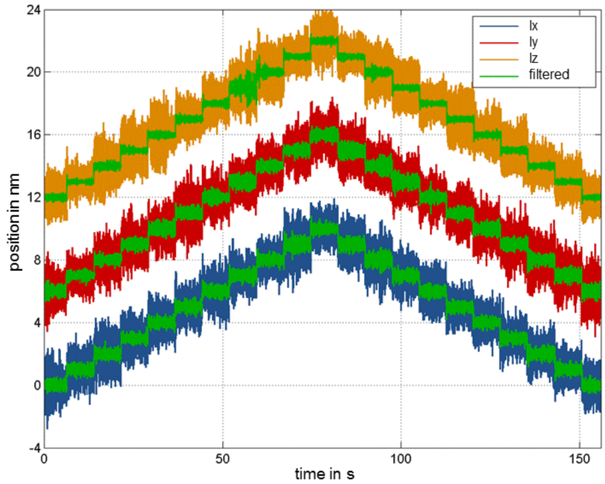

Figure 4. Filtered position measurement values for set point positions with a distance of 1 nm.

The first verification of the measurement capability was carried out with a laser focus sensor [2] as a non-contact zero point sensor. Height measurements of a special 15 mm step height standard have shown a standard deviation of 6 nm [4]. This result was mainly influenced by a flatness error of ±4 nm of the standard itsself.

5. Conclusion and Outlook

A universal nanopositioning and nanomeasuring machine NPMM 200 with a measuring volume of 200 mm × 200 mm × 25 mm and a resolution of 20 pm was realized. The machine works under normal air conditions as well as in an active thermally controlled vacuum chamber at 1mbar where a measurement uncertainty of less than 30 nm can be achieved. The positioning stability as well as the repeatability at one point within the whole measuring range is less than 2 nm. The first verification of the measurement capability was carried out with a laser focus sensor. Nevertheless, the application of other optical, tactile or AFM sensors is possible. Therefore, the NPMM-200 is a highly powerful measuring and positioning machine and opens up new opportunities in the field of 3D high-precision multi-scale measurement technology.

6. Acknowledgements

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