Publishable JRP Summary Report for IND58 6DoF Metrology for movement and positioning in six degrees of freedom

Background

Current trends in precision engineering demand ever higher accuracies for industrial high-end production and measurement equipment. This requires control of positioning systems over measurement ranges from nanometres to hundreds of millimetres in all 6 degrees of freedom (DoF). The application of high precision motion systems ranges from nanometrology (AFM, SEM) to industrial production technologies (machine tools, CMM, photo lithography) to large scale applications like telescopes. Improved precision engineering tools using thermal insensitive design principles is beneficial not only for tool manufacturers but also for European key-industries, especially smaller companies, in terms of more efficient production processes and reliable, better products, an important condition to ensure a competitive advantage of European industries on the world market. This will also help to reduce the number of defective parts, leading to savings in raw materials, and reductions of machine time per part.

Need for the project

Mechatronic motion systems are the basis of most production systems ranging from tool machines for wafer scanners in semiconductor circuit production to robotic applications as well as for associated measurement equipment like coordinate measuring machines and scanning probe microscopes. Positioning to the required precision is challenging under dynamically changing and possibly harsh conditions. A trade-off has to be established in being fast and accurate.

Wafer stepping devices of the semiconductor industry are key examples of these demands. Larger wafer diameters and high production throughput pose tighter limits for the positioning tools and metrology platforms. More generally, the trend for higher integration in terms of packaging size and multi-functionality, such as in photonics and nanotechnology and for a broad range of applications (telecom, computation, navigation, aerospace), requires precision production equipment.

Needs for improved positioning control range from the nano-scale (metrology frames for AFM) and micro-scale (CMM, tomography stages) to mechatronics positioning in automotive and aerospace systems, including traditional cartesian motion systems as well as more general positioning devices (hexapods, goniometers). Similarly rich is the spectrum of required accuracies (sub-nm to metre scale), dynamics (fast microscopy MHz-scale scanning to low frequency mHz-scale noise spectra of astronomy instrumentation), and simultaneous multi-axes measurement and control. Selection and number of the targeted DoF, measurement range, uncertainty and temporal dynamics depend on the specific applications and the actual on-site ambient conditions. Highest level system validation in 6DoF to the nanometre and microradian can only be achieved in terms of a test facility at measurement laboratory level.

Scientific and technical objectives

The project focuses on the calibration of motion systems with high uncertainty requirements and the development of methods for the analysis of the associated measurement uncertainty as well as methods for error mapping for real time corrections. Different approaches and instrumentation developed for the measurement of 6DoF motions as well as important aspects of motion systems like straightness and orthogonality will be analysed and compared. Additionally, the project aims to improve nano positioning systems for the relevant high-tech fields of the future, not only by novel hardware technology but also by optimised sensor and actuator components as well as optimised measurement and control strategies. The high-level objectives are:

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- **Determination of the straightness of motion with accuracy less than 10 nanometers.** This project will implement a deflectometric method using three parallel interferometers and compare the results with other optimised instruments and methods.
- **Development of a compact interferometer to simultaneously measure all six degrees of freedom from one interface**. For use in verifying motion systems in industry such as tool machines, the interferometer has to be reasonably cheap and has to allow for easy adjustment. A method to track the refractive index of air near the measurement path will be included. Measurement uncertainties in the 10^{-7} region at below 10 nm are projected.
- **Implementation of methods for the characterisation of motion systems with large angular motion like hexapods or stacked systems with mixed angular and linear motion axes**. Characterisation of the motion in six degrees of freedom by step-by-step measurements of reference points on the stage with a coordinate measuring machine and in comparison with laser tracers.
- **Calibration and error mapping in 6DoF of nanopositioning stages regarding positioning errors, angular deviations, straightness of motion and orthogonality.** This objective includes the development of a high precision low cost interferometer capable of measurement of six measurement axes able to operate at a high dynamic to support traceability for video rate AFM and the setup of a testbed for mapping errors of nanopositioning stages in all six degrees of freedom.
- **Improvement of the measurement speed of AFM to allow measurements of larger areas and to reduce drift in the instrumentation.** In addition to achieving increased scanning speed by the use of metrology enhanced stiffer scanning units, schemes of non equidistant sampling will be determined. This focuses on determining the optimum path for an AFM tip to scan the surface in minimum time. This path will be created on the basis of information from a lower resolution image of the whole working area of the sample.

Expected Results and potential impact

Determination of the straightness of motion with accuracy less than 10nm:

A crucial problem in multi axes interferometry is the influence of the mirror topography. Different methods for the measurement of straightness are currently in common use. In mask measurement tools the preferred method for correcting straightness and orthogonality errors is self-calibration by measuring sequentially in rotated and shifted positions of the mask. The limitation of this method is the reproducibility of the mask mounting and of the tool with changed load conditions. The external calibration of the measurement mirrors of CMMs by a Fizeau interferometer is another common method. One challenge of this method is the referencing of the external measured values to the machine coordinate system. Another limitation is the accuracy of the Fizeau interferometers in the order of 5 nm, which can be overcome by the use of deflectometric methods like direct deflectometry, difference deflectometry or exact autocollimation deflectometric scanning, which allows for sub-nm accuracy with a limited lateral resolution. All the above methods as well as straightness interferometry will be compared to allow for a secure base for the choice of an appropriate method in ultra precision engineering.

Deflectometry is already in use for the measurement of topographies of especially large mirrors or gratings, e.g. in electron storage rings, and has now for the first time successfully been adapted for position measurements. This length comparator at PTB has been prepared with three interferometers for the use of a deflectometric method. This has allowed the performance of the first deflectometric measurement of straightness using direct traceable laser interferometry. Measurement uncertainties below 5 nm could be demonstrated, giving significant benefits over self-calibration techniques, which required performance of multiple measurements at different positions and orientations of the sample and therefore much more time and effort. These deflectometric technologies can also be widely used for other length measurement principles like straightness encoders.

PTB can now supply a calibration service for calibrations of 1D+ encoders, and straightness interferometers with uncertainties in the nanometer region, which has not been available before. Optical plates and line scales will follow after upgrading the optical microscope of the comparator. The wider application of straightness sensors as well as the inline use of deflectometry has the potential to substantially increase position accuracy in measurement and manufacturing tools based on multiple stacked axes with low cost compared to the use of more precise mechanical guidance systems.

Development of a compact interferometer to simultaneously measure all six degrees of freedom from one interface:

For traceable measurement of positioning devices, laser interferometers are a key technology. Laser interferometers are therefore widely used to characterise the positioning performance of machine axis. Based on a technology using a CCD chip combined with an FPGA for fast data processing of interference patterns, a simple optical setup has been designed to measure for the first time simultaneously all six degrees of freedom of a linear motion axis with a single interface. This is intended for faster characterisation of linear machine axes and tool inspection and also for easy adjustment, which is intrinsic to the processing of the interferograms by a CCD sensor. Due to the simple optical design, these products will be very cost effective. The possibility to measure all axes of a linear stage simultaneously together with a large angular acceptance range, which minimises adjustment times, will also reduce cost of ownership in industry.

To support the work on interferometry a stabilised DBR laser diode at 632 nm wavelength has been developed. Based on a new low noise current source the laser diode has been characterised and was stabilised to an iodine absorption line. With the same technique the stabilisation to a material reference is also possible, which allows for a partial compensation of the refractive index and thermal dilatation of tools.

Implementation of methods for the characterisation of motion systems with large angular motion like hexapods or stacked systems with mixed angular and linear motion axes:

The most complex class of motion systems combines linear and large angular motion like Hexapods or a combination of linear and rotary axes. This allows for more universal solutions for measurement and production and will also become more important in ultra-precision engineering and also for nanotechnologies. The problem is that proven techniques like laser interferometers cannot be used in the traditional way. A new method developed in this project to overcome this problem is the use of coordinate measurement machines with tactile or optical probing of reference points on the motion stage. At METAS,measurements of the position of balls attached to a 2D rotational stage have been performed on a micro coordinate machine. The stability of the position readings were about 1.5 nm RMS and a measurement uncertainty below 80 nm was achieved.. Additionally a small Hexapod was calibrated along its main axes on the METAS µCMM using a fully automated measurement program. For translations the repeatability of the stage was in an acceptable range of max 0.24 µm, but the absolute position deviations were considerable with max. 25 µm. The measurement uncertainty of the calibration system is 10 times lower than the repeatability of the stage. This new calibration method will be compared and verified by the use of laser tracers. Tracers are commonly used in large scale applications, therefore a larger hexapod will be used. The use of the calibrated 6DoF interferometer will allow for an improved test of the coordinate measurement machines and the laser tracer in a subset of their motion range.

METAS and PTB will for the first time provide a calibration service for 6DoF stages with large angular motion axes like Hexapods or stacked linear and rotational axes on coordinate metrology machines over the whole motion range with different measurement volumes and accuracy after the verification. This calibration service will reduce the effort and therefore cost for the instrumentation manufacturers to establish the traceability required for quality management.

Calibration and error mapping in 6DoF of nanopositioning stages regarding positioning errors, angular deviations, straightness of motion and orthogonality:

To meet the requirement for more accurate traceable characterisation of stages used for nanometrology, a test bed has been constructed at NPL using newly developed interferometers. At PTB mono atomar flat silicon surfaces with dimensions up to 200 µm have been manufactured, which are perfect straightness standards for the test bed. Nanopositioning devices are utilising directly the voltage at the piezo actors or, in improved versions, capacitive sensors. In the first case the main problem is the hysteresis, for capacitive sensors the linearity due to sensor geometry and alignment must be compensated. The test bed for nanopositioning devices will allow manufacturers to let their devices to be calibrated without the need to set up their own interferometers. NPL will supply this service after the end of the project to the public.

Improvement of the measurement speed of AFM to allow measurements of larger areas and to reduce drift in the instrumentation:

AFM as a scanning instrument is limited in measurement range by the necessary time and the stability of the tool and the tip. The project deals with these problems in different ways. Two tools have been tested regarding long time stability to perform tip wear investigations. The results will be published as a guide for tip use in practice. New intelligent scanning strategies with non-equidistant sampling and associated data processing have been implemented in the form of libraries. These libraries have been implemented as part of the open source software GWYDDION developed by CMI and should be compatible with most metrology SPMs and will allow for non-equidistant path planning, data interpolation. To be able to perform non equidistant sampling new positioning commands have to be implemented to the control electronics of the AFM instruments. Exemplarily the mAFM controller at LNE has been upgraded to manage a trajectory defined by a cloud of points. An intelligent scanning function taking into account the topography of the sample is under test. Concerning the model of the measurement system of LNE's mAFM, first results have been presented to EUSPEN 2015. Statistical tools as Morris' design and Sobol' indices are used to identified and classified several components impacting the positioning of the instrument according to their influence. Monte Carlo raws are currently under generation to finalise this work.

Users of the software will benefit from the possibility of faster AFM measurements using a higher density of measurement points at areas of interest, and the ability to resample the data points to allow for standard data processing. Faster measurements as well as reliable long range measurements will increase the industrial use of scanning probe microscopy (SPM) and will allow for a growth of the SPM industry and new tools for quality assurance of some products.

Another possibility to enhance the measurement range is the use of high speed video rate AFMs. For the first time a video rate AFM has been combined with reference metrology by applying laser interferometers to characterise the stage offline. The use of those results could significantly reduce the effects of hysteresis of the piezo actors. The integration of an interferometer for online correction is in progress using the above mentioned interferometers, which allows for faster AFM imaging over large areas without sacrificing the image quality.

<table>
<tr><td>JRP start date and duration:</td><td>1 June 2013, 36 months</td></tr>
<tr><td colspan="2">JRP-Coordinator:
Dr. Jens Flügge, PTB Phone: +49 531 592 5200 E-Mail: Jens.Fluegge@ptb.de
JRP website address: http://www.ptb.de/emrp/6dof.html</td></tr>
<tr><td>JRP-Partners:
JRP-Partner 1: PTB, Germany
JRP-Partner 2: CMI, Czech Republic
JRP-Partner 3: LNE, France</td><td>JRP-Partner 4: METAS, Switzerland
JRP-Partner 5: NPL, United Kingdom</td></tr>
<tr><td>REG-Researcher 1
(associated Home Organisation):</td><td>Josef Lazar
ISI, Czech Republic</td></tr>
<tr><td>REG-Researcher 2
(associated Home Organisation):</td><td>Eberhard Manske
TU-IL, Germany</td></tr>
<tr><td>REG-Researcher 3
(associated Home Organisation):</td><td>Nataliya Vorbringer-Dorozhovets
TU-IL, Germany</td></tr>
<tr><td>REG-Researcher 4
(associated Home Organisation):</td><td>Mervyn Miles
UoB, United Kingdom</td></tr>
</table>

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