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Traceable 5D-nanofabrication with nano positioning and nano measuring machines

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Abstract
Today, besides the ongoing progress in the reduction of feature sizes, the measuring and fabrication of freeform surfaces with nanometre uncertainty, e.g. for aspheric lenses or structures with high aspect ratios, are a challenging task. Usually, dealing with such objects is limited by the local tilt angle between the object surface and the tool axis. There are different approaches to perform such measurements. In this paper, an extension of the Nano Measuring Machine NMM-1 with two rotational axes is described.
With the proposed setup, it is possible to orientate the tool-axis perpendicular to the sample in every position, allowing larger angles to be measured / structured and minimising the uncertainty of the process e.g. due to the tilt dependency of the tool. Various machine designs are investigated and finally a solution with one rotary and one goniometer stage is integrated, preserving the existing machine infrastructure and allowing the addressability of a full hemisphere without limiting the measuring volume. As the tool centre point maintains its position during tool rotation, the Abbe principle is still fulfilled in every angular orientation. Emphasis was put on the metrological traceability of the whole system, including linear and rotary axes as well the tool itself. This was achieved by using a reference hemisphere, compensating the trajectory errors of the rotational axes.
For the developed arrangement, the measurement uncertainty was investigated and several strategies for an in-situ-calibration of the additional axes are described. Finally, nanofabrication on large slopes is demonstrated.

Keywords: Nanomeasuring Machine, Nanofabrication, multiaxial, 5-axis operation, sub-nanometre precision, extended working range

1. Introduction

In the optical industry, aspherical optical components play a central role in various applications, because by completely relinquishing the symmetry of the functional surface, an optical system can be much more flexibly designed. Depending on the desired accuracy, the manufacturing process of such free-form optics is always an iterative process of successive measuring and processing steps. To reduce the measurement deviation, the surface must be probed as orthogonally as possible. If the local angle between the surface and the probing direction becomes too large, unwanted measurement deviations will occur or the surface cannot be probed at all. This applies to two-dimensional interferometric techniques as well as pointwise probing with a coordinate measuring machine (CMM). Therefore, in the course of this paper, the Nano Measuring Machine 1 (NMM-1) [01] is to be extended by two rotational axes so the probe system can always be aligned orthogonally to the measurement surface. This way, the excellent metrological properties of the NMM-1 shall be extended to heavily curved surfaces.
In this paper, the concept of the sensor rotation is described and examined in the context of the overall metrological concept. The attempt is based on a reference measurement system that tracks the path deviations caused by the rotational axes, enabling an online correction in the machine control system. Furthermore, the technical and constructive implementation of the proposed concept in a prototype setup is described.

2. State of the art

2.1 Nano-CMMs

In general, coordinate measuring machines consist of a 3-axes positioning system. This also applies to the Nanopositioning and Nanomeasuring Machines (NPMMs), which were developed in the last decades at the Technische Universität Ilmenau and resulted in three machine generations: the NMM-1 with a measuring volume of 25 mm x 25 mm x 5 mm [01], the NPMM-200 with 200 mm x 200 mm x 25 mm [02] and the Nano Fabrication Machine NFM-100 with a cylindrical measuring volume of Ø 100 mm x 5 µm [03].
Common feature of these machines is the operation in the sample scanning mode, where the probe / tool and the measuring systems are fixed to a metrological frame and the sample is moved.
Furthermore, all measuring axes (defined by the beams of the laser interferometers for length measurements) are arranged in a way, so they intersect in the tip of the probing / tooling system (tool centre point, TCP) at any time (fig. 1). This way, the compliance with the extended 3D Abbe comparator principle [04] in all three moving axes is guaranteed, reducing measuring errors to a minimum and allowing for three dimensional measurements with nanometre precision in the whole measuring volume [05].
Focusing on fulfilling the Abbe-principle in all three measuring directions requires a special design of the driving, guiding and

measurement systems. This design lead to the first nano-CMM following this design principles, the NMM-1 [06].

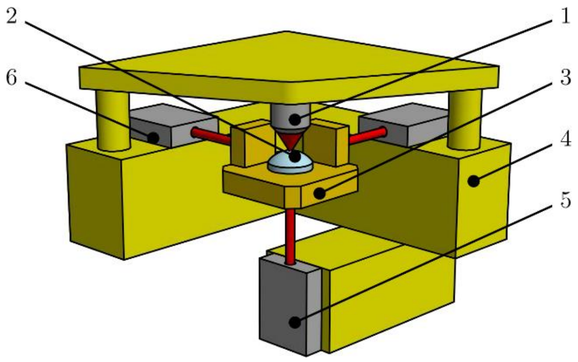

Figure 1. Structure of the NMM-1 with an optical probe (guiding and driving systems not shown): 1 probing system; 2 measuring object; 3 corner mirror; 4 metrological frame; 5 z-interferometer; 6 y-interferometer.

Although first order measuring errors are effectively prevented by the described principle, form deviations of the mechanical roller guidings lead to tilting of the machine table. Hence, second order measuring errors still exist in theory. To solve this problem, in the NPMMs the tilting of the moving stage is measured by angular sensors (autocollimators or angular interferometers) and closed-loop controlled. This way, form deviations of the guiding systems can be compensated and the machine table can be traversed exactly parallel through the complete measuring volume. So, second order errors can be prevented and even higher positioning precision can be achieved.
To preserve the inherent advantages of this design and transfer them to the technical realisation, additional effort needs to be taken. First of all, the complete machine coordinate system is based on the moving corner mirror which is carrying the measuring object. Therefore, this part is made of thermally stable material and the surface topography of the reference mirrors is calibrated after manufacturing [07] and compensated in the machine control system.

2.2 Limitations in 3D Nano-CMMs

The possibilities for measurements or fabrication on strongly curved surfaces are limited by the admissible tilt angle between the probe / tool working axis and the local surface normal. The admissible tilt angle is subject to the type and set-up of the utilised sensor or tool. Optical sensors rely on a signal reflected from the surface. With an increasing tilt angle between the probed surface and the optical axis of the sensor, the amount of light reaching the sensor will decrease. Depending on the sensor type and the utilised optics, measurements up to a slope of several degrees are still possible [08]. However, even at low tilt angles, systematic errors can occur. For high tilt angles, no more light reaches back into the sensor and the measurement becomes impossible.
In tactile sensors, the mechanical probing object is usually a sphere. When the local slope of the measured object changes, the mechanical contact occurs at a different location. Therefore, the form deviation of the probing sphere induces a systematic measurement deviation which can only be compensated when the actual shape of the sphere is known as precisely as possible [09].
Depending on the sensor used, the measurement of curved surfaces with a NPMM is possible up to a certain tilt angle, but as the slope increases, the measurement uncertainty increases too, the measurement becomes impossible or even the tool can be damaged.
Hence, to achieve larger angles and a minimal measurement uncertainty, the tool must be placed optimal (in general perpendicular) to the local surface.

3. Additional degrees of freedom for the NMM-1

As stated above, the tilt dependent behaviour of the sensor or fabrication tool should be compensated by additional rotational movements, integrated in the NMM-1. There, important aims were to preserve the overall machine structure, the compliance with the Abbe-principle (see sec. 2.1) as well as the size of the working volume. This leads to the demand for the additional rotational axes to intersect in the virtual intersection point of the interferometer beams, the Abbe-point. The theory for including additional rotational axes was extensively investigated in [10]. Summarised, the additional rotations must be reliable from a metrological point of view and a rotation of the tool is preferred over a rotation of the measuring object. To achieve the addressability of a full hemisphere while not limiting the measurement volume, an arrangement was chosen with two perpendicular axes, intersecting in the TCP/Abbe-point which allows a constant position of the TCP during rotation.
However, the additional rotational axes themselves are non-ideal and increase the uncertainty for the position of the TCP when rotating the sensor. A reproducible motion error can be calibrated and corrected in the machine control system. However, random path deviations of the rotational axes are especially critical for fabrication processes, as they lead to deviations in the produced structures which might be outside the permissible tolerances and on top of that impossible to repair. For that reason, it is necessary to track the errors of the rotational axes by a reference system. This way, a movement of the TCP during a rotation can be detected and compensated by a counter-movement of the existing x-, y-, z- stage. Due to the position and arrangement of the rotation axes, the sensor rotates solely around the Abbe-point. Hence, the position of the sensor can be measured relative to a hemispherical reference surface concentric to the Abbe-point. This surface is currently realised as a hollow, turned and polished metal half-cut sphere, firmly connected to the metrological frame. The distance of the TCP to this reference surface is determined by three cartesian arranged distance sensors (fig. 2).

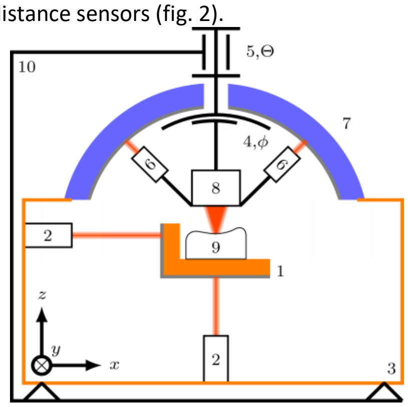

Figure 2. Metrological setup of the 5 axis Nanomeasuring Machine NMM-1 (2D visualisation, only 2 of 3 interferometers and distance sensors are shown.): 1 mirror corner; 2 interferometers; 3 metrological frame; 4 goniometer axis; 5 rotational axis; 6 sensors of the reference system; 7 reference hemisphere; 8 tool; 9 measuring object.

4. Experiments

Systematic deviations of the reference measurement system can be a consequence of a non-ideal adjustment of the functional units shown in fig. 2. To reduce these systematic deviations, an in-situ calibration procedure was developed that allows the calibration of the reference measuring system in the installed state with the aid of the available sensors. Furthermore, an adjustment strategy for the alignment of all components of the reference measurement system was developed and evaluated.

4.1 Adjustment strategy for the additional axes

When the TCP is not ideally located on the axis of the Θ rotational stage, it will move on a circular path in the x-y-plane during a rotation of axis 5 in fig. 2. To be able to measure this movement with existing sensors of the NMM-1, the corner mirror of the NMM-1 is disassembled, so the interferometer beams can indeed intersect in the Abbe-point. Furthermore, for this special examination task, the tool is replaced by a sphere with a refractive index n=2, also located in the Abbe-point, simultaneously serving as the new measuring reflector for all three length interferometers of the NMM-1, see fig. 3.

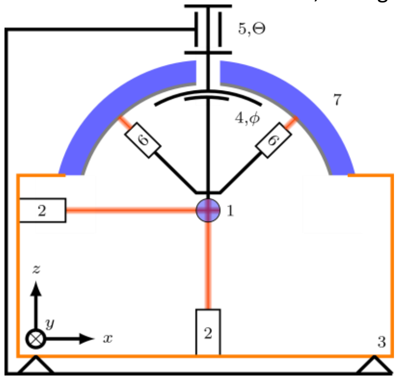

Figure 3. Setup for in-situ calibration of the reference hemisphere with existing sensors (NMM-1 without corner mirror): 1 n=2 sphere; 2 interferometer; 3 metrological frame; 4 goniometer axis; 5 rotational axis; 6 sensors of the reference system; 7 reference hemisphere.

In the described setup, the displacement of the n=2 sphere in the x-y-plane is tracked by the x- and y-interferometers of the NMM-1 with a phase shift of π/2. The gathered length information of both interferometers can be used to calculate the radius r of the circular path when the axis is rotated 360° (fig. 4). When the TCP has to adjusted to be coincident with the Θ-axis, this is equivalent to adjust the radius of the circular path to a minimum, which can be easily measured with the given set-up. The same procedure applies for the goniometer axis (4 in fig. 2). A similar approach can be made to adjust the centre of the hemisphere to be coincident to the Abbe-point. There, the tool has to be rotated with the rotational as well as the goniometer stage. The resulting displacement of the TCP is measured by the x-, y- and z-interferometers of the NMM-1 and by the reference system (2 and 6 in fig. 2). There, the interferometers of the NMM-1 are considered error-free. The calculated shape of the hemisphere (single sectional plane shown in fig. 5) can then be approximated by an ideal sphere and the centre point can be adjusted to be coincident with the Abbe-point.

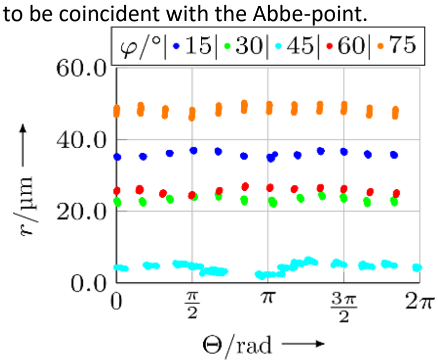

Figure 4. r- and Θ-position of the TCP at different goniometer angles φ for a full revolution Θ of the rotational axis. The data indicates the distance of the perpendicular axes which should ideally be zero.

4.2 In-situ calibration of the reference hemisphere

The hollow hemisphere serves as a reference system for determining the displacement errors during a sensor rotation. Hence, form deviations of the hemisphere directly lead to systematic measuring errors in x-, y- and z-direction. To reduce these errors, the actual form of the hemisphere has to be determined and can then be compensated in the control system of the NMM-1. The calibration can be carried out for example with a special Fizeau-interferometer outside the NMM-1. There, the different conditions concerning orientation and fixation lead to systematic but unknown calibration errors. For that reason, the hemisphere was calibrated in-situ in this project [11]. When driving the newly implemented rotational axes, the lateral displacement is traced by two measurement systems: the interferometers of the NMM-1 via the n=2 sphere and the hemisphere reference system (fig. 3). Again, presuming the laser interferometers as almost error-free in this setup, all deviations between the positions measured by the NMM-1 and the spherical reference system can be ascribed to form deviations of the hemisphere (fig. 5).

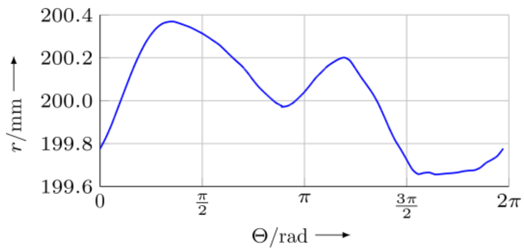

Figure 5. Local radius values r of the hemisphere, obtained by a single reference sensor taking a full revolution of the Θ-axis.

4.3 Nanoimprint Lithography on Plano-Convex Lenses

Nanoimprint lithography (NIL) is a high resolution nanofabrication process for fabrication of structures in the sub-10 nm range [12]. As there is a mechanical contact between the stamp and the sample during the imprint process, position accuracy, position stability and trajectory fidelity are essential for a correct imprint result. Obviously, when using NIL on large surfaces, an exact orientation of the stamp to the sample has to be guaranteed and the stamp has to be positioned exactly perpendicularly to the imprint surface. Because the extended NMM-1 matches these requirements perfectly, it is a suitable tool for investigations of NIL on curved surfaces.

NIL on curved surfaces without rotating the imprint tool was already shown in [12]. There, a compact and adjustable soft UV-NIL process was designed, assembled and integrated into the NMM-1 machine. The successful implementation of the fundamental process created a foundation for making a NIL tool to be combined with extended NMM-1 with two additional rotational axes. The combination enables five degrees of freedom of motion for orthogonal moulding and demoulding on edges of curved substrates (fig. 6). The rotating NIL tool addresses the generally overlooked challenge of patterning and characterisation on the edges of a curved substrate.

Regardless of restricted measurement capabilities at high inclinations for high resolution nanostructures, it was possible to perform SEM imaging of the structures on top of the lens substrate as well as at inclination of 45° outside the NMM-1. It has displayed imprinting capabilities on the edge of curved substrate with radius of curvature of approximately 25 mm at a surface normal tilted to 45°. The method enables precise imprinting capabilities at high inclinations, thereby presenting a novel approach of soft NIL on curved surfaces.

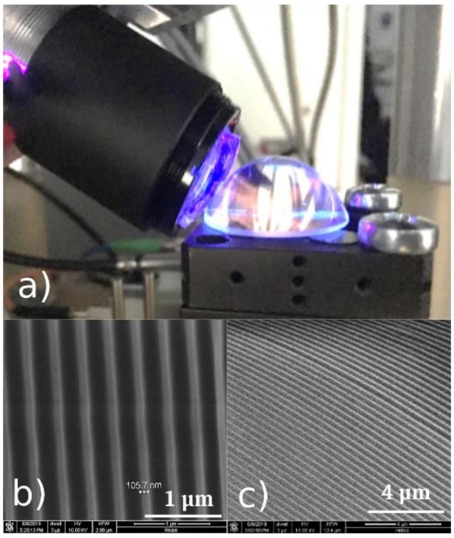

Figure 6. Nanoimprint on a plano-convex lens. a) Experimental setup with lens on NMM-1 machine table and NIL stamp, inclined by 45° to the z-axis. b) image of imprint result on the top of a sample (imprint at ϕ=0°) c) image of imprint result at the edge of a sample (imprint at ϕ=45°)

5. Conclusion and Outlook

Aspherical optics open up new possibilities for the design of optical systems. However, with an increasing slope, the requirements for measuring the functional surface of such optical parts are increasing as usual probing systems are limited in the acceptable angle between their tool axis and the surface to be probed. Several attempts were developed for measuring such surfaces. In this paper, the extension of the Nanomeasuring Machine NMM-1 is described to qualify this machine for measuring highly curved samples. Two additional rotational axes allow the rotation of the probing system around the machine centre point (Abbe-point) which leads to an error minimal configuration. The rotational concept furthermore preserves the basic setup of the NMM-1 and does not reduce the available measuring volume. The inherent motion errors of the rotational axes are taken into account by introducing a measuring system, based on a hollow hemisphere as a reference surface and three interferometers, probing this sphere. With this system, the motion errors can be measured and compensated by the machine control system. Furthermore, the adjustment and the calibration of all newly added functional units is described.
Finally, the performance of the extended NMM-1 is demonstrated by realising nanoimprint lithography on large slopes up to 45° on a plano-convex lens.
For the future development, the adjustment of the reference measuring system will be improved to reduce the measurement uncertainty even further. Additionally, based on the calculated uncertainty budget, the reference hemisphere will be replaced by a part made of low-thermal-expansion material with smaller dimensions, less form deviations and a better mechanical stability.
For the NIL process, the optimisation and implementation of a step and repeat process for higher throughput will be the next task.

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