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On the development and qualification of multiaxial designs of nanofabrication machines with ultra precision tool rotations

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Abstract
The majority of nanopositioning and nanomeasuring machines (NPMMs) are based on three independent linear movements in a Cartesian coordinate system with a repeatability in the nanometer range. This in combination with the specific nature of sensors and tools limits the addressable part geometries. This article contributes to the enhancement of multiaxial machine structures by the implementation of rotational movements while keeping the precision untouched. A parameter based dynamic evaluation system with quantifiable technological parameters has been set up and employed to identify general solution concepts and adequate substructures. It further on contains data based on comprehensive design catalogues, uncertainty calculations and CAD-model based footprint analysis for specific setups. First evaluations show high potential for sample scanning mode variants considering linear movements of the object in combination with angular movements of the tool, considering a goniometer setup in specific. Based on this, positioning systems for the tool rotation of a NPMM were selected and the positioning properties of different arrangements were determined in test series using autocollimators. General properties of the influence of the arrangement were derived. The arrangement of the substructures which fulfils the previous given requirements is integrated into the NPMM and investigated for long-term stability using a retroreflector as a tool and various laser interferometers. The influence of the additional positioning systems on the existing structure of NPMMs are investigated and solutions for the optimization of the overall system with regard to reproducibility and long-term stability are developed. For this purpose, comprehensive FEA simulations are carried out and structural adjustments are derived via topology optimizations. After all, the knowledge gained is formed into general rules for the verification and optimization of design solutions for multiaxial nanopositioning machines.

Keywords: multiaxial nanopositioning and nanofabrication, ultra precision machine designs, advanced design principles of nanopositioning and nanomeasuring machines, ultraprecision rotations, design rules, qualification strategies for multiaxial nanopositioning machines, 5-axis operation

1. Introduction

As result of a comprehensive literature survey, the majority of nanopositioning and nanomeasuring machines (NPMMs) are based on three independent linear movements in a Cartesian coordinate system with a repeatability in the nanometer range. This in combination with the specific nature of sensors and tools (further on summarized as tool) limits the addressable part geometries. Depending on the tool in use, spherical and aspherical geometries as well as free-form surfaces cannot be measured or only to a certain limit. This article contributes to the enhancement of multiaxial machine structures by the implementation of rotational movements while keeping the precision untouched. Approaches are known, which allow the movement with a degree of freedom of four or five, which is required for addressing freeform surfaces orthogonal to the surface [1-3]. In comparison to this, our aim is the extension of NPMMs with additional degrees of rotational freedom for multitool concepts and freeform manufacturing.

2. Evaluated multiaxial NPMMs

A parameter based evaluation system was created to identify solution concepts fulfilling given requirements [4]. The combined rotation of the tool around two of the main axes of the Cartesian system of the NPMM showed a high application potential [5].

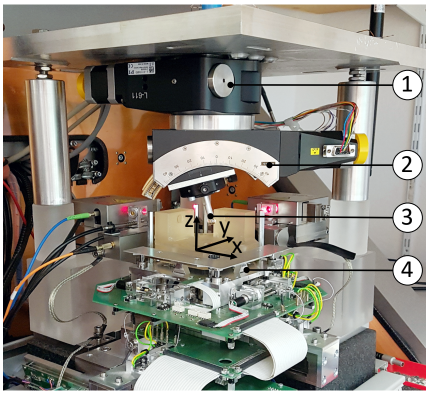

Figure 1. NPMM [6] inside a climatic chamber with additional tool rotations; **1** rotary stage (Φ_z) [7], **2** goniometer stage ($\Phi_{x,y}$) [8], **3** tool center point (TCP), **4** linear stage (x,y,z)

Alternatively, separated rotations of the sample and the tool should be considered. In general, kinematics with a high degree of fulfilment consider a common instantaneous center of rotation in the tool center point (TCP). In addition, the tool center is in compliance to the Abbe Point of the NPMM, thus avoiding first order positioning errors. To ensure that the measurement uncertainties of the NPMM do not increase significantly, the additional rotations should have a high position repeatability. Then, the path deviations in the TCP can be taken into account by corresponding lookup tables.

A further reduction of positioning uncertainties is achieved by the in situ measurement of the path deviations. A combination of a rotary stage and a goniometer has been chosen as the setup in specific (figure 1).

3. Tool rotation without in situ deviation measurement

Measurement series are required to take the positioning uncertainty of the rotation into account. The overall positioning uncertainty of the tool can be a combination of the individual axes or by measuring the end effector (tool) directly. For this purpose, the rotation axes (figure 1) were measured with a universal autocollimator [9] along the respective axis with regard to their tilt-repeatability of different stage setups (standing, hanging, single or combined stages). There are no significant changes of the repeatability caused by the arrangement. The repeatability depends on the angular position and the design of the positioning system. For the rotary stage in a setup equivalent to figure 1, the maximum repeatability within the positioning range is ± 8,7 µrad. For the goniometer, the same conditions result in ± 17,95 µrad. For the measurement of the combined rotational movement around two axes, a glass sphere with a refractive index of two was used as a retroreflector in the TCP (figure 1) [10]. After removal of the linear stage, the three laser interferometers of the NPMM were used to determine the vibration and positioning characteristics of the tool center in x,y and z-directions. For this purpose the three interferometers were used in vibrometer or length measuring mode over the combined rotation range of the tool Φ_z and $\Phi_{x,y}$. The maximum measured position repeatability over the entire rotation range and all measurement series is ± 100 nm for the x- and y-direction and ± 150 nm in the z-direction.

4. Tool rotation with in situ deviation measurement

The measurement and machining accuracy of the multiaxial NPMM depends on the positioning accuracy. If the rotation of the tool is not measured in situ and a calibration is performed on a suitable artefact, the achievable accuracy is limited by the repeatability of the positioners. Additional measuring systems for the closed loop rotation enable the measuring and machining accuracy to be increased and the machining time to be reduced. A parameter based dynamic evaluation system with quantifiable technological parameters is performed to identify general solution concepts. The number, arrangement and operating principle of the measuring system and its reference were systematically investigated (figure 2).

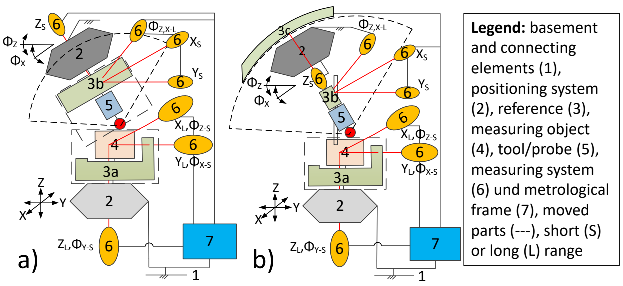

Figure 2. NPMM variations with measured tool rotations (excerpt)

First evaluations show the highest degree of fulfilment for the combined measurement of the deviations in the TCP considering compact laser interferometers attached to the tool and a hemispherical concave mirror as reference, attached to the metrological frame (figure 3). This enables the strict separation of the force frame (blue colored), the metrological frame (yellow colored) and thermal shielding of the largest heat source (rotary stage). Using a glass sphere with a refractive index of two in the TCP, an in situ calibration of the NPMM is possible. The hemisphere and the interferometer carrier as part of the metrological frame should be of highest longterm dimensional stability. For this purpose FEM-supported design optimizations were carried out, including geometry and material variations.

Figure 3. Conceptual design of the NPMM [6] with in situ deviation measurement of the tool center; **1** rotary stage (Φ_z) [7], **2** force frame, **3** hemispherical concave mirror, **4** three compact laserinterferometers (x',y',z') [11], **5** goniometer stage ($\Phi_{x,y}$) [8], **6** tool center (TCP), **7** mirror corner of the linear stage (x,y,z), **8** metrological frame with three Laserinterferometers (x,y,z)

5. Conclusion

A systematic parameter based dynamic evaluation approach was developed for the creation and selection of adequate machine structures for multiaxial nanopositioning systems (DOF>3). Out of these investigations, a rotation of the tool is a favourable solution. Kinematics with a high degree of fulfilment consider a common instantaneous center of rotation in the tool center point (TCP). Compared to a fixed tool position this leads to shifting deviations of the TCP due to deformations of the frame, positioning errors of the rotational axes, vibrations and thermal influences. The strict separation of the force frame and the metrology frame, thermal shielding and direct measuring systems for the deviation of the TCP can compensate the effects that are dependent on the selected overall structure and positioning system. The in situ deviation measurement of the TCP around two axes simultaneously can be achieved considering a hemispherical concave mirror as reference and compact laserinterferometers.

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