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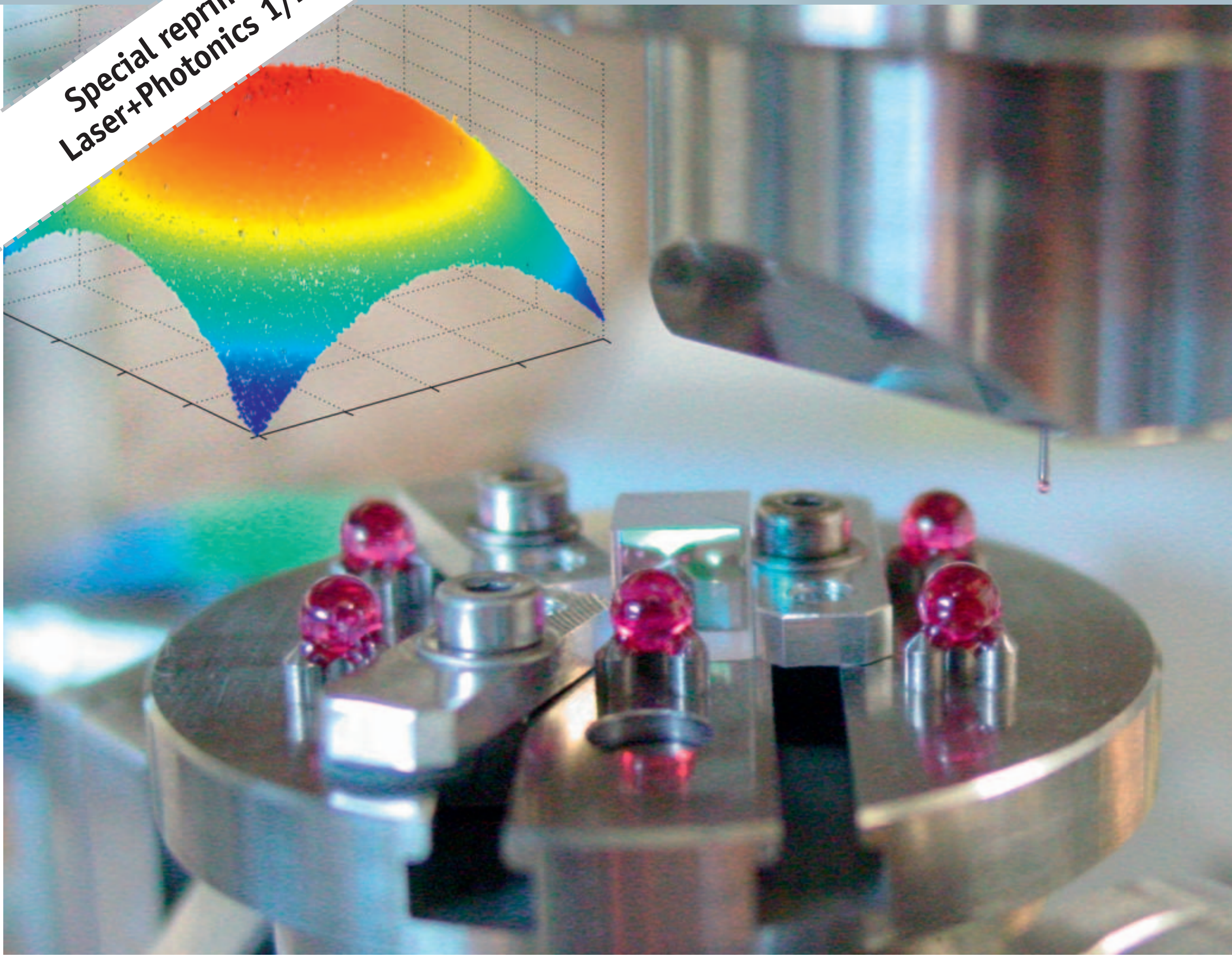

3D capability for nanopositioning and nanometrology

PRECISION, FLEXIBLE, BROAD-RANGE MEASUREMENT OF THREE-DIMENSIONAL OBJECTS

Many branches of industry and fields of research require tactile 3D coordinate measurement systems with sub-nanometer resolution for proofing high-precision, fine-mechanical and optical components as well as for manufactured elements and for tooling used for manufacturing microlenses. In order to meet these requirements, nanopositioning and nanomeasuring machines have been upgraded by incorporating 3D functionality and tactile 3D microprobes.

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The ability to perform nanometer-precision metrology is becoming increasingly influential throughout all phases of product development and manufacture, from engineering development, through prototyping and manufacturing, to quality control, process analysis and final inspection of components and workpieces. In particular, advances in the miniaturization of components, such as microdrives or injection nozzles and extrusion dies, all having extremely small dimensions and subject to stringent tolerances, has driven the need to measure three-dimensional shapes with nanometer precision. Exact machining of press tools, molding dies and optical components with nanometer precision and optical finish has also led to demands for high-precision metrological systems, as accurate information on the dimensions and shape of processing tools, components and workpieces is needed in those areas as well.

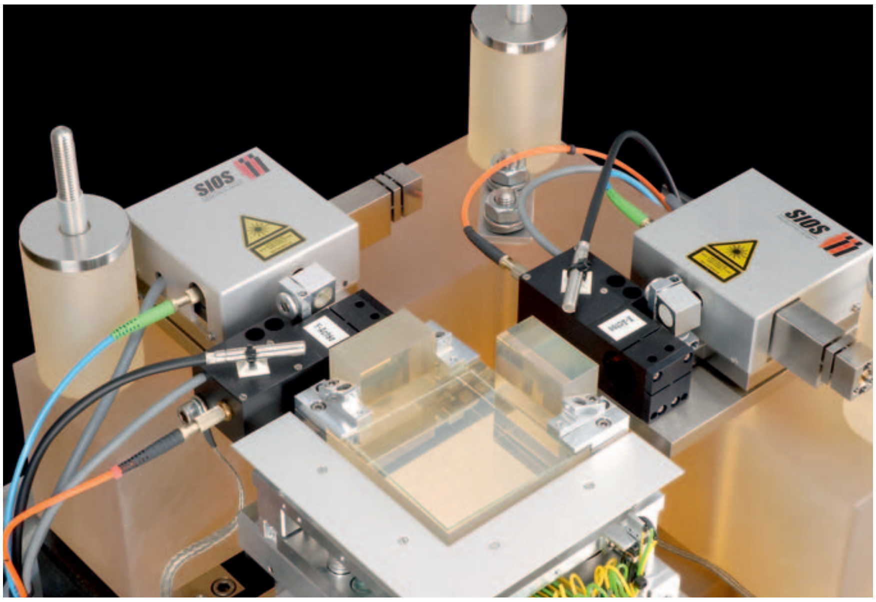
The ›NMM-1‹ nanomeasuring machine, developed at the Technical University of Ilmenau's Institute for Process Measurement and Sensor Technology and produced by Sios Messtechnik, provides the opportunity for conducting many different types of measurements (Figure 1 and 2). The NNM-1 exhibits 0.1 nm resolution in a measurement volume of 25x25x5 mm^3 and can be equipped with various types of tactile microprobes.

Engineering design features

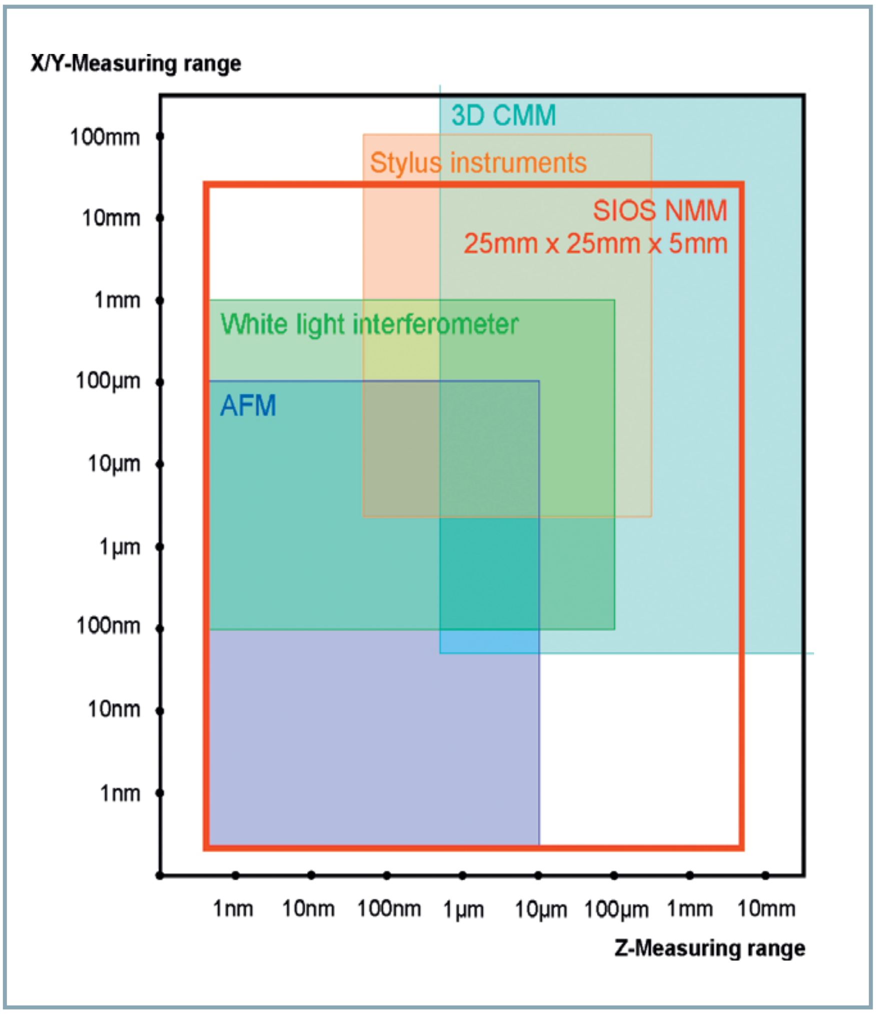
The NMM-1 is composed of *xyz* guidance and drive systems, upon which a corner mirror is mounted that serves as the reflector for three fiberoptic-coupled laser interferometers. The laser interferometers are mounted on a thermally stable, metrology frame. The basis for its high precision is the arrangement of the three laser interferometers used for positional measurements. Their three measurement beams intersect at a single point that coincides with the probe system's contact point. The object being measured is attached to the corner mirror and moves with it – compliance with the principle that forms the basis for the operation of an Abbe comparator will be maintained on all three axes at all times, as the object being measured and the component utilized for determining its dimensions are colinearly arranged, thus minimizing the effects of systematic errors in the guidance system and any resulting misalignment of the corner mirror. In order to provide for ultraprecise measurements, tilting of the corner mirror is measured by a pair of angle sensors and corrected for by the *z*-axis drive via a closed-loop regulation circuit. This approach avoids any remaining residual errors (Figure 3).

Within the NMM-1, the probe system acts as a zero-point indicator. Widely varying types of sensors and processing systems may be readily incorporated, thanks to the open interface. Non-contacting metrological systems, such as focus sensors or white light interferometers, as well as scanning force microscopes or tactile 3D microprobes exerting low tactile forces, are currently being employed (Figure 4).

The NMM-1 thus has various application areas, such as positioning, manipulation, processing and measurement of microelectronic, micromechanical, optical and microsystem objects (such as microlenses or membranes) as well as the high-precision calibration of ring gauges, lateral displacement standards and step-height standards. Measurement precision in the subnanometer range is attainable, although the overall measurable range



1 The nanopositioning and nanomeasurering machine NMM-1



2 Comparison of the measurement ranges for the NMM-1 with alternative methods

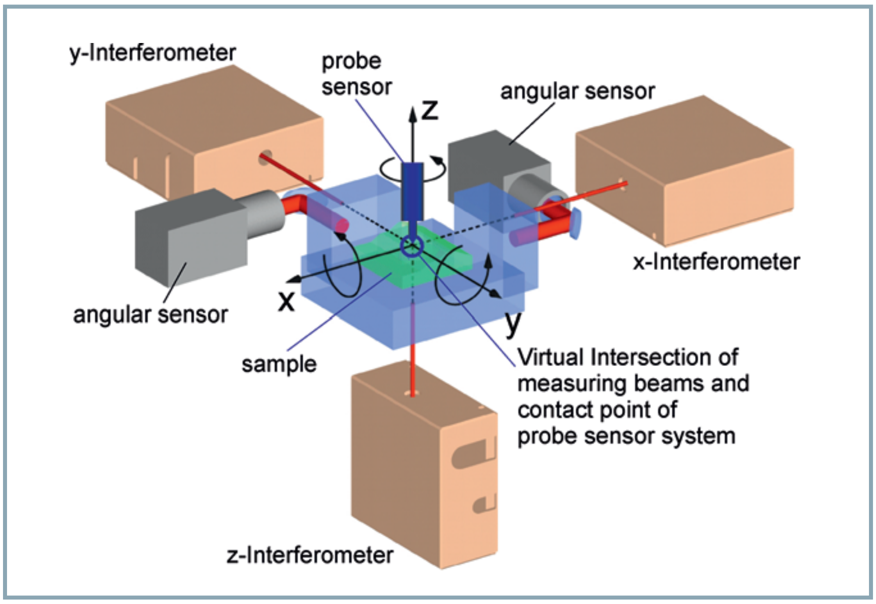
can be vastly expanded when used in combination with a scanning probe microscope. The employment of laser interferometers for the positional measurements also allows tracing measurements back to reference objects for calibration purposes.

Extended 3D functionality

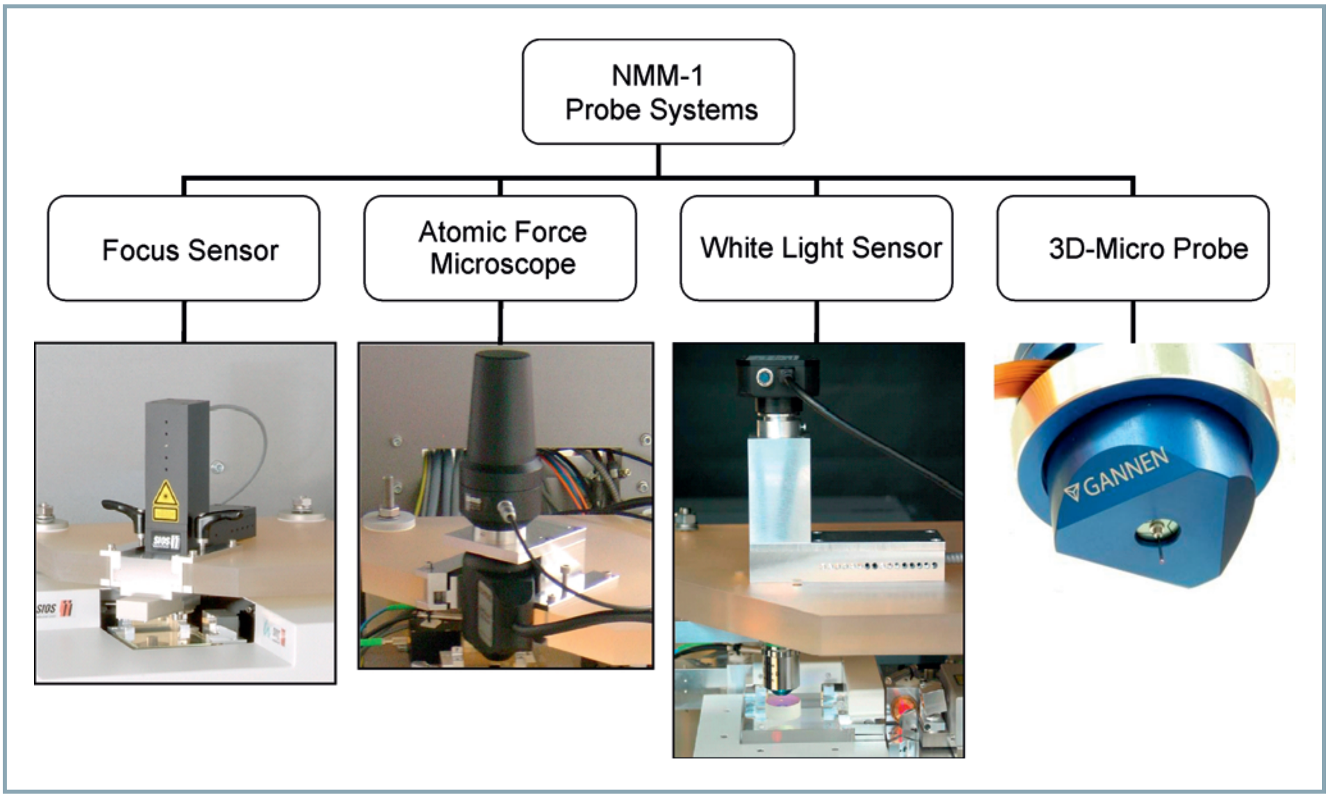
The concept on which the NMM-1 is currently based permits using just the *z*-axis as the tactile-probing direction, which means that precisely one height measurement will be correlated to every point on the *xy*-plane. Such measurements are termed ›2.5D‹ surface measurements. The NMM-1's excellent metrological characteristics are being exploited for calibrating transfer standards, such as step-height standards, one-dimensional and two-dimensional lateral-displacement standards, planarity standards and roughness standards, at several government institutions around the world. Several round-robin comparative measurements have demonstrated its potential.

However, vertical surfaces can be neither detected nor analyzed using 2.5D profile measurements. Problems can also arise at steep surface gradients that exceed a certain angle, for example as present on the curved surfaces of lenses or press tools. In order to meet all of the demands imposed on high-precision measurements of microcomponents, the NMM-1 was upgraded by adding 3D functionality. In large part, this essentially meant modifications to the firmware (also developed by the Technical University of Ilmenau) by incorporating many commands from the I++/DME specification (a non-proprietary interface between metrological software and metrological instrumentation).

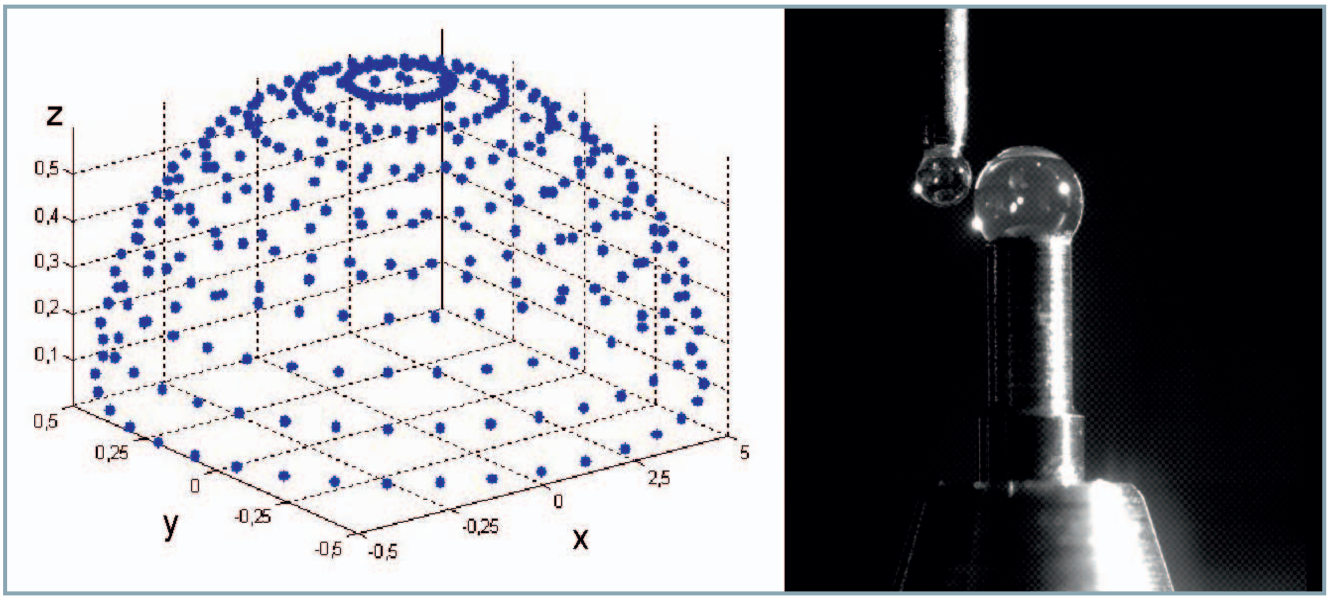
Open-loop scan commands allow driving the probe sensor to approach and contact the surface of the object being measured and subsequently translating the table along a defined trajectory. The probe system will then be deflected by surface irregularities. Closed-loop scan commands allow translating the table along a straight line in space, or around



3 **Schematic of the NMM-1**



4 **Probe sensors for the NMM-1**



5 Measurement of a spherical surface

a circular path in a predefined direction, where the probe sensor's scanning force will be held constant at all times during scanning. Various options for conducting free-form measurements utilizing probe sensors that have responsivities on all three spatial axes have been incorporated, where the scanning direction will be computed based on the signals received from the sensor. Commands for making single point measurements have also been incorporated. Additional commands (that are not part of the I++/DME specification) have also been incorporated in order to allow employment of probe systems, such as white light interferometers and other types of surface sensors that provide no feedback signal for regulating positioning.

Probe systems having responsivities on all three spatial axes are essential in making measurements on three-dimensional objects. The ›Gannen XP‹ microtactile-probe system supplied by Express Engineering has been incorporated into the NMM-1. The basis for this system is a silicon membrane, incorporating twelve piezoresistive elements arranged in groups of four, and with the groups spaced evenly (every 120°) around the probe tip. Each group is connected to a Wheatstone bridge and provides a measurement signal. The probe tip is attached directly to the membrane so that this assembly can be replaced as a unit (the manufacturer offers a choice of various probe tip diameters and membrane stiffnesses). However, the three signals from the membrane vary with the probe's orientation within the NMM-1, which is why probe signals must be recalibrated whenever a membrane is replaced. A small cube is usually employed for this purpose, the probe tip being scanned over the cube in both directions along all three spatial axes and the resultant signals recorded. Calibration factors obtained in this manner may be used to compute a coefficient matrix that, together with the specific springiness of any one membrane, may be used to compute the probe's force vector. High-precision, free-form surface measurements and three-dimensional scanning and tactile measurements on microcomponents are thus possible (Figure 5).

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Summary

The NMM-1's extended 3D functionality represents an effective tool for manufacturing, quality assurance and research and development. Ultraprecise, quantitative, dimensional measurements over a 25x25x5 mm^3 workspace can be made with a resolution of 0.1 nm. By equipping the NNM-1 with different probe sensors, it is capable of handling various 2D and 3D metrological tasks.

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