Joint International IMEKO TC1+ TC7+ TC13 Symposium
August 31st – September 2nd, 2011, Jena, Germany
urn:nbn:de:gbv:ilm1-2011imeko:2

MODELING OF 3D-MEASUREMENT CHAINS IN NANOPOSITIONING AND NANOMEASURING MACHINES

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Abstract – Nanopositioning and Nanomeasuring Machines are devices used for coordinate measurement and object manipulation in cm-ranges with nanometer precision. To decelerate a value for the position- or measurement uncertainty a 3D metrological model is necessary. The structure of such models depends on the arrangement of the machine parts in the measurement circles. The paper describes several model structures in vectorial form.

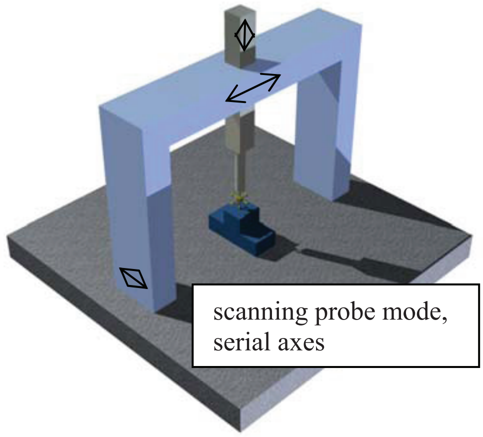
Keywords: Nanopositioning- and Nanomeasuring Machines, model structures, vectorial 3D-modeling

1. INTRODUCTION

To measure cm-sized objects with nm-precision you have to have Nanopositioning- and Nanomeasuring Machines (NPMM). Those devices consist of a 3D-stage-system with interferometers and angle sensors in each axis and a common 3D-mirror carrying the object to be measured [1], [2]. The benefits of such an arrangement are to avoid Abbe-errors and to control guiding errors. Moving a 3D-mirror including the object to be measured and have the probe system and the interferometers fixed denotes moving heavy masses in case of large measuring ranges (300 cm or larger in x- and y-axis). This causes not good dynamic characteristics. In case of large measurement ranges an alternative solution is to move the probe system and the 3D-interferometersystem and fix the 3D-mirrors and the object to be measured. Both solutions have their own metrological models for the measuring chains. These models are described in the next chapter.

2. MODEL STRUCTURES OF NPM-MACHINES

There are two possible arrangements of conventional Coordinate Measuring Machines (CMM) (Fig.1) – the scanning probe mode type and the sample scanning mode type. In the first case the probe system is moved and in the second case the object to be measured is moved. In praxis there also exist combined systems. Due to the fact that in both cases the measurement axes are arranged serially, we have got 18(+3) degrees of freedom in the measurement circles (6 in each axis and 3 in the orthogonality of the coordinate system). In NPMM we use an arrangement with decoupled measurement axes. So we have to consider only 6(+3) degrees of freedom (Fig.2).



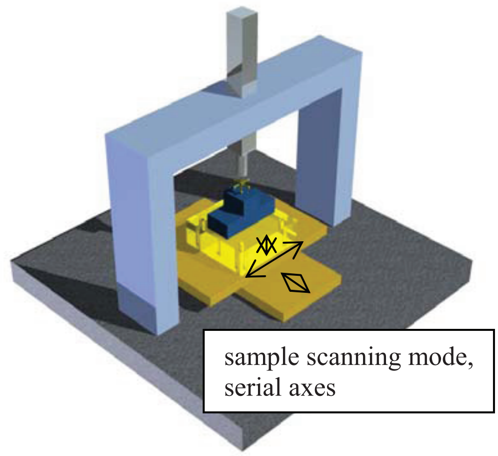


Fig. 1. Arrangements of CMMs

All 6 degrees of freedom have to be controlled by the laser measurement systems. There are used six laser beams for this task. A 3-beam laserinterferometer controls the z-axis and the φ_x and the φ_y angles. A 2-beam laserinterferometer controls the x-axis and the φ_z angle. At least a 1-beam interferometer controls the y-axis. The reduced degrees of freedom afford a more effective control, error reduced measurement strategies and lower measurement uncertainties. NPMMs can be built as sample scanning mode type or as scanning probe mode type.

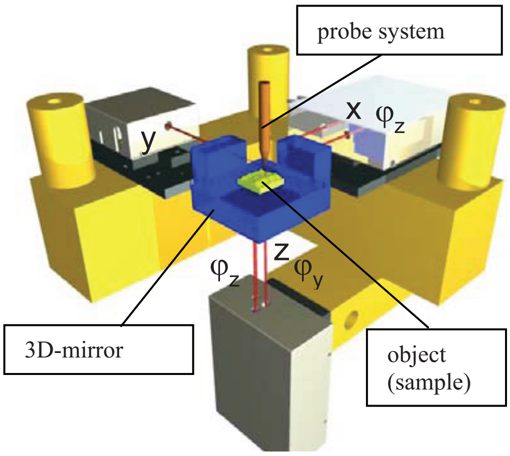


Fig. 2. NPMM structure with sample scanning mode

2.1. Metrological model structures

The two types of metrological chains for NPMM are drawn in Fig. 3. The red arrows show the respective moving parts.

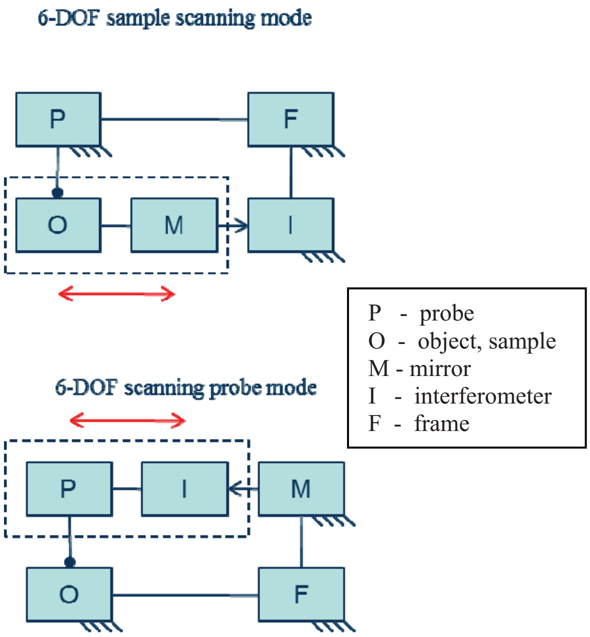


Fig. 3. Metrological chains of NPMMs

In case of measuring ranges of 400 cm x 400 cm x 50 cm the mass of the mirror is more than 20 kg and the sample can be up to 6 kg. Therefore the scanning probe mode is the better solution in case of high dynamic measurement tasks.

2.2. Vectorial modeling

The goal is now to create an effective mathematical model on the base of the two metrological chain types. Because off it's a 3D- measuring system we need a 3D- model for the uncertainty budgeting.

Vectorial modelling of the system parts is an effective approach to solve the problem, because we can use for each chain type the same or similar vectorial sub models. The difference is only the arrangement order of the connected sub model vectors when building the whole metrological vector chain. Fig. 4 shows the vector chains for a sample scanning mode type NPMM.

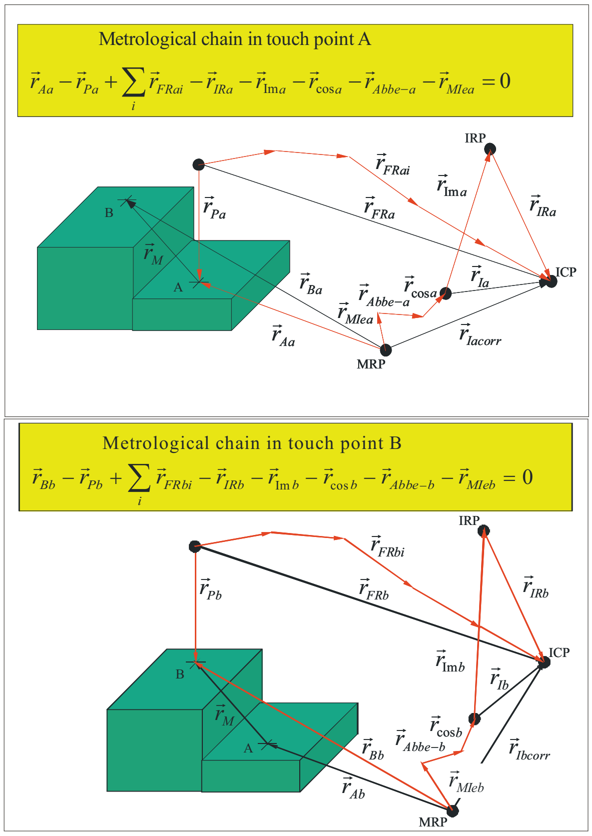


Fig. 4. Vectorial metrological chains for to touch points

If we want to measure a distance we have to touch the sample twice. For each touch point we create a vector chain.

The connected vectors in each vector chain represent metrological sub models (Table I).

TABLE I. Vectorial submodels

$\vec{r}_P$	Probe system vector
$\vec{r}_{FRi}$	Frame system vector
$\vec{r}_{IR}$	Interferometer reference path vector
$\vec{r}_{\mathrm{Im}}$	Interferometer measurement vector
$\vec{r}_{\cos}$	Cosine-error vector
$\vec{r}_{Abbe}$	Abbe-error vector
$\vec{r}_{MIe}$	Mirror-error vector

The main vectorial model is created by the difference of the two vector chains:

$$\vec{r}_{Bb} - \vec{r}_{Aa} = \vec{r}_{Pb} - \vec{r}_{Pa} + \sum_i \vec{r}_{FRai} - \sum_i \vec{r}_{FRbi} - \vec{r}_{IRa} + \vec{r}_{IRb} - \vec{r}_{\mathrm{Im}a} + \vec{r}_{\mathrm{Im}b} - \vec{r}_{\cos a} + \vec{r}_{\cos b} - \vec{r}_{Abbe\text{-}a} + \vec{r}_{Abbe\text{-}b} - \vec{r}_{MIea} + \vec{r}_{MIeb} \quad (1)$$

The distance vector to be measured between points *A* and *B* at time *b* results from the following equation:

$$\vec{r}_M = \vec{r}_{Bb} - \vec{r}_{Aa} - \vec{r}_{ab} \quad (2)$$

The vector $\vec{r}_{ab}$ considers the possible shift of the distance vector itself between time *a* and time *b*.

2.3. Uncertainty consideration

The combined uncertainty of the distance vector $\vec{r}_M$ can be calculated according to the GUM [3]

$$\vec{u}_c(\vec{r}_M) = \sqrt{\sum_i \left(\frac{\partial f}{\partial \vec{r}_i}\right)^2 \cdot u^2(\vec{r}_i) + 2\sum_i \sum_j \frac{\partial f}{\partial \vec{r}_i}\frac{\partial f}{\partial \vec{r}_j} \cdot u(\vec{r}_i, \vec{r}_j)} \quad (3)$$

with the correlation between the input values having to be considered. The differentiated model function in Eq. (3) is established by the combination of the sub model equations. The uncertainty of the norm of the distance vector is given by

$$u_c(|\vec{r}_M|) = \sqrt{\frac{x_M^2 \cdot u^2(x_M) + y_M^2 \cdot u^2(y_M) + z_M^2 \cdot u^2(z_M)}{x_M^2 + y_M^2 + z_M^2}} \quad (4).$$

The uncertainties $u(x_M)$, $u(y_M)$ and $u(z_M)$ in Eq. (4) are derived from the uncertainty vector (3):

$$\vec{u}_c(\vec{r}_M) = \begin{bmatrix} u(x_M) \\ u(y_M) \\ u(z_M) \end{bmatrix} \quad (5)$$

For an NPMM with a measuring range of 200 x 200 x 5 mm^3 and a distance vector directed from the centre to the coordinates {100; 100; 2,5} the uncertainty budget was simulated [4]. Under vacuum conditions an expanded uncertainty (coverage factor 2) of less than 35 nm was achieved. In the case of the assumed small input uncertainty values the calculation by means of the Monte-Carlo-Method produced the same results. The uncertainty budget shows that especially the mirror errors including its deviation from orthogonality which is not exactly known exert a major influence on the 3D-uncertainty.

3. CONCLUSION

The Paper described, based on the model structures of conventional Coordinate Measuring Machines, the special structures of Nanopositioning- and Nanomeasuring Machines. The metrological chains of the sample scanning mode machine type and the scanning probe mode machine type are modelled by vectors. So we can use the same sub model structures for each type. The vectorial approach includes the benefit of easily extending the whole model. The vectorial metrological model can be used for the calculation of the measurement uncertainty of the measurement value. The calculation of the uncertainty budget was done according to the “Guide to the Expression of Uncertainty in Measurement”[3].

ACKNOWLEDGEMENT

The authors would like to thank all of their coworkers at the Technische Universität Ilmenau who participated in the research work and the German Research Foundation for the funding of the SFB 622.

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