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

Overview

Precision engineering equipment for industrial production, such as that found in automotive and aerospace systems, requires ever higher accuracies for improved positioning and measurement control. This project developed approaches for measuring positioning systems over measurement ranges from nanometres to hundreds of millimetres in all six degrees of freedom (6DoF). 6DoF being the ability of an object to move freely in three-dimensional space.

The project developed new measurement equipment, facilities, modelling approaches and standardised procedures, which can be used by a range of European industries in machine tools, coordinate metrology and manufacturing semiconductor circuits and optics, in order to enhance their precision engineering capabilities and to develop higher-performance, internationally competitive products.

Need for the project

Mechatronic motion systems are the basis of most production systems, from tool machines scanning wafers in semiconductor circuit production to robots assembling cars. These systems have associated measurement equipment such as coordinate measuring machines (CMM) and scanning probe microscopes. Positioning of an object to the required precision is challenging, and demand for higher throughput requires increased speed of positioning.

Improved position measurement and control devices would be beneficial for European tool manufacturers, and manufacturing industries using these tools, in terms of more efficient production processes and reliable, better products. This would improve the competitiveness of European industries and help to reduce the number of defective parts, leading to savings in raw materials and machine time.

Improved positioning control is needed across a range applications, from the nano-scale (metrology frames for atomic force microscopy (AFM) and micro-scale (CMM, tomography stages) to mechatronics positioning in automotive and aerospace systems. Most of the positioning systems in use are based on carthesian axes, where straightness and angular deviations must be determined and kept under control. But motion systems which combine large linear and angular ranges like hexapods are becoming more common and their calibration is more complex, however no convincing and accurate methods are currently available to characterise the overall positioning accuracy of such devices. Common problems to be addressed in all multi degree of freedom positioning systems include calibration time, long term stability, cost, speed of measurement and the effect of ambient conditions.

Scientific and technical objectives

The project focused on the calibration of motion systems with challenging uncertainty requirements and the development of methods for analysing the associated uncertainty and error mapping for real time corrections. In the first three objectives, different approaches and instrumentation for measuring 6DoF motions as well as important aspects like straightness and orthogonality were to be analysed and compared. In the final two objectives, the project aimed to improve nano-positioning systems for relevant high-tech fields through novel hardware technology, optimised sensor and actuator components, and optimised measurement and control.

EMRP
European Metrology Research Programme
Programme of EURAMET

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

The objectives are:

1. **Determination of the straightness of motion with an accuracy of less than 10 nanometers.** The project will implement a deflectometric method using three parallel interferometers and compare the results with other optimised instruments and methods.
2. **Development of a compact interferometer to simultaneously measure all 6DoF from one interface**. The goal is the development of an 6DoF-interferometer with a relative length measurement uncertainty in the 10^{-7} region respectively for short length a noise level below 10 nm.
3. **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 will be done with a coordinate measuring machine and compared with laser tracer techniques.
4. **Calibration and error mapping in 6DoF of nanopositioning stages regarding positioning errors, angular deviations, straightness of motion and orthogonality.** This includes the development of a high precision low cost interferometer capable of measuring six axes, setting up a test bed for nanopositioning using conventional interferometers and testing sensors.
5. **Improvement of the measurement speed of AFM to allow measurements of larger areas and to reduce drift in the instrumentation.**

Results and conclusion

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

Interferometers measure length using light with a traceable wavelength. The beam is split into two and then after reflecting on a mirror the beams are recombined and the phase difference between the two beams gives a measured distance. For 1 dimensional (1D) measurements the beam hits the same point on the mirror along the measurement path, this means that the measurements are largely independent of the shape of the mirror. Going to 2D or 3D, the laser beam has to move along the measurement mirror, where topography becomes an important factor as the mirror polishing process generates deviations of typically more than 10 nm over a range of some 10 mm.

The project developed a new method of traceable multiple-interferometer-based deflectometry which can be used during the measurement process to compensate for the mirror topography. A length comparator at PTB was prepared with three interferometers and a 750 mm mirror on a Zerodur tray for the implementation of a Traceable Multi Sensor (TMS) method. This TMS method has been successfully compared to different conventional methods for the measurement of straightness.

Additionally, 1) a new straightness interferometer was set-up, so that a high sensitivity could be achieved even for small beam angles, and 2) using the project's TMS method a superior method was developed to measure straightness of axes on interferometric measurement machines, which can be extended to other measurement systems like encoders.

These new methods developed by the project can be applied in the calibration of straightness references on encoders for tool machines and line standards for coordinate measurement systems. The measurement principle can also be applied to inline metrology.

Development of a compact interferometer to simultaneously measure all 6DoF from one interface

Laser interferometers are a key technology for traceable measurement of positioning devices and are therefore widely used to characterise the positioning performance of machine axes. A simple optical setup was developed based on a technology using a charge-coupled device (CCD) chip combined with fast data processing of interference patterns. This optical setup simultaneously measures all 6DoF of a linear motion axis with a single interferometer block from one direction using only two CCD sensors. Due to the simple optical design and the large acceptance angle, which could be achieved by using complementary metal-oxide semiconductor (CMOS) cameras and a field-programmable gate array for the data processing, the optical setup provides a nearly ideal device for checking machine axes and performing acceptance tests onsite.

In addition a laser diode based stabilised light source was developed by the project. The stabilisation of the laser diode to an iodine absorption line was demonstrated. The frequency stability is comparable to a helium–neon (HeNe) laser whilst allowing a higher output power and a more compact device which is important for a transportation. The stabilisation light source can also be applied to material length references, which gives a first order compensation of the air reflective index and thermal dilatation of a machine, making it a perfect companion for 6DoF interferometer for onsite acceptance tests.

To support this work an iodine stabilised laser diode at 632 nm wavelength was developed by a researcher excellence grant (REG)ISI. Comparisons with a HeNe laser at NPL showed that the diode laser gave equivalent stability at 10^{-8} but at a much higher intensity level.

Implementation of methods for the characterisation of motion systems with large angular motion

The most complex class of motion systems combines linear and large angular motion to allow for rotating parts of tools or probes in order to manufacture and measure more complex parts e.g. with holes in different directions in one clamping or for adjustment of optical components. Compared to stacked linear and angular axes, hexapods have smaller moving masses which gives a higher dynamic range of the tools. Proven techniques like laser interferometers or encoders cannot be used in the traditional way, as the interference contrast goes down due to the tilt of the measurement mirror. Therefore the project developed optimised methods for laser tracer measurements used to perform hexapod calibrations in the sub-micrometre range.

METAS now possesses a procedure for calibrating 6DoF systems where no pre-knowledge of the actuator geometry is required and the procedure is general enough to be applied to any 6DoF actuator geometry. As demonstrators, a piezo motor driven 6DoF actuator small enough to fit into the measuring volume of the METAS micro-CMM and a Hexapod was used. The implemented correction in the two cases, showed an improvement of the positioning accuracy of 20 times in translation and 50 times in rotation for the small 6DoF piezo driven stage, and of 10 times for the Hexapod.

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

Nano positioning stages are a basic component of high resolution scanning microscopes such as AFMs. Nano positioning devices usually use piezo activators or, in improved versions, capacitive sensors. However, in the former hysteresis is an issue, and in the latter geometry and alignment are.

To meet the requirement for more accurate and traceable characterisation of stages used for nanometrology, a test bed was constructed at NPL using newly developed interferometers. Using this test bed a high speed AFM was characterised and a large improvement in linearisation of the generated images could be shown. The interferometry of the test bed was integrated in a new scanner to set-up the first ever metrological high speed AFM. The new test bed means that NPL can now supply a new calibration service for stage manufacturers and AFM users. For a large range positioning stage, no straightness standards were available, but PTB has manufactured perfect mono-atomic flat silicon surfaces with dimensions up to 200 µm and reference samples can now be supplied to end users.

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 its measurement range by the scanning time and the path length. Increasing the scanning speed reduces the measurement time, but also reduces the signal to noise ratio of the measurement. A longer scanning time causes larger errors due to drift in the tool and a longer path in addition increases the wear of the AFM tip. Often not all areas on a sample are of the same importance. Therefore, denser scanning in the interesting areas could reduce time and tip wear, however prior to this project the data processing software required equidistant sampling.

Different aspects on long range AFM were investigated in the project. Tip wear was measured for different commercial tips using different form, materials and coatings. The measurements were done with variations of the instrument parameters and the results were compiled in a good practice guide.

The open source software GWYDDION, which is used for data processing of AFM data by a large community of users was extended by routines for intelligent scanning. This included different forms of scan trajectories with a non-homogenous density of measurement points together with routines for resampling. From this measurement times can be reduced resulting in smaller measurement uncertainties due to lower drift and the possibility to measure larger samples. The routines were successfully tested using the AFM of the project partners.

These developments were supplemented by programming a virtual AFM to calculate the measurement uncertainty of specific measurement sequences. The virtual AFM can also be used to calculate the uncertainty of different scanning modes in a long range AFM.

Actual and potential impact

Dissemination

The project published 27 papers and 48 presentations or posters were given at various conferences, as well as 15 presentations were given at stakeholder sites. 3 workshops were held, one as part of the European Society for Precision Engineering and Nanotechnology (EUSPEN) conference 2016 in Nottingham.

During the project many techniques and mathematical models were developed, which have been published in papers presented at European conferences to give manufacturers and users the opportunity to use the knowledge. In additional, good practice guides have been developed from AFM measurements over long paths to ensure minimal tip wear by (REG)TU-IL and from modelling of an AFM by partner LNE to improve instrumentation and calculation of the measurement uncertainty.

Impact on standards

The results of the project have been presented regularly to the members of the EURAMET technical committee for length (TC-L), which includes specialists on dimensional metrology at the European NMIs. EURAMET TC- L will provide information from the project to non-participating NMIs; and is also responsible for reviewing new measurement services recommended by the project.

The results of the projects regarding the CMM based 6DoF calibration and laser tracer measurements were reported to the ISO "Laser tracker Taskforce" and the VDI groups "Production Measurement Technology" and "Coordinate Measurement Equipment".

Results from the work on fast AFM metrology and information about the test bed for nanopositioning devices were reported to the ISO TC 201 as well as to ISO 229 WG2 and the VDI group "Surface Metrology in the Micro- and Nanometre-range".

Actual impact

The project has developed new calibration services which are now supplied by the project partners. These new services include:

- PTB can now supply a calibration service for combined length and straightness encoders like Heidenhain 1D+ Encoders, and straightness interferometers with uncertainties in the nano-meter region using the TMS method. These calibrations were previously only available with uncertainties more than 10 times higher.
- METAS can 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 CMMs over the whole motion range. This calibration service will reduce the time and costs for the instrumentation manufacturers to establish the traceability. Due to the modelling developed by METAS, this data can directly be used to improve the positioning accuracy of the calibrated stages.
- NPL can now supplies calibration services for nanopositioning stages for device manufacturers as well as for end users, which can also use the supplied measurement data for corrections using the software GWYDDION.

- PTB can supply samples with mono atomic flat surfaces up to 200 µm as standard for straightness measurements at nanopositioning devices.

The project enabled the University of Bristol (as REG(UoB) and NPL to considerably improve the imaging quality of high speed AFM using offline corrections based on the NPL test bed for nanopositioning stages, as well as designing and manufacturing a stage for online metrology. This improvement is already in use by academic collaborators of REG(UoB) for DNA sequencing and the measurement of component lifetime of turbine blades.

The stabilised laser developed by REG(ISI) is used in an interferometric feedback system of an electron beam writer of the company TESCAN (a producer and supplier of scanning electron microscopes and focused ion beam systems).

The non-equidistant scanning library developed by CMI and NPL allows a significant reduction in scanning time for typical tasks used in dimensional metrology. The library was included in the open source software GWYDDION which is widely used by AFM users worldwide in different areas of surface metrology like nano roughness, investigation of wearing processes, local mechanical and electrical material parameters as well as in biological and medical applications.

METAS has also provided their measurements and compensation models on the test hexapods to the project stakeholders, Physik Instrumente (PI) GmbH & Co. and SmarAct GmbH, who are both manufacturers of small to medium size 6DoF positioning systems.

Potential impact

The comparison of different straightness measurement systems will help users and manufacturers to find optimal solutions, when designing 2D and 3D measurement systems. PTB intends to further develop the mathematics developed for straightness measurements using the TMS method and self-calibration for a 2D-measurement machine combining rotation measurements of the sample with deflectometric measurements for more accurate position determination.

During discussions at precision engineering conferences and company visits it was highlighted m to the project that ‘straightness’ for tool machines and coordinate metrology, was gaining more and more importance. In nearly all tool machines with stacked axes the lateral motion of the axes are not detected, this means that the accuracy of the machine depends on the reproducibility of the guidance systems. This could be solved by using multi-axes encoder systems in combination with corrections based on the TMS method.

The project’s 6DoF-interferometer has been promoted at exhibitions, which has initiated discussions to commercialise the prototype with MPRO, a startup company developing electronics for length and temperature measurement, as well as another larger company with which discussions are still confidential. However further hardware and software development is required.

While the project has developed a method to calibrate hexapods, it will still be necessary to speed up the measurements without reducing accuracy. This may be done by developing smaller, more accurate laser trackers, which can make use of the beam directions, so that three tracers could simultaneously follow three targets on the hexapod stage.

In order to use AFM as a measurement tool in production processes it needs to be faster. Therefore further investigations based on the results of this project are needed.

List of publications

1. N. Vorbringer-Dorozhovets, B. Goj, T. Machleidt, K.-H. Franke, M. Hoffmann, E. Manske, Multifunctional nanoanalytics and long-range scanning probe microscope using a nanopositioning and nanomeasuring machine, *Meas. Sci. Technol.* **25** 044006 (2014)

2. P. Klapatek, M. Valtr, L. Picco, O.D. Payton, J. Martinek, Y. Yacoot, M. Miles, Large area high-speed metrology SPM system, Nanotechnology 26 (2015) 065501 (2015)

3. H. Bosse, B. Bodermann, G. Dai, J. Flügge, et.al, Challenges in nanometrology: high precision measurement of position and size, Shaping the future by engineering: 58th IWK, Ilmenau Scientific Colloquium, Technische Universität Ilmenau (2014)
4. A. Küng, A. Nicolet and F. Meli, A 5 degrees of freedom µCMM, Proc of 14 EUSPEN International Conference DubrovnikVI, 269, (2014)
5. A. Yacoot, Performance verification of a dual sensor stage, Proc of 14 EUSPEN International Conference Dubrovnik, P4.38, 309V1, (2014)
6. J. Hrabina, M. Sarbort, O. Acef, F. du Burck, N. Chiodo, M. Hola, O. Cip and J. Lazar, Spectral properties of molecular iodine in absorption cells filled to specified saturation pressure, Applied Optics, Vol 53, Issue 31, pp 7435-7441 (2014)
7. P. Ceria, S. Ducourtieux and Y. Boukellal, Development of a virtual metrological atomic force microscope to better estimate the measurement uncertainty using Monte Carlo method, Proc of euspen's 15th International Conference &Exhibition, Leuven, O3.3, 107 (2015)
8. P. Ceria, S. Ducourtieux and Y. Boukellal, Développement d'un microscope à force atomique métrologique virtuel pour mieux estimer l'incertitude de mesure en utilisant la méthode Monte Carlo, Proc of 18ème Forum des microscopies à sonde locale, 11 (2015)
9. P. Ceria, S. Ducourtieux and Y. Boukellal, Estimation of the measurement uncertainty of LNE's metrological Atomic Force Microscope using virtual instrument modeling and Monte Carlo Method, Proc of 17th International Congress of Metrology, article 14007 (2015)
10. N. Vorbringer-Dorozhovets, R. Füßl, E. Manske, Ongoing trends in precision metrology, particularly in nanopositioning and nanomeasuring technology, tm – Technisches Messen 2015; 82(7–8): 359–366 (2015)
11. N. Vorbringer-Dorozhovets, E. Manske, Imrovement in long term stability of the long range AFMs, Proc. IMEKO XXI World Congress1, p. 866-871 (2015)
12. E. Manske, R. Füßl, R. Mastylo, N. Vorbringer-Dorozhovets, O. Birli, G. Jäger, Ongoing trends in precision metrology, particularly in nanopositioning and nanomeasuring technology, tm – Technisches Messen 2015; 82(7–8): 359–366 (2015)
13. N. Vorbringer-Dorozhovets, E. Manske, G. Jäger, Interferometer-based scanning probe microscope for high-speed, long-range, traceable measurements, PAK 2014 Bd. 60, nr 02, s. 069-072 (2014)
14. A. Koppe, Untersuchungen der Abnutzung von AFM-Spitzen, Masters Thesis, http://www.tu-ilmenau.de/pms/publikationen/nur-studienabschlussarbeiten/ (2015)
15. N. Vorbringer-Dorozhovets, E. Manske, Long term stability of the long range AFMs, http://www.ptb.de/emrp/ind58-publications.html (2015)
16. N. Vorbringer-Dorozhovets, E. Manske, New scanning strategies for long distance AFM measurements, http://www.ptb.de/emrp/ind58-publications.html (2015)
17. M. Holá, J. Lazar, O. Číp, Z. Buchta, In-beam tracking refractometry for coordinate interferometric measurement, Proc. SPIE 9132, Optical Micro- and Nanometrology V, 91321K (2014)
18. S. Rerucha, A. Yacoot, T. P. Minh, M. Cizek, V. Hucl, J. Lazar, O. Cip, Laser source for dimensional metrology: invesitgation of an iodine stabilized system based on narrow linewidth 633 nm DBR diode, Meas. Sci. Technol. 28 045204 (2017)
19. P. Köchert, R. Köning, C. Weichert, J. Flügge, E. Manske, An upgraded data acquisition and drive system at the Nanometer, Proc. ASPE, Precision Interferometric Metrology (2015)
20. J. Hrabina, O. Acef, F. du Burck, N. Chiodo, Y. Candela, M. Sarbort, M. Hola, J. Lazar, Comparison of Molecular Iodine Spectral Properties at 514.7 and 532 nm Wavelengths, Meas Science Review, Vol 14, Issue 4, pp 213-218 (2014)
21. P. Ceria, S. Ducourtieux, Y. Boukellal, A. Allard, F. Nicolas, F. Nicolas, Modelling of the X,Y,Z positioning errors and uncertainty evaluation for the LNE's mAFM using Monte Carlo method, Meas. Sci. Technol. 28, 034007, 16pp (2017)
22. A. Küng, A. Nicolet and F. Meli, Calibration and correction of a 6 degree of freedom piezo driven stage, P1.59, Proc of 16 EUSPEN International Conference Nottingham (2016)

23. P. Köchert, Ch. Weichert, S. Strube, R. Köning, J. Flügge, E. Manske, A fully-fibre coupled interferometer system for displacement and angle metrology, P1.59, Proc of 16 EUSPEN International Conference Nottingham (2016)

24. O. D. Payton, L. M. Picco, T. B. Scott, High-speed atomic force microscopy for materials science, International Materials Reviews, vol 61, issue 8, p 473-494 (2016)

25. E. Manske, Ch. Weichert, G. Ehret, Good practice guide for straightness and orthogonality measurements (2016)

26. C. Weichert, H. Bosse, J. Flügge, R. Köning, P. Köchert, A. Wiegmann, H. Kunzmann, Implementation of straightness measurements at the nanometer comparator, CIRP Annals, 65, 1, 507-510 (2016)

27. C. Weichert, P. Köchert, E. Schötka, J. Flügge, A straightness measuring interferometer characterized with different wedge prismas, (2017) approved awaiting publication.

JRP start date and duration:	1 June 2013, 36 months
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	
JRP-Partners: JRP-Partner 1: PTB, Germany JRP-Partner 2: CMI, Czech Republic JRP-Partner 3: LNE, France	JRP-Partner 4: METAS, Switzerland JRP-Partner 5: NPL, United Kingdom
REG-Researcher 1 (associated Home Organisation):	Josef Lazar ISI, Czech Republic
REG-Researcher 2 (associated Home Organisation):	Eberhard Manske TU-IL, Germany
REG-Researcher 3 (associated Home Organisation):	Nataliya Vorbringer-Dorozhovets TU-IL, Germany
REG-Researcher 4 (associated Home Organisation):	Mervyn Miles UoB, United Kingdom

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union