Final Publishable JRP Summary for JRP IND62 TIM
Traceable in-process dimensional measurement

Overview

Reliable on-machine measurements are needed by industry for effective process control and quality assurance of manufactured parts. However, the accuracy of measurements on machine tools is affected by the unfavourable dynamically changing ambient conditions, vibration, noise, sound and light that prevail in or close to the production floor as well as the high probing forces of measurement devices. This research project has contributed to the development of appropriate standards and procedures which ensure traceable in-process dimensional measurements on machine tools.

Need for the project

Traceable in-process dimensional measurements on machine tools offer high product quality, lower manufacturing costs, high productivity and prompt and real-life assessment of product quality. One key benefit is the reduction of scrap in fabrication processes. The resulting reduction in energy use and material consumption contributes directly to decreasing CO_2 emissions which is a requirement for reducing global warming. From an economic point of view, the reduction in energy uptake and material consumption, higher product quality, leads to lower production costs and increases the competitiveness of European industry.

The continuing trend to manufacture products with increasing precision requires high precision measurement capability with accuracies higher than those of the geometric product specification. This is driven by the simple reason that the uncertainty of measurement has to be much smaller than the specified part tolerance. Therefore the factors associated with measurement errors on machine tools under shop floor conditions (such as static, kinematic, thermo-mechanical, and dynamic machine errors and errors of the probing system) need to be known and quantified.

For quick inspection, of whether a produced part is within the specified tolerance or not, it has to be measured on the machine tool immediately after machining. Decisions related to compliance with specification are based on part tolerances, the measurement value and, not least, on the achieved measurement accuracy of the on-machine measurement. Therefore the fitness for purpose of the on-machine measuring process has to be ensured in a wide range of situations and operating conditions, in particular those arising from changing environmental conditions. While there are various procedures to establish traceable measurements under nearly constant conditions, it is a huge challenge establishing traceability for shop floor machine tools that are exposed to dynamically changing ambient conditions. This requires the provision of a new generation of thermally invariant material standards, procedures and guidelines for the assessment of machine tool measurement performance directly on the shop floor. The foundation of traceability of measurement is provided by national metrology institutes (NMIs) to the industrial end-users through national standards.

Scientific and technical objectives

The overall objective of this project was to develop and test material standards and verification procedures for machine tools with a measuring accuracy of a few µm within a metre cube under shop floor conditions.

The scientific and technical objectives of this project comprise:

1. Establishing the scientific and technical backgrounds for developing standards and procedures for assessing and assuring traceability of in-process measurements.
2. Developing methods for implementing high accuracy dimensional measurements on machine tools by developing high precision and robust material standards that are deployable on the industrial machine tools which are used in the manufacturing industries, and beyond.

Report Status: PU Public

EMRP
European Metrology Research Programme
Programme of EURAMET
The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

3. Development of a portable shop floor chamber suitable for simulating manufacturing floor environmental conditions to enable the study, prediction and prevention of their influences on the quality of manufactured parts.
4. Provision of procedures, and a good practice guide that ensures reliable measurements on machine tools.
5. Ensuring a smooth uptake of the project’s results through industrial demonstrations and through the involvement of end-users in their implementation. This will focus on the potential economic and technological impacts in the manufacturing and machine tools industry and beyond.

Results

1. Establishing the scientific and technical backgrounds for developing standards and procedures for assessing and assuring traceability of in-process measurements.

Literature studies and an industry survey about the current state of dimensional in-process metrology and the industrial needs gave an overview of current standards, ongoing developments, and current and possible future needs of industrial in-process metrology. An investigation on available in-process measurement methods in different industrial sectors, on specifications and requirements was carried out, covering tool making, mechanical engineering, metal cutting, the automotive industry and the wind energy sector. An overview of existing material standards available on the market, as well as customised material standards developed by industry and academic laboratories in the areas of dimensional in-process metrology was compiled.

A framework for the traceability and verification of dimensional measurements on machine tools. Possible traceability routes for size, form and position measurements in in-process measurement were investigated with respect to free-form measurements, measurements on regular geometry elements and volumetric error mapping with tactile and/or optical on-board metrology systems. Several approaches for mapping machine tool measurement errors, determining uncertainties and the assessment of maximum permissible errors. This objective was achieved, several in-process measurement concepts addressing the identified industrial needs were developed.

2. Developing methods for implementing high accuracy dimensional measurements on machine tools by developing high precision and robust material standards that are deployable on the industrial machine tools which are used in the manufacturing industries, and beyond.

Material standards are used in metrology to verify the measurement capability of measuring systems. Therefore a standard and its characteristics need to be well known and its calibration needs to be traceable to the definition of the corresponding SI unit. Due to the diversity of on-machine measurement equipment and its applicability, there cannot be a general standard that meets all specific demands. Based on the industry survey, twelve different material standards were designed and manufactured. They were for the accurate mapping and fast periodic verification of geometric and task-specific machine tool errors, for the verification of on-board area scanning metrology systems, as well as for the detection of drift and noise of industrial roundness measurements. Since a significant part of the geometrical errors of machine tools are caused by thermal effects, most of the material standards are made of thermo-invariant material. The project specified a number of procedures and methods to be used for calibrating these material standards.

Inter-comparison measurements on a novel roundness material standard, on an innovative, newly designed hole-bar standard, and on a novel prismatic material standard especially designed for optical, non-contact probing have been successfully performed. Several NMIs now have the standards available for loan to all interested parties, such as other NMIs, calibration laboratories, machine tool manufacturers and end users, as well as to manufacturers of measurement instruments. This objective was achieved; the designed standards were successfully manufactured, calibrated with small uncertainties, and their use and application has been successfully demonstrated.

3. Development of a portable shop floor chamber suitable for simulating manufacturing floor environmental conditions to enable the study, prediction and prevention of their influences on the quality of manufactured parts.

More than 70 % of all manufacturing errors are induced by temperature effects, often caused by process heat e.g. generated by machining, cooling lubricants or environmental temperature variations. Accuracy can be affected through the temperature-induced expansion and bending of workpieces and of the structure of the machine tools.

In order to investigate environmental influences on machine tools, a portable climate simulation chamber - large enough to house a medium-size machine - was developed to facilitate and accelerate the metrological verification of machine tools. In the first step the technical requirements and geometrical attributes of the portable simulation chamber were specified. A design of a portable chamber was devised and translated into a functional system with a precise description of the required parts and their interactions. A computational fluid dynamics simulation was performed to predict temperature distributions within the chamber and to verify the functionality of the chamber and the sensor network. Two temperature sensor networks were used to validate the required temperature stability of ±2 K as well as the required heating/cooling performance of ±3 K/h. The experiment proved that the simulation chamber works within its specifications. Finally the chamber was used to verify the metrological performance of a prototype machine tool under various temperature conditions. The mobility of the chamber allows its industrial use and machine tool operators themselves can investigate and optimise the running parameters of their machines and the on-board measurement systems.

The chamber is now available for end users to rent, such as machine tool manufacturers or manufacturers of precision parts, as well as to laboratories or NMIs which want to investigate environmental influences. A number of enquiries have been made and it is expected that the chamber will be in use in the near future, supporting businesses to understand and improve their processes. This objective was achieved, as the mobile climate simulation chamber reaches the required heating/cooling performance and temperature stability when a medium-size machine tool is in use inside it.

4. *Provision of procedures, and a good practice guide that ensures reliable measurements on machine tools.*

Improving in-process metrology requires efficient and verified procedures to extract kinematic and thermo-mechanical errors, as well as errors induced by the machining process (such as loads, dynamic forces, motion control and control software). Procedures can then separate and compensate for them, as far as possible. Procedures based on the developed material standards were provided, verified and demonstrated in practice. The procedures deal with the detection and compensation of: a) geometrical and temperature-affected machine tool errors by using novel, thermo-invariant and dimensionally stable ball bar and hole bar standards or laser measurements, b) thermally caused machine drift and noise, and c) task-specific errors by using multi-feature and prismatic standards with and without superimposed perturbations.

Procedures for assessing the fitness-for-purpose of on-machine measurements were provided, and a procedure for evaluating task-specific uncertainties for harmonic amplitudes in the roundness measurement of rollers was developed. The uncertainty evaluation was based on Monte-Carlo-Simulations and it was the first task-specific uncertainty evaluation ever done in industrial roller measurements. This objective was achieved; the practical applicability, accuracy and reliability of these procedures was verified. Five good practice guides are available on the project website, and then will be available on the PTB website.

5. *Ensuring a smooth uptake of the project's results through industrial demonstrations and through the involvement of end-users in their implementation. This will focus on the potential economic and technological impacts in the manufacturing and machine tools industry and beyond.*

For demonstrating the project's outcome and verifying the required accuracies under shop floor conditions, several procedures for determining machine tool errors, and for fast machine tool verifications have been specified and implemented in industry. For instance, verification measurements to demonstrate the fitness-for-purpose of the thermally invariant ball-bar standard were successfully carried out at two industrial partners. The measurements revealed that this ball-bar standard and the associated measurement procedure are very well suited for investigating the measurement performance of machine tools with a target uncertainty of $U < 5$ µm. The developed hole-bar standard has been successfully applied to determine the 21 errors of the three linear axes of a machine tool under shop floor conditions. The demonstration of the free-form material standards revealed a measurement uncertainty of the machine tool tested of less than 4 µm for tactile probing. Temperature-dependent error corrections implemented on a five axis machine tool reduced the maximum error on the centre planes by about 80 %. The newly manufactured roundness disc with undulations and form errors of 10 µm was tested on a four-point roll geometry measurement device at an industrial partner. The tests verified the usefulness of the roundness standard. The deviations of the harmonics 3 to 30 were calculated to less than 1 µm compared to laboratory measurements. However, for the second harmonic a deviation of 2.3 µm was detected which was caused by the coupling between the disc and its shaft. A cure for this has been designed and a modified disk was manufactured, but the effectiveness of the design change has not yet been tested.

This objective was achieved; it was successfully demonstrated that the developed material standards and procedures meet the required target uncertainties of less than 5 µm in a cubic metre under shop floor conditions.

Actual and potential impact

Dissemination of results

The results and newly gained knowledge have been continuously transferred to interested researchers, stakeholders and to the industry as well. In the course of the project, 19 articles were submitted for publication in international journals (listed in the next section), including articles in high impact journals such as Measurement and Precision Engineering. Thirteen papers were presented at various conferences, including the Laser Metrology, Coordinate Measuring Machine and Machine Tool Performance (LAMDAMAP) conference. Two workshops, attended by 50 people from industry and academia, were held during the project on traceable machine tool verifications. A course on roller measurements had almost 80 participants. Five good practice guidelines were developed and are downloadable via the project website. These guidelines a) help industry to check the geometric performance of machine tools by means of temperature-invariant material standards, b) give end users technical information for assessing the fitness-for-purpose of machine tools, c) instruct users how to map task-specific errors of machine tools, and provide information on appropriate material standards, d) provide guidance for the verification of area-scanning, optical metrology systems on machine tools, and e) give good practice guidelines for roundness measurements and uncertainties.

Early impact

Investigations carried out during this project, as well as developed procedures have been submitted to several standardisation bodies especially to the international standardisation organisation (ISO), its technical committee (TC) 213 ‘Dimensional and geometrical product specifications and verification’ and the working group (WG 10) ‘Coordinate measuring machines’ and ‘Geometrical tolerancing’ (WG 18). WG 18 is related to roundness measurements described in the ISO 1101 standard. The draft version of the new ISO 1101 (DIS) reflects the results from objective 4.

A Slovenian company has shown huge interest in fast machine tool verifications using the 1-D thermo-invariant ball-bar material standards that were developed in objective 2. Contractual negotiations for its use and possible follow on collaborations between the company and UM, the Slovenian NMI, are in progress.

The demonstration of the roundness disk Type C developed in objective 2 indicated a failure in a roundness measurement device for large scale rollers at an industrial partner that had not been detected until then. This was an impressive demonstration of the usefulness of the standard that led to a closer cooperation between the industrial partner and VTT-MIKES.

The NMIs have gained knowledge in manufacturing thermally invariant material standards with complex forms, in particular in the high-precision machining of samples from Zerodur or Invar with micron level tolerances and robust coating processes for precise optical probing. These developed material standards are available to end users for assuring traceability for dimensional measurements on machine tools in hostile environments and can be loaned at the participating NMIs.

Potential future impact

Novel 3-D calibration procedures for machine tools equipped with an on-board metrology system and temperature-invariant measurement standards which are dimensionally stable even under varying environmental conditions are both key for meeting future production requirements. The new procedures developed will enable dimensional measurements on machine tools which are accurate, reliable and traceable. This will allow users to assess whether or not a machined part meets the quality specifications – and this without the need to bring the machined part into a temperature controlled, remote metrology room. This reduces production downtimes and will lead to substantial cost savings, in terms of transportation and expensive temperature-controlled metrology rooms.

In-process measurements by machine tools offer high product quality, lower manufacturing costs, high productivity and a real-life assessment of product quality. The outputs of this project are procedures and methods that will provide impact by improving manufacturing processes and the manufacturing quality of machined parts by incorporating traceable dimensional measurement into the production process. This will enhance the European measurement capability in the field of the engineering, particularly in the automobile industry.

In order to introduce the traceability chain into on-machine geometric measurements several novel material standards have been produced: 1-D, 2-D, and 3-D length standards with identically shaped form elements and multi-purpose material standards containing commonly machine manufactured geometries eg balls, holes, rings, flats, cones, etc. Most of them are made from thermo-invariant material, which allows users to investigate the thermo-mechanical error behaviour of machine tools and their on-board metrology system at regular time intervals. A few of the material standards have perturbations superimposed on their form, which allow users to determine the measurement uncertainty for selected features on a workpiece whilst taking into consideration different measurement and probing strategies as well as ambient conditions. These are now available as appropriate transfer standards for checking the overall performance of machine tools and for determining the task-specific uncertainties for dimensional measurements on machine tools directly on the shop floor. Companies and end-users can hire each of these standards at usual market prices at the participating NMIs. The licensing of the material standards developed within the project is also a possibility.

The mobile simulation chamber allows designers and developers to investigate the accuracy of machine tools and their on-board metrology system under varying environmental conditions without having to ship the machine tool to stationary climate chambers which would be highly costly. Companies and end-users can hire this simulation chamber at market prices from PTB. The reduction of scrap in fabrication and the resulting reduction in energy use and material consumption, gives a direct contribution to decreasing CO_2 emissions which is a requirement for reducing global warming. Higher product quality will lead to lower production costs and it will increase the competitiveness of European industry.

List of publications

[1] T. Widmaier, P. Kuosmanen, B. Hemming, V.-P. Esala and D. Brabandt, “New material standards for traceability of roundness measurements of large scale rotors”, *Proc. 58th IKK, Technische Universität Ilmenau*, 2014.

[2] B. Ačko and M. Milfelener, “Temperature-Invariant Material Standard For Monitoring Performance Of Machine Tools”, *Proc. 18th International Research/Expert Conference ”Trends in the Development of Machinery and Associated Technology” TMT 2014,* pp. 297-300, Sep. 2014.

[3] K. Simson, I. Lillepea, B. Hemming, T. Widmaier, “TRACEABLE IN-PROCESS DIMENSIONAL MEASUREMENT - European Metrology Research Programme, project No. IND62”, *Proc. 9th International DAAAM Baltic Conference INDUSTRIAL ENGINEERING*, Apr. 2014.

[4] B. Hemming, T. Widmaier, I. Palosuo, V.-P. Esala, P. Laukkanen, L. Lillepea, K. Simson, D. Brabandt, J. Haikio, “TRACEABILITY FOR ROUNDNESS MEASUREMENTS OF ROLLS - European Metrology Research Programme, project No. IND62”, *Proc. 9th International DAAAM Baltic Conference INDUSTRIAL ENGINEERING*, Apr. 2014.

[5] B. Ačko, R. Klobučar, M. Ačko, “Traceability of In-Process Measurement of Workpiece Geometry”, *Procedia Engineering, Vol. 100, pp. 376-383,* Feb. 2015.

[6] I. Linkeová, P. Skalník, V. Zelený, “Calibrated CAD model of freeform standard“, *Proc. XXI IMEKO World Congress*, Sep. 2015.

[7] M. Dury, S. Brown, M. McCarthy, S. Woodward, “Blowing hot and cold: temperature sensitivities of 3D optical scanners”, *Proc. 15th Euspen*, pp. 161-162, May 2015.

[8] A. Forbes, M. McCarthy, “Calibration of grid plates bearing a high density of targets”, *Proc. 15th Euspen*, pp. 129-130, May 2015.

[9] I. Linkeová, V. Zelený, “Design and calibration of free-form standard”, *Laser Metrology and Machine Performance XI*, pp. 147-148, May 2015.

[10] M. Dury, S. Brown, M. McCarthy, S. Woodward, “3D optical scanner dimensional verification facility at the NPL’s “National FreeForm Centre”, *Laser Metrology and Machine Performance XI*, pp. 187-197, Mar. 2015.

[11] F. Viprey, H. Nouira, S. Lavernhe, C. Tournier, “Novel multi-feature bar design for machine tools geometric errors identification”, *Precession Engineering*, June 2016.

[12] T. Widmaier, B. Hemming, J. Juhanko, P. Kuosmanen, V.-P. Esala, A. Lassila, J. Haukio, “APPLICATION OF MONTE CARLO SIMULATION FOR FOUR-POINT ROUNDNESS MEASUREMENTS OF ROLLS”, *Precision Engineering*, **submitted**.

[13] M. Ačko, R. Klobucar, M. Milfelner, “Design of a Measurement Standard for Monitoring Metrological Performance of Machine Tools”, *Proc. In-Tech*, pp. 104-107, Sep. 2015.

[14] S. Woodward, S. Brown, M. McCarthy, “SURFACE FINISH AND 3D OPTICAL SCANNER MEASUREMENT PERFORMANCE FOR PRECISION ENGINEERING”, *ASPE*, Nov. 2015.

[15] S. Woodward, S. Brown, M. McCarthy, “Performance analysis of a 3D laser line scanner mounted on an articulated arm, while constrained by a linear guide”, *ASPE*, **approved, awaiting publication**.

[16] D. Berger, D. Brabandt, G. Lanza, “Conception of a mobile climate simulation chamber for the investigation of the influences of harsh shop floor conditions on in-process measurement systems in machine tools”, *Measurement*, *Vol. 74, pp. 233-237*, Oct. 2015.

[17] S. Woodward, S. Brown, M. Dury, M. McCarthy, “Producing dimensional transfer artefacts for the assessment of workshop machine tool performance”, Proc. 16th Euspen, May 2016.

[18] M. Dury, S. brown, M. McCarthy, S. Woodward, “Assessing fringe projector volumetric error sources”, Proc. 16th Euspen, May 2016.

[19] R. Klobucar, B. Ačko, “Experimental evaluation of ball bar standard thermal properties by simulating real shop floor conditions”, *International Journal of Simulation Modeling*, **approved, awaiting publication**.

JRP start date and duration:	01 June 2013. 36 months
JRP-Coordinator: Klaus Wendt, Dr. Ing., PTB, Tel: +49 531 592 5323 E-mail: klaus.wendt@ptb.de JRP website address: www.ptb.de/emrp/tim.html	
JRP-Partners:	
JRP-Partner 1: PTB, Germany	JRP-Partner 9: Daimler, Germany
JRP-Partner 2: SEM, Spain	JRP-Partner 10: EMO, Slovenia
JRP-Partner 3: CMI, Czech Republic	JRP-Partner 11: Gorenje, Slovenia
JRP-Partner 4: LNE, France	JRP-Partner 12: IK4-TEKNIKER, Spain
JRP-Partner 5: Metrosert, Estonia	JRP-Partner 13: MAG IAS, Germany
JRP-Partner 6: VTT, Finland	JRP-Partner 14: RRI, Finland
JRP-Partner 7: NPL, United Kingdom	JRP-Partner 15: UNIZAR, Spain
JRP-Partner 8: UM, Slovenia	JRP-Partner 16: Veplas, Slovenia
REG-Researcher (associated Home Organisation):	Thomas Widmaier, Dr. Aalto, Finland
REG-Researcher (associated Home Organisation):	Gisela Lanza, Prof. Dr.-Ing. KIT, Germany

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