COMBINING SENSORS AND INTERFEROMETERS

A nanomeasuring and nanopositioning machine/platform, in combination with an atomic force microscope, an optical sensor or a microprobe, can be used to perform high-precision free-form surface measurements as well as three-dimensional scanning and tactile measurements on microcomponents. Uncertainties in the nanometer range are achievable, and the use of laser interferometers for position measurement allows traceability of measurements for the purpose of sensor calibration.

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AUTHORS' NOTE

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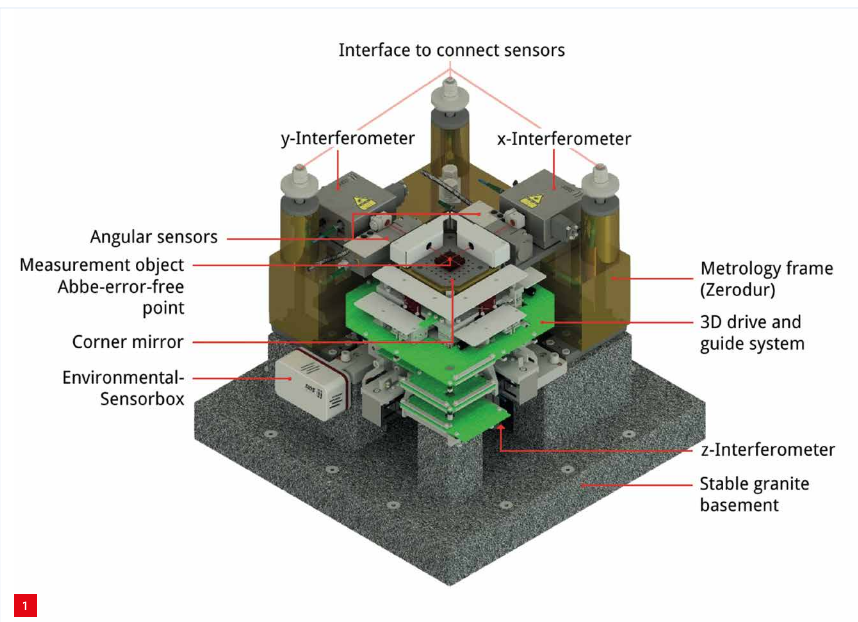
Introduction

The ability to perform nanometer-precision metrology is increasingly influencing all phases of product development and manufacturing, from design engineering, prototyping and manufacturing to quality control, process analysis and final inspection of components and assemblies. Examples include prototyping, quality control, process analysis and final inspection of components and assemblies. The shape and dimensions of workpieces, optical components and surfaces also require high-precision metrology equipment.

Metrological concepts for nanopositioning

Laser interferometry is a commonly used technology when the metrological aspect of the measurement is the focus of the application. In addition to high resolution, laser interferometers offer the possibility of metrological traceability of the length information to the international standard. Their theoretical resolution can be achieved in the range of a few picometers, but in practice this can only be realised in special arrangements [1]. The most important feature of single-beam laser interferometers therefore, in contrast to linear scales, is the ability to realise Abbe-error-free measuring arrangements.



Concept of the nanomeasuring and nanopositioning machine NMM-1.

One of the critical parameters of any nanometrology measurement set-up is its long-term thermal stability. Since the measurement can be performed over several hours, the influence of thermal drifts on the measurement set-up should be avoided. Two different approaches can be realised in practice, with measurement set-ups based on either an ultra-stable measurement frame or an ultra-stable differential interferometer.

The first approach, based on an ultra-stable metrological frame, has been successfully realised in the nanomeasuring and nanopositioning machine NMM-1. The device has a Zerodur metrological frame as the basis for the positioning feedback sensors as well as the probing systems. The main advantage of the compact set-up is a clear definition of the thermal behaviour of the system. However, extending the measurement range will increase the cost of the metrology frame.

The second approach is only possible if laser interferometers with a thermally perfect qualification can be used, which enables compensation of refractive index and thermal drifts by a differential principle. They can be mounted on a thermally unstable base if they work against an external reference point. This approach has been followed in the nanopositioning platform NPP-1, of which the architecture is scalable and can be applied for different positioning ranges.

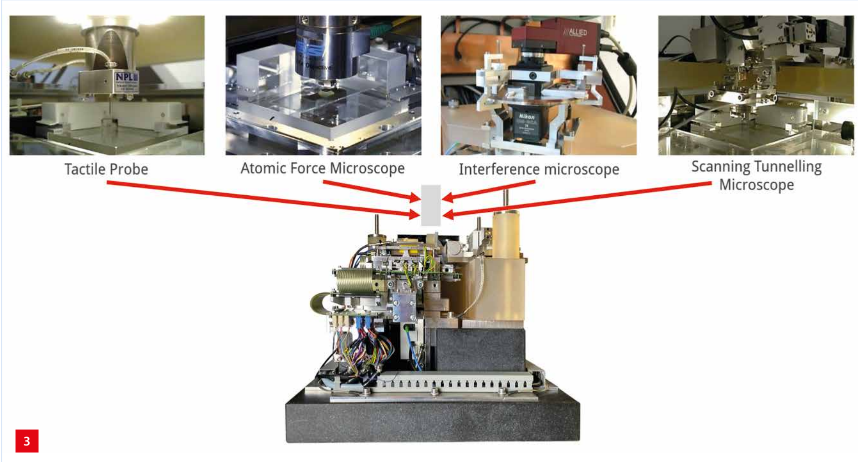
Nanomeasuring machine NMM-1

The nanomeasuring and nanopositioning machine NMM-1 from SIOS Meßtechnik is a 3D measuring device with an open sensor architecture that realises an Abbe-error-free measuring arrangement in the three positioning axes *x*, *y* and *z* [2] [3]. The laser interferometers are mounted on a long-term stable metrological base and all three beams intersect at the virtual measuring point, where the probe point of the mounted sensor is located. Figure 1 shows the measurement set-up of the NMM-1.

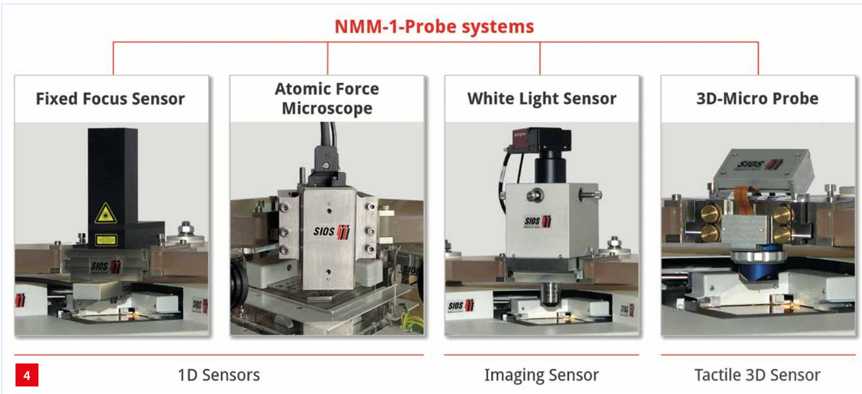
The high-accuracy mirror corner of the NMM-1 forms the coordinate system for the instrument and is positioned over the laser interferometer readings with sub-nanometer accuracy over the entire 25 mm x 25 mm x 5 mm measurement volume. Figure 2 shows the capability of the positioning system in closed-loop mode.

Probing sensors can be calibrated in-situ on the NMM-1 by built-in laser interferometers and controlled to a fixed setpoint throughout the measurement. This allows the sensors to be used with a small measuring range, so that only the smallest controller deviations are recorded during the measurement. Therefore, the laser interferometers, which form the metrological basis for the measurement result, are decisive for the measurement uncertainty.
The measured value is the combination of the sensor value and the laser interferometric measurement.

The high positioning accuracy of the NMM-1 provides the basis for metrological measurements, while the open hard ware architecture allows the NMM-1 to be used as a calibration platform for basic research and sensor development. Figure 3 shows several examples of sensors that can be easily calibrated on the NMM-1 platform. The sensors to be calibrated must have either analog outputs or a synchronisable interface. The acquisition of the sensor data is done simultaneously with the interferometer readings with a high sampling frequency and all measurement data can be stored immediately on the main computer.
Depending on the sensor used, different measurement tasks can be accomplished. Figure 4 shows the range of standard sensors that can be used with the NMM-1. Surface scans can be conducted with an optical single-point LFS fixed focus sensor, and when using an atomic force microscope line scans can be performed according to the described control principle over several millimeters with highest lateral resolution.

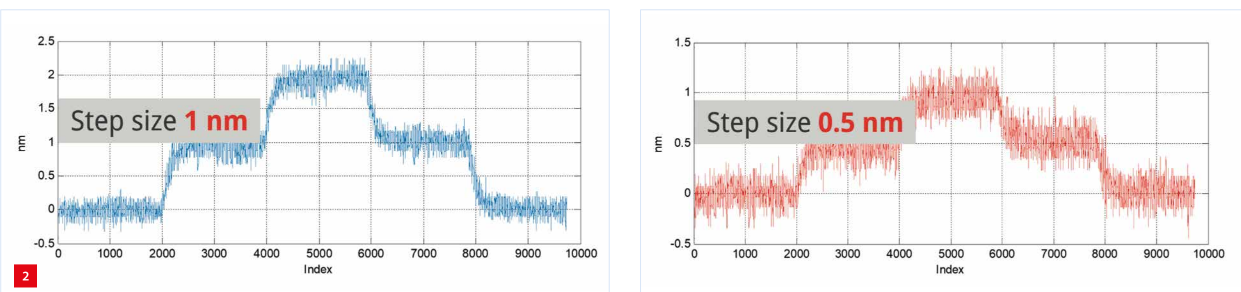


NMM-1 positioning platform for the calibration of various sensors.

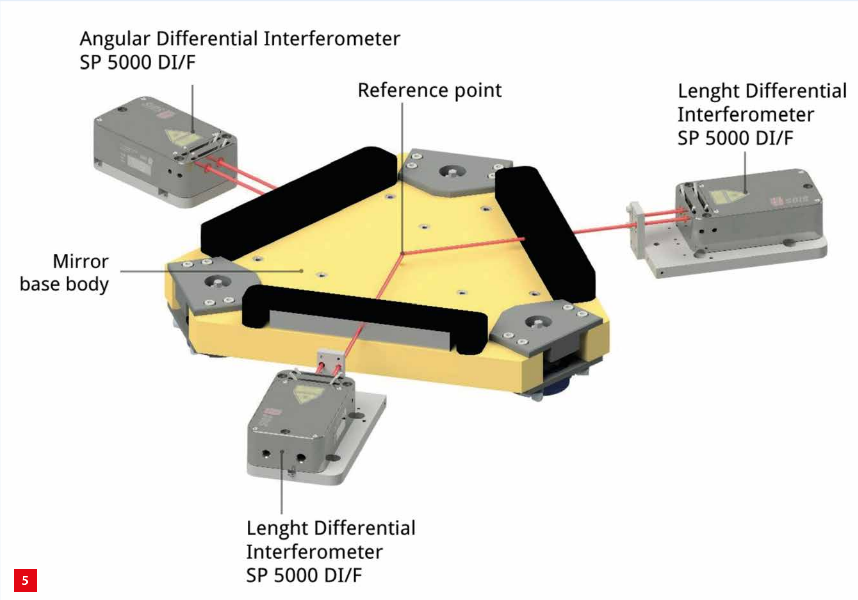


Various probing systems for the NMM-1.

The biggest challenge is the 3D measurement on the NMM-1 with a microprobe. The 3D probe transforms the NMM-1 into a nano-CMM (coordinate measuring machine), where all problems of a CMM regarding the interaction with the measuring surface also apply to the NMM-1. The use of 3D microprobes for nanometer-accuracy measurements requires special care in selecting the probing strategy. Due to the small diameter of the microprobe's stylus ball and the low probing force, surface effects of the target have a greater influence on the measurement result than with macroscopic styli. Examples include surface roughness, ball flattening, plastic deformation of the target surface, and wear. The probe can be calibrated in-situ on the NMM-1.



Positioning stability performance of the NMM-1 positioning stage, for step sizes of 1 nm and 0.5 nm, on the left and right, respectively: measured position (variation) for a long series of measuring points (denoted by Index).



5

Arrangement of the interferometers for positioning the reference mirrors that are attached to the mirror base body (the carriage). Note: the mirrors are not semi-transparent; the red lines just indicate the reference point.

Ultra-stable interferometry for positioning platform

The NPP-1 nanopositioning platform employs ultra-stable differential laser interferometers for closed-loop control. They use external references to minimise thermal drift and air refractive index drift, and are specified with thermal drifts < 10 nm/K. With a range of motion of Ø100 mm, this newly developed nanopositioning platform is used to explore atomic force microscopy on large surfaces with the highest precision. The system uses a planar direct-drive system to position the carriage holding the sample (surface). Three actuators based on electromagnetic force generation are used to provide non-contact force transmission. Each actuator consists of two fixed coils that act on magnets attached to the carriage.

The drive forces of the three linear actuators act simultaneously on the carriage. The 120° arrangement allows the resulting force to be applied in any direction within the x-y plane, while also enabling rotation around the z-axis. The rotation is measured by a third differential interferometer, of which the two beams are reflected by the same measurement mirror, providing a high-resolution angle measurement with low nonlinearities. Figure 5 shows the arrangement of the interferometers on the carriage, with their beams intersecting in the virtual Abbe point.

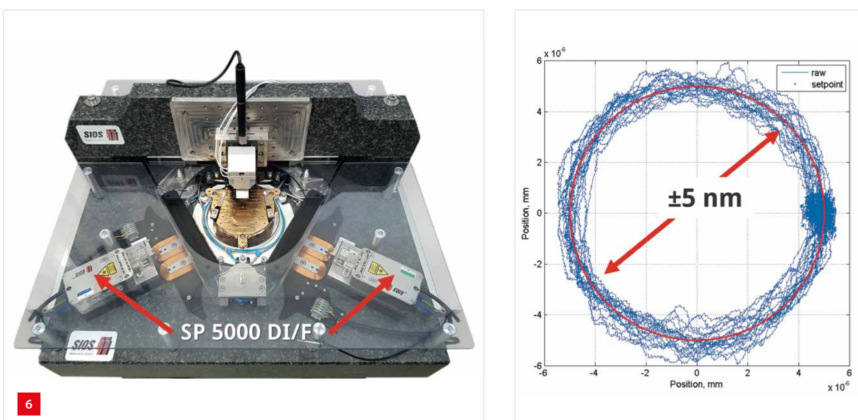
The measuring mirror is rigidly connected to low-friction air-bearing guides. This results in a measurement arrangement that can support much heavier objects than NMM-1 (up to 2 kg) and still have very good control characteristics. Figure 6 shows the measurement set-up and the result of positioning in a circle with a radius of 5 nm. Possible applications and measurement results of the NPP-1 are presented in [4].

Conclusions

Using the NMM-1 in combination with an atomic force microscope, an optical sensor or a microprobe, enables high-precision free-form surface measurements as well as three-dimensional scanning and tactile measurements on microcomponents. The positioning resolution < 1 nm can be achieved in the full range of 25 mm x 25 mm x 5 mm.

This opens up many new applications for the NMM-1, such as positioning, manipulation, manufacturing and measurement of microelectronic, micromechanical, optical and microsystem objects. Furthermore, high-precision calibrations of ring gauges, lateral grating standards and step height standards are possible. Uncertainties in the nanometer range are achievable, and the use of laser interferometers for position measurement allows traceability of measurements for calibration purposes. Another approach for nanopositioning based on ultra-stable differential interferometers with thermal expansion coefficients < 10 nm/K allows the realisation of scalable architectures such as NPP-1. The key to such metrological designs is the proper qualification of the interferometer properties as well as the correct definition of the reference points for the positioning systems.

REFERENCES
[1] Huaman, A.S., *et al.*, "Picometer-Scale Positioning of a Linear Drive System via Feedforward-Feedback Control", *2021 IEEE International Conference on Mechatronics*, pp. 1-6, *doi.org/10.1109/ICM46511.2021.9385699*
[2] Jäger, G., "Three-Dimensional Nanopositioning and Nanomeasuring Machine with a Resolution of 0.1 nm", *Optoelectronics, Instrumentation and Data Processing*, vol. 46, pp. 318-323, 2010.
[3] Jäger, G., Manske, E., and Hausotte, H.-J., "The metrogical basis and operation of Nanopositioning and Nanomeasuring Machine NMM-1", *Technical Measurement*, vol. 76 (5), pp. 227-233, 2009.
[4] Stauffenberg, J., *et al.*, "Measurement precision of planar nanopositioning machine with a range of motion of Ø100 mm", *Applied Sciences*, 12, 7843, 2022.



6

Positioning platform based on ultra-stable laser interferometers; the platform is supported by three air bearings at the three corners, while the three actuators are located at the middle of the three sides of the triangular platform.
On the right, the measurement result of positioning in a circle with a radius of 5 nm.