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The implementation of ultra precision rotations to multiaxial nanofabrication machines: challenges and solution concepts

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Abstract
Existing long-range nanopositioning and nanomeasuring machines are based on three independent linear movements in a Cartesian coordinate system. This in combination with the specific nature of sensors and tools (further on summarized as tool) 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. 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. The evaluation system is further enhanced by the implementation of data based on comprehensive design catalogues, uncertainty calculations and CAD-model based footprint analysis for specific setups. To support the selection, detailed parameter sets are generated containing explicit moving ranges, uncertainties, resolutions, reproducibilities and costs. This approach is also applied to the rotation of the object. The results are compared to the tool rotation and mixed versions. 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, 5-axis operation

1. Introduction

As result of a comprehensive literature survey, the majority of nanopositioning and nanomeasuring machines (NPMM) are based on three independent linear movements in a Cartesian coordinate system with a repeatability in the nanometer range. 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. 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 [4].
Suitable concepts of the overall machine structure were investigated. A parameter based evaluation system was created to identify solution concepts fulfilling given requirements [5]. The rotation of the tool in use showed a high application potential.
This article contributes to the systematic development of multiaxial machine structures based on existing NPMMs [4, 6] in the early design state. An evaluation system is developed which supports the user in the selection of sub structures (positioning and measuring systems) fulfilling given requirements in the best possible manner. This paper presents derived exemplary solutions based on chosen requirements, a summary and an outlook for further developments.

2. Rotation of the tool

In a first step, the rotation of tools with a maximum mass of 2 kg and an extension in the measuring direction of 50 mm is considered. For this purpose, a total of 23 suitable kineamtic variants for addressing a hemisphere orthogonally to its surface are determined by means of a structural synthesis, by varying the position of the instantaneous center of rotation and the number of joints. In the following, kinematic variants are selected by use of a parameter-based evaluation system. The evaluation criteria diploid are mainly based on quantitative characteristics in order to minimize subjective influences. To achieve this, typical values of positioning systems are derived from comprehensive design catalogs and software-supported [7] parameter studies of the geometries and motionranges.

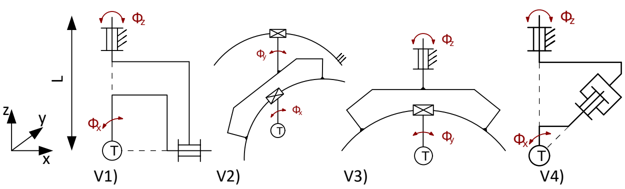

Figure 1. Four variations of kinematics

Figure 1 shows the kinematics with the highest degree of fulfilment. Kinematics with a high degree of fulfilment consider a common instantaneous centre of rotation in the tool center (TCP). This results in maximum rotation angles of 90° for Φ_y and 360° for Φ_z as well as minimized mass and no required linear correction movement . In addition they are in compliance to the Abbe Comparator Principle, thus avoiding first order positioning errors.

3. Rotation of samples

In analogy to the rotation of the tool, possible kinematic variants are determined and evaluated for the rotation of the sample by use of the parameter based evaluation system. The solution variants for the rotation of the tool show in comparison the higher degree of fulfilment. However, different arrangement sequences must be selected for addressing a hemisphere orthogonally to its surface for rotations of samples. Since the sample has a unknown structure, linear correction movements are necessary to address the whole sample surface. As a result, the adressable sample points or the angle of rotation of the positioning system used, are considerably restricted. With additional rotations the sample dimensions are restricted to a part of the carthesian volume. Depending on the kinematic variants, characteristic addressable volumes were calculated showing the limits for the hemispherical and orthogonal surface contact for a given rotation kinematic (figure 2). If the sample fits to the dimensions derived from the given carthesian volume, any hemisphere within the characteristic volume can be measured.

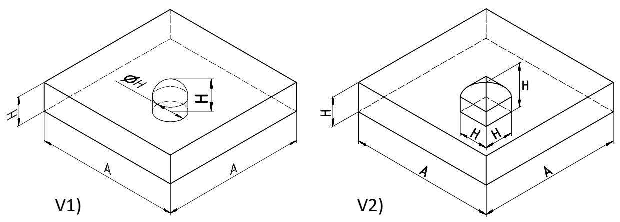

Figure 2. Characteristic sample volumes of kinematic variants (V1, V2)

4. Uncertainty

A higher degree of freedom influences the achievable uncertainty of the NPMM [6]. The exact position of the tool centre point (TCP) is not measured directly. The displacement as a consequence of the error motion can be calculated by geometric dimensions of the substructures. Every substructure is described by a characteristic length L (figure 1) and six error motions. There are three translational (t_x, t_y, t_z) and three rotational (r_x, r_y, r_z) errors (figure 3) which are dependent on the actuation angle α. The movement of the TCP can be calculated by a superposition of the components resulting from those error motions. Positioning systems mostly include a measurement system for the actuation angle α which is used to determine the orientation of the tool. For tool rotation principles with a instantantaneous centre of motion in the TCP the resolution and measurement uncertainty of the rotation measurement system does not affect the position of the TCP. The sample rotation can be described in the same manner as for the tool rotation. Since the TCP is fixed, the position of the sample is now affected by the error motion of the positioning system. Due to the dimension of the sample (d_s) the sample position is not independent from the properties of the angular measurement system.

$$e_{x1} = \sin(\alpha) \cdot d_s \qquad (1)$$

$$e_{y1} = \cos(\alpha) \cdot d_s \qquad (2)$$

Also the knowledge about the dimension d_s is limited to the uncertainty of the NPMM. With the information given in datasheets and the described model, a theoretical uncertainty based on GUM is calculated for the different principles. The error motion of the positioning system is modelled identical for each system, not taking into account that the error motion tend to be larger for smaller rotation systems.

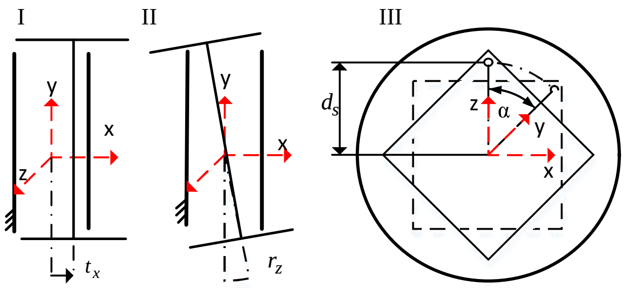

Figure 3. Error motion in x-direction. I: tranlational error; II rotational error; III sample rotation error

Although the characteristic lengths are much smaller for the sample rotation the described systematic error leads to a comparable uncertainty for both approaches.

Table 1 GUM based theoretical measurement uncertainty

	Char. length	Version	3D uncertainty
Tool rotation	100mm	V1	$\pm 1.1 \mu m$
Sample Rotation	25mm	V1	$\pm 1.4 \mu m$

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). It incorporates data of appropriate components taken from comprehensive design catalogues, calculated uncertainty budgets based on GUM and CAD-based construction space investigations. Out of these investigations, a rotation of the tool is a favourable solution. Kinematics with a high degree of fulfilment consider a common instantaneous centre of rotation in the TCP. In coming work, concepts for the strict separation of the force frame and the metrology frame and direct measuring systems for the deviation of the TCP will be investigated.

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