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Dynamic sensor positioning in large measuring volumes by an inverse kinematic concept

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Abstract. The growth in measuring objects and the demand for measurement precision in the sub-nanometer range are the challenges for future nano positioning and nano measuring machines (NPMMs). However, the usual moving stage principle will reach its limits due to the larger moving masses it entails for large measuring volumes. Therefore, an inverse kinematic concept for NPMMs is proposed, which permits to reduce the moving masses to a few kilogram. In this concept, the interferometers and the probe are moved, while the measuring object and the interferometer mirrors are fixed. The probe position is measured and controlled in 6 DOF.

1. Introduction

A major challenge for precision length measurements is the demand for increasing measuring range due to growing measuring objects. Simultaneously, the request for the measuring precision is heading to the nanometer and sub-nanometer range. For many years, the International Technology Roadmap for Semiconductors (ITRS-Roadmap) [1] has been identifying the tendencies in the semiconductor development. On the one hand, the size of single structures is shrinking to a few nanometers, while on the other hand the diameter of the processed wafers is tending to 675 mm. The examples of increasing demands for precision in growing measuring volumes are increasing and are related to the permanent technical progress.

2. State of the art

In the past years, the development of high-precision nano positioning and nano measuring machines (NPMMs) was expedited. Based on the nano measuring machine NMM-1 [2] with a measuring volume of 25 x 25 x 5 mm^3, the NPMM-200 [3] with a measuring range of 200 x 200 x 25 mm^3 was developed at the Technische Universität Ilmenau to tackle the problem of growing measuring objects. In the NMM-1 and NPMM-200, the demands for precision are fulfilled by following the Abbe principle with a fixed sensor and a moving measuring object (figure 1).

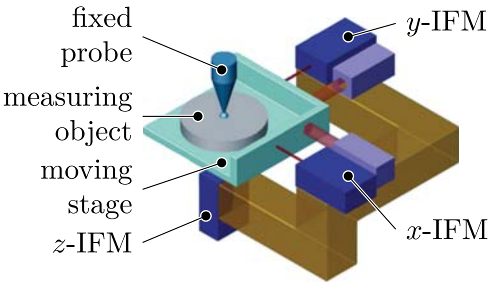

Figure 1: Operation principle of the NPMM-200. The measuring object is moved beneath the fixed probe, whose contact point is located in the (virtual) intersection of the interferometer (IFM) beams.

To cope with the problem of large moving masses, there are several attempts for the separation of functions like moving the measuring object in x-direction and the probe in y-z-direction. In general, the Abbe principle is not followed in those cases. The Isara400 is an example for an high precision measuring machine following the Abbe principle. It has a measuring volume of 400 x 400 x 100 mm^3 [4]. To reduce the moving masses, the measuring object is positioned in x-y-direction while the metrological frame together with the z-measuring system and the probe is moved in z-direction. Further NPMs with large measuring ranges are listed in table 1.

Table 1: Nano measuring and nano positioning machines with a large measuring volume.

NPMM	Isara400 [4] TU Eindhoven	TriNano [5] TU Eindhoven	F25 [6] Zeiss	UA3P [7] Panasonic
principle	mixed mode	moving stage	moving stage	moving probe
meas. range / mm^3	400 x 400 x 100	$64{\cdot}10^9$ (bipyramid)	135 x 135 x 100	200 x 200 x 45
uncertainty / nm	100	<100	250	100

3. Limits of the moving stage and mixed mode principles

In the set-up shown in figure 1, the axes of the three length measuring systems intersect in the Abbe point, where the tip of the fixed probe is located as well. However, this principle will reach its limits with future measuring tasks, because there are two contrary demands. The large and therefore heavy measuring object and interferometer mirrors will have a considerable mass of appr. 300 kg for a measuring range of 700 x 700 x 50 mm³ (extrapolated from the moving masses of the NPMM-200). Together with a large and heavy machine stage, they have to be positioned with a very high precision while at the same time, the dynamic has to be increased significantly to be able to execute measurements in an acceptable time.

However, for the moving stage and mixed mode principles, the demand for a larger measuring volume can in general not be satisfied by more powerful propulsion systems, because their power loss has to be discharged elaborately not to interfere with the sensitive measurement. Furthermore, the large moving masses entail enormous requirements for the machine basement, which has to bear the dynamic forces and damp vibrations effectually.

4. Inverse concept

To allow the enlargement of the measuring volume without drastically increasing the moving masses, we propose an inversion of the kinematic concept. In this concept, the heavy and voluminous precision mirrors as well as the large and heavy measuring object are arranged stationary. The measuring object is then measured by a moving measuring head which contains the probe as well as an interferometer system. Figure 2 shows an exemplary layout for an inverse concept. In this figure, the Abbe principle is fulfilled, as the interferometer axes intersect in the contact point of the probe.

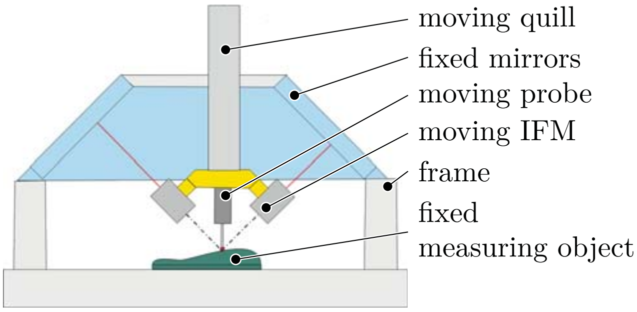

Figure 2: Inverse concept following the Abbe principle. The large measuring object and the mirrors are fixed, the probe and IFMs move inside the measuring volume. The axes of all IFM intersect in the contact point of the probe (third IFM not shown).

By utilising the inverse principle, the moving mass can be reduced from appr. 300 kg (mirror + measuring object) down to appr. 1 kg (miniature IFMs + probe). Therefore a very high measuring dynamic and position accuracy can be achieved. However, the shown principle in figure 2 has an impractical relation between measuring range and size of the mirrors. Furthermore, the movement of the probe has to be realised by an outward directed quill. This entails problems concerning the driving and guiding mechanisms.

To realise a minimal size of the mirrors together with a small and lightweight measuring head, the demand for strictly following the Abbe principle has to be relinquished.

When the touching point of the probe is arranged beside the IFM axes, the tilt errors of the measuring head have to be observed and compensated. This can be realised by additional IFM axes in the measuring head (figure 3).

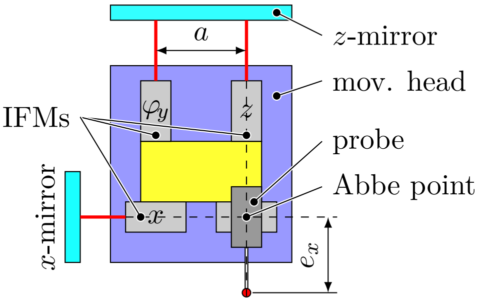

Figure 3: Compact measuring head containing the IFMs and the probe with its touching point e_x away from the Abbe point. The tilt errors are measured by additional IFM axes, e. g. φ_y with a beam spacing a to the z-IFM.

The remaining length error, e. g. Δl_x for the x direction, is $\Delta l_x = e_x \sin\varphi_y$. For Δl, the achievable angular resolution φ_q of the corresponding interferometer is essential. It is determined by the length resolution s_q as well as the beam spacing a: $\varphi_\mathrm{q} = \arctan(s_\mathrm{q}/a)$. When $e = a$, the achievable length error Δl equals the interferometer resolution s_q, currently appr. 20 pm. This way, the Abbe error can be compensated by high-precision angular measurement and control.

With this interferometer set-up, it is possible to arrange the moving axes coaxial with the mirror perpendiculars and the interferometer axes. This way minimal mirror sizes and a compact overall machine size can be achieved (figure 4).

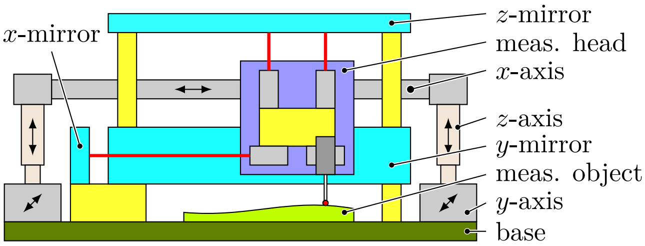

Figure 4: Compact inverse concept, relinquishing the Abbe principle. The tilt errors of the measuring head are measured by additional IFM axes. The driving systems are arranged outside the measuring volume.

To proof the capability of the inverse concept, a demonstrator was build (figure 5). The moving range is 400 mm in a single direction only, but the position of the sensor head is measured in 6 DOF by fibre coupled IFMs. The driving system consists of two cylindrical air bearing and two linear motors and the metrological frame as well as the mirrors are made of Zerodur.

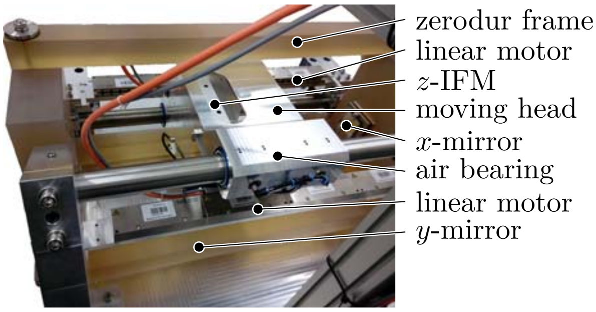

Figure 5: Single axis demonstrator for the inverse concept. The position of the sensor head is measured in 6 DOF (z-mirror disassembled).

5. Conclusion and Outlook

The moving stage or mixed mode principles reach their limits with increasing measuring volume due to the large masses that have to be moved dynamically and positioned with a precision in the sub-nanometer range. Therefore, an inverse kinematic concept for nano measuring and nano positioning machines is proposed to tackle the problem of growing measuring objects. The inverse concept does not follow the Abbe principle. Instead, the tilt errors of the probe head are measured and controlled. This way, the Abbe errors can be reduced down to the size of the interferometer resolution. The verification of the new concept was realised with a single axis demonstrator with a 6 DOF interferometer measuring system.

Future work will include a three axis demonstrator and the consideration of the mirror flatness deviations. For that purpose, additional interferometer axes will be included in the measuring head to determine the actual mirror geometry during operation of the nano measuring machine. Possible applications of the inverse concept include the measurement of future semiconductor wafers with a large diameter as well as large optical parts like aspheres, EUV mirrors or diffraction gratings.

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