FINAL PUBLISHABLE JRP REPORT

JRP-Contract number	IND62
JRP short name	TIM
JRP full title	Traceable in-process dimensional measurement
Version numbers of latest contracted Annex Ia and Annex Ib against which the assessment will be made	Annex Ia: V1.1 Annex Ib: V1.01
Period covered (dates)	From 01 June 2013 To 31 May 2016
JRP-Coordinator	

Name, title, organisation	Klaus Wendt, Dr.-Ing., PTB
Tel:	+49 531 592 5323
Email:	klaus.wendt@ptb.de

JRP website address	www.ptb.de/emrp/tim.html
Other JRP-Partners	CEM, Spain CMI, Czech Republic LNE, France Metrosert, Estonia VTT, Finland NPL, United Kingdom UM, Slovenia Daimler, Germany EMO, Slovenia Gorenje, Slovenia IK4-TEKNIKER, Spain MAG IAS, Germany RRI, Finland UNIZAR, Spain Veplas, Slovenia
REG1-Researcher (associated Home Organisation)	Thomas Widmaier, Dr. (Aalto, Finland) — Start date: 01.06.2013 Duration: 36 months
REG2-Researcher (associated Home Organisation)	Gisela Lanza, Prof. Dr.-Ing. (KIT, Germany) — Start date: 01.06.2013 Duration: 36 months

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

TABLE OF CONTENTS

1 Executive Summary

Introduction

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.

The Problem

The particular challenge in the area of in-process dimensional measurements is to detect and control the aforementioned errors on the manufacturing floor, as they are not constant and vary under the influence of diverse environmental impacts. Existing standards for machine calibration do not adequately address the environmental conditions on the shop floor. Therefore there is an urgent need for a new generation of robust material standards with corresponding procedures and guidelines for the assessment of machine tool measurement performance directly on the shop floor.

The Solution

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 such as balls, holes, rings, flats, cones, etc. Most of them are made from thermo-invariant material, which allows us, in particular, 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 especially allow us to determine the measurement uncertainty for selected features on a workpiece taking into consideration different measurement and probing strategies as well as ambient conditions.

Impact

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.

In-process measurements by machine tools offers high product quality, lower manufacturing costs, high productivity and a real-life assessment of product quality. The outcome of this project provides procedures and methods for improving manufacturing processes and the manufacturing quality of machined parts by incorporating traceable dimensional measurement into the production process. This enhances the European measurement capability in the field of the engineering and in the automobile industry. The project provides financial benefit to developers and end users of machine tools within the EU and beyond. To satisfy future production requirements novel 3-D calibration procedures for machine tools equipped with an on-board metrology system have been developed together with temperature-invariant measurement standards which are dimensionally stable even under varying environmental conditions. The procedures and methods developed in this project enable dimensional measurements to be performed, on machine tools, which are accurate, reliable and traceable. This allows users to assess whether or not a machined part meets the quality specifications without the need to bring the machined part into a temperature controlled, remote metrology room. This reduces production downtimes and leads to substantial cost savings, for instance for transportation and/or by eliminating the need for expensive temperature controlled metrology rooms.

2 Project context, rationale and objectives

Context

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.

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.
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.

3 Research results

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

To identify challenges and end-users' needs the partners firstly reviewed existing measurement standards and company-specific test procedures in the field of in-process metrology. UM, CEM, and LNE supported by PTB and Metrosert undertook a survey of international and national measurement standards – including both written standards and material standards – for performing verification tests of machine tools and coordinate measuring machines (CMMs). The survey was based on a study of the literature, scientific contributions in internationally reviewed journals, web data, and on information available from national and international standardisation bodies.

To ascertain the involvement of national and international standards in the 'Machine Tool Manufacturing' industry, NPL designed a pan European survey. A selection of several hundred companies was targeted including, the aero industry, car manufacturing, small independent companies as well as the manufacturers of machine tools themselves. The survey was split into several areas: their involvement in machine tool manufacturing, how this manufacturing process is monitored, and their activities for traceability and verification of on-machine measurements, along with environmental conditions, and information referring to the individual company. The aim was to find out which standards they used and to identify any issues that they had with using these standards. Results from this survey were used when designing novel material standards. This concerns, for instance, the size and the material of the material standards manufactured during the project.

Metrosert, CEM and REG(KIT) studied different methods of in-process metrology especially with respect to the influence of the environmental conditions on the measurement accuracy as well as on the machine tool performance. They were supported by the unfunded partners MAG IAS, Daimler, IK4-TEKNIKER, and UNIZAR.

The aforementioned survey carried out by NPL focused on CNC (Computer Numerical Control) metal cutting machine tools such as turning, drilling, milling, or grinding machines. In addition, VTT-MIKES and REG(Aalto) focused their study on roller measurements in the paper and steel industry. They prepared a review of existing roundness standards and investigated challenges in roller measurements encountered by roller manufacturers and end-users.

After studying the state of the art in dimensional in-process measurements the partners developed a valid definition of the traceability and verification requirements of in-process metrology on machine tools and machining centres under harsh environmental shop floor conditions. An investigation of possible traceability routes for size, form and position in in-process measurements was performed and a catalogue of requirements for material standards which are suitable for ensuring the traceability of machine tools under harsh environmental conditions has been compiled. In total, 12 material standard designs were selected for development by the TIM consortium.

Since this research project focused on studying the influence of thermal effects on the accuracy of machine tools and on-machine measurements, reliable surface temperature measurements of the workpieces are required. Therefore, CMI investigated methodologies for traceable surface temperature measurements in in-process (on-site) conditions. They provided an overview of requirements for surface temperature sensors, examples of use and a methodology for the calibration of these sensors regarding the uncertainty budget as well as possible error sources.

Objective 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.

With the progress of technology, the demand for highly accurate parts becomes a classical need in industry. The manufacture of these parts is usually performed via high precision machine tools (MTs) traceable to the SI metre definition published at the intergovernmental organisation “Bureau International des Poids et Mesures (BIPM)”. Hence, the traceability of MTs represents a new challenge for several researchers involved in National Metrology Institutes (NMIs) and/or in manufacturing laboratories or plant. Some of them investigate the calibration of MTs using physical standards previously calibrated on a high precision coordinate measuring machine (CMM). This method of MTs calibration can be carried out on-line. Other researchers extend the calibration process to inspect parts produced under the manufacturing process, directly in the MTs. Several error sources in MTs can be identified in the literature (e.g. thermal, geometrical, resolution, and vibration). The geometrical error is the most important one: it can be estimated to be more than 70 % of the entire error.

Several material standards have been developed during the project, which cover a wide field of measurement tasks and are based on different approaches for mapping, detection and investigation of machine tool errors. The developed standards can be separated by their task. These tasks are the detection of volumetric machine tool errors, the mapping of volumetric and task-specific machine errors, as well as the determination of noise and thermal drift of the measurement equipment. To ensure their insensitivity to temperature variations, most standards were manufactured from materials such as Invar, Rigor®, and Zerodur®, which can be rated as nearly thermally invariant in the range of maximally occurring environmental temperature differences.

Depending on the material standard, the measurements can be performed either with tactile or optical probes, in single point probing or in scan mode. The 3D material standards (3D-MS) enable the users to determine volumetric errors, or the maximal length measurement error of a machine tool. The knowledge and consideration of these errors enables machine tool users to improve their machining accuracy.

The task-specific material standards enable users to detect task-specific measurement errors (e.g. measurement errors of specific diameters, forms or lengths). Repeated measurements on these calibrated artefacts allow us to estimate experimentally the measurement uncertainty for specific quantities. There are two kinds of standards. TSEM-MS are material standards with negligible form errors, designed to detect, in particular, task-specific errors caused by kinematic and thermo-mechanical machine errors. In contrast, TSMU-MS are material standards with superimposed form perturbations to be used for the determination of the machine’s capability for inspecting size, form, position tolerances and to derive reliable information on the achievable measurement accuracies.

A freefrom material standard (FF-MS) has been developed and manufactured for checking area-scanning on-board metrology systems as well as tactile probing systems.

Three different material standards in the form of discs with different roundness profiles have been developed. These roundness material standards (R-MS) can be used to calibrate and check measurement devices used in the roundness measurements of large rollers which are e.g. used in the paper and steel industry.

Workpiece replica material standards (WR-MS) are produced on the machine tool under investigation. Thus they incorporate all error contributions of the machining process such as kinematic errors, thermo-mechanical errors, loads, dynamic forces as well as motion control and control software. These standards are used to assess the measurement uncertainty and the fitness-for-purpose of the onboard metrology systems for specific measurement tasks.

PTB – Hole plate (3D-MS)

Purpose and design

The hole-plate standard is designed to check and map the volumetric errors of coordinate measuring machines and multi axes machine tools. The plate is made from Zerodur® and its dimensions are 610 mm in length and width and 30 mm in thickness. There is a double row of 12 bore holes along the edges of the plate which enables the error vectors in the plate plane to be determined at a total of 80 positions. The use of this standard allows the determination of the 21 errors of the three linear axes according to the ISO standard 230 part 1 of a machine tool and in a second step the component and position errors of its rotary axes. To map the geometric errors of the linear axes in the whole working volume of the machine tool the hole plate must be measured in at least four positions, two vertical and two horizontal set-ups. According to the lengths of the axes the plate must be shifted along the axes to cover the whole working volume. This leads to an additional number of measurements.

The errors of a rotational axis are determined by measuring the position of at least three holes for several positions of the rotational axis. The six error motions are obtained by solving a system of linear equations by a Gaussian (e.g. least squares) fit. The location and orientation errors are then separated from the error motions by application of the definitions given in the ISO standard 230 part 1.

Calibration

The hole plate has been calibrated on a coordinate measuring machine (CMM) of the type LEITZ PMM 866. The reversal method was applied during the calibration to eliminate the systematic geometry errors of the CMM. The expanded measurement uncertainty for the distance L between two arbitrary hole centres, obtained from their calibrated coordinates, is $U(L)=((0.4\ \mu m)^2+(L\times0.5\times10^{-6})^2)^{1/2}$.

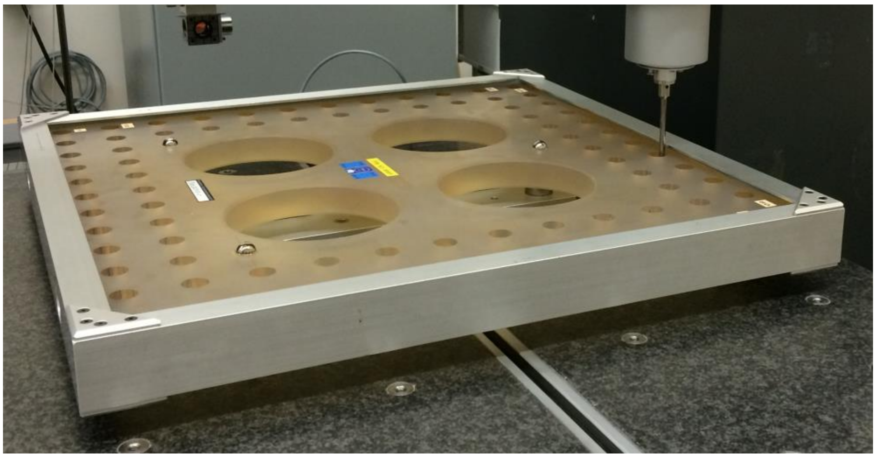


Figure 1: Calibration of the hole plate

LNE – Multi-Feature Bar (3D-MS)

Design and procedure

A new design of the Multi-Feature Bar (MFB) has been proposed by LNE. Thanks to its new geometric pattern, it allows us to identify 1 linear positioning error and 2 straightnesses of any linear mechanical guiding system of the MT, and just with 1 measurement of the MFB. The identification of 3 parameters for one orientation of the MFB leads to the minimisation of a MT's downtime. Furthermore, the combination of measurements performed on two parallel positions of the MFB leads to a maximum number of identified geometric errors of 5 (1 linear positioning error, 2 straightnesses and 2 angular errors for each axis).

The new design of the MFB consists of a repetition of a 3D pattern in one direction. Each pattern contains 7 features: 4 flat surfaces (vertical planes) and 3 cylinders (one vertical inner cylinder and two horizontal outer cylinders). The patterns are repeated along the direction Δ as illustrated in Figure 2a, where $1 \leq i \leq N$ and $1 \leq j \leq N - 1$. Once measurements on each pattern are carried out, the processing of the measured data allows us to extract one point corresponding to the intersection of the 7 features mentioned previously. The expected measurements and the post-processing of the measured data can be completed with respect to the following steps:

- At least 8 points should be measured on each hole HOL_i with a touch probe, as shown in Figure 2b. A nominal cylinder is associated to the 8 measured points by applying the least squares criteria. Thereafter, the intrinsic characteristics of each associated feature establishing the common datum shall be considered to determine the $AXIS_i$ as shown in Figure 2b;
- At least 4 points should be measured on each flat surfaces PL with a touch probe, as shown in Figure 2c. The post-processing of the measured dataset with the least squares plane association allows us to define the associated integral feature (nominal plane PL_{Lj} or PL_{Rj});
- For each horizontal outer cylinder CYL_j, 12 points shall be probed as shown in Figure 2d. The analysis of the measured data using the least squares method allows us to determine $AXIS_j$;
- The points PL_j and PR_j are obtained mathematically and correspond to the intersection of $AXIS_j$ with both planes PL_{Lj} and PL_{Rj} as illustrated in Figure 2e. The horizontal least squares plane PL_i is associated to the 4 points P_{Lj-1}, P_{Rj-1}, P_{Lj} and P_{Rj}. The last step consists of the identification of the point of interest O_i that corresponds to the intersection of $AXIS_i$ and PL_i;

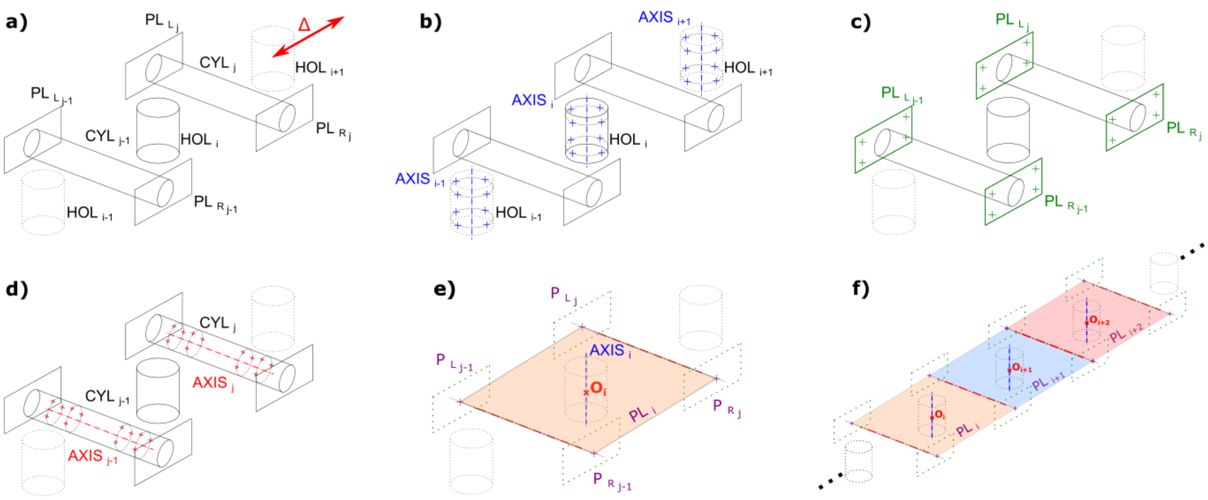


Figure 2: Principle of the MFB: probing points, and points of interest

The selected material of the MFB combines a small coefficient of thermal expansion (CTE), with a high toughness and small brittleness. Thus, the invar material seems the best candidate material compared to Zerodur, Alumina, and steel.

The 3D CAD model is depicted in Figure 3. This model is composed of 12 holes, so it is possible to extract 12 points of interest O_i. The setting up of the MFB is ensured by using an isostatic work holder built from a modular equipment system.

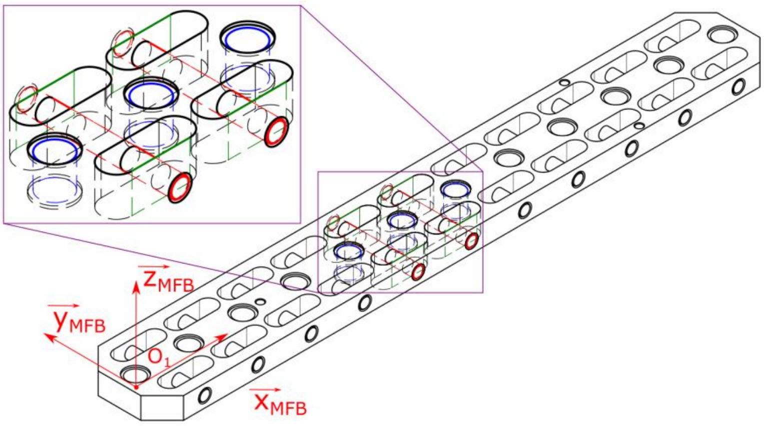


Figure 3: 3D CAD model of the MFB

Calibration

A thorough calibration of the MFB has to be performed to extract the intrinsic geometric errors: one linear positioning error ($E_{XX, MFB}$) and two straightnesses ($E_{YX, MFB}$, and $E_{ZX, MFB}$). For the calibration of the MFB, the reversal technique is applied in order to separate the motion errors of the accurate CMM that was used, from the geometric errors of the MFB.

Finally an inter-comparison was performed between 4 European NMIs. An example of the calibration results of $E_{YX, MFB}$ is given in Figure 4.

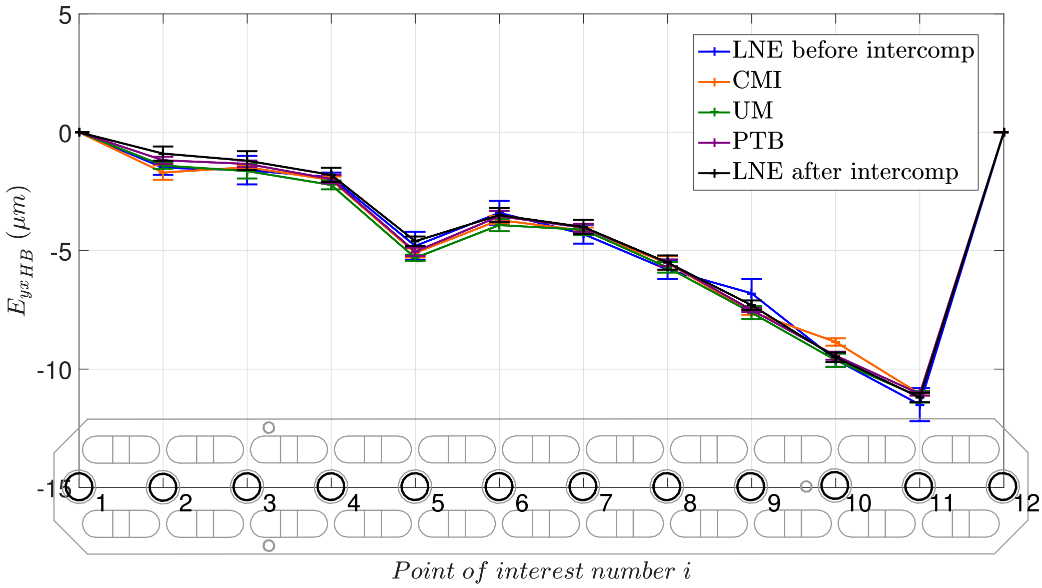


Figure 4: Horizontal straightness error $E_{YX, MFB}$

UM – Ball-bar (3D-MS)

Objective

The main goal of UM was to design, manufacture and calibrate a one-dimensional thermo-invariant length standard for fast verification of the length measurement performance of machine tools (3D-MS). The main design characteristics of the standard, which were defined based on the survey of industrial needs, are the following:

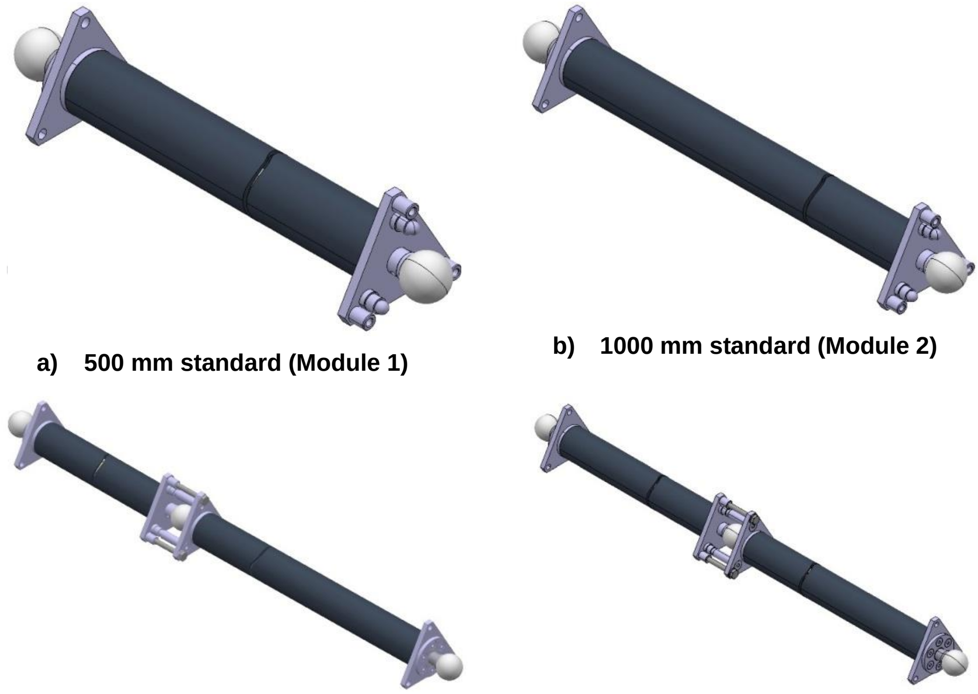
- Low weight (carbon fibre composite material of the main body),

- Thermal expansion near to 0 (less than 1 µm/m/°C),
- Modular construction (4 modules enabling different lengths: 500 mm, 1000 mm, 1500 mm and 2000 mm),
- Low cost, easy to use and to transport,
- Enables fast and cheap machine tool verification.

UM specified detailed design data on the technical attributes, function, construction material, manufacturing techniques and uncertainty for the designed 3D-MS standard, and provided a document specifying the exact properties of the standard, detailed instructions for the manufacture of all constructional parts and backgrounds for calibrating and evaluating the uncertainty of the calibration. These data were supplemented with instructions for using the 3D-MS standard.

Design and manufacturing

UM has manufactured and successfully tested the standard within this project. EMO Orodjarna produced all of the stainless steel parts (joints), while aluminium parts were produced by Gorenje Orodjarna. The main body that was made of composite material was produced by Veplas. UM purchased ceramic balls and assembled the standard. Steel parts (joints) and composite tubes (main body) were glued together with special glue, while other parts were screwed together. A special issue related to the aluminium “thermal compensator”, which had to be cut to the right dimension after performing thermal expansion experiments. After assembly, stability and thermal expansion tests have been performed on a CMM.



a) 500 mm standard (Module 1) **b) 1000 mm standard (Module 2)**

c) 1500 mm standard (Modules 1+3) **d) 2000 mm standard (Modules 2+3)**

Figure 5: Ball standard - combination

Calibration

A guideline specifying the measurement and calibration tasks for the material standard including procedures and methods to be used was provided. The guideline provides exact instructions on the calibration and measurement process, including the number of probing points, the probes to be used, the number of repetitions, and the evaluation of measurement uncertainty. The calibration of the standard was performed on a tactile CMM ZEISS UMC 850. The modules were calibrated separately by applying the normal measurement procedure (probing balls in at least 20 points each, repeating measurements 5 times for each distance, calculating average distances and standard deviations). The ball distances on the combined modules were calculated by considering the geometrical properties of the joints between the modules. The standard was calibrated in May 2015 for the first time. However, after the first calibration, extensive thermal expansion tests were undertaken and the standard had to be modified - the lengths of the thermal expansion compensators were changed in all modules. After that, a new calibration was necessary. Finally the calibration certificate was issued in December 2015. The measurement uncertainty of the calibration was evaluated to be: $U = 2.1$ µm + $L \times 3.3 \times 10^{-6}$; $k = 2$.

NPL – Prismatic artefacts (TSEM-MS/TSMU-MS)

Design of standards

NPL specified specific attributes, suitable construction materials, manufacturing methods and techniques for three different standards. The standards were designed for specific applications and their design features and parameters were very important. In total three different standards were manufactured: a rotated squares standard, a circles standard and a prismatic standard.

The rotated squares standard is an artefact of six squares stacked on top of one another. Their centres are on axis and their orientations are staggered by 45° increments as each level increases (Figure 6b). The standard has been designed to enable analysis of the orthogonality of machine tool axes.

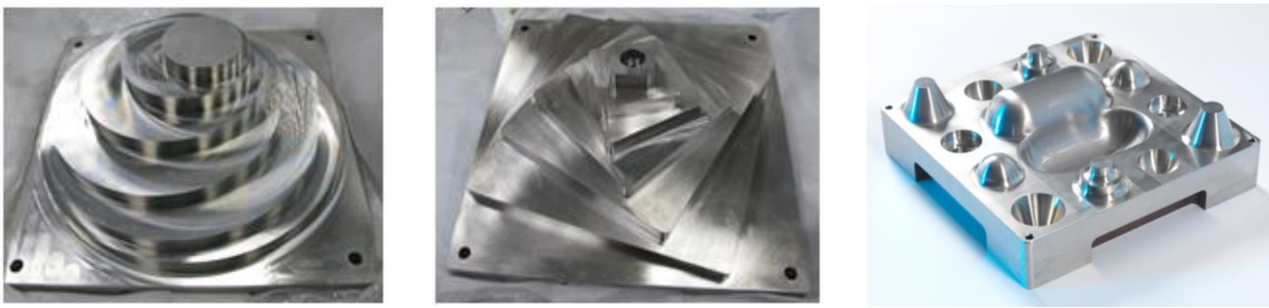
The basic design of the circles standard (Figure 6a) is a stack of differing diameter discs stacked on top of one another. Each disc is positioned off centre to the previous discs. The standard is finished to a roughness of $R_a = 0.4$ µm and a tolerance of 0.02 mm. The standard was designed to evaluate the three linear axes, the eccentricity of machining or, if used the rotary table of machine tools. Circles are relatively easy to manufacture on CNC systems, and relatively easy to measure and define by optical and mechanical systems. This data can be used to evaluate the deviation from a best fit cylinder, and the centre of that cylinder. To be able to estimate the positional error in the cylinder centres the machined discs are shifted.

The prismatic material standard (Figure 6c) is designed to contain several geometries, including hemispheres, cylinders and cones. Where linear distances may be required, each of these may be measured as individual items or as a group. Half of the top surface has a perturbation superimposed on the flat section. Due to the fact that the NPL prismatic material standard has been designed and manufactured to enable measurements to be carried out using optical systems, the surface has been treated to be optically compliant, the surface finish of the particular part is approximately $R_a = 5$ µm.

All of these material standards are manufactured from Invar and they have a nominal coefficient of thermal linear expansion of 1.6×10^{-6} K^{-1}. CAD models in STEP format (STandard for the Exchange of Product model data) are available for all standards and were supplied prior to measurements being taken by the participating institutes. Furthermore, a guideline containing directives which describe the procedures to be used for the calibration of the measurement standards was produced by NPL.

Investigation of materials and their optical properties

From the survey, it was decided that the material standards were to be used in the harsh environments of a typical work shop floor. Therefore the standards have been manufactured from Invar which fulfils the temperature invariant requirements of the project. However, Invar is reactive to moisture which would tarnish the surface and it is also, in a finished machine state, a surface which is highly reflective and therefore not conducive to optical measurement techniques such as fringe projection. Using Invar as the base material requires treatment or coating of the surface in a manner that would not only protect the surface but that would also make the surface conducive to the proposed optical techniques. Therefore the optical surface properties of the proposed coating materials have been investigated. Specific attention was paid to the variation in illumination (colour, angle, ambient conditions), Lambertian properties, and surface contamination to determine whether the surface is optically cooperative or not, and if not, how the surface would subsequently have to be machined, anodised, etched or coated. Further, different machining surfaces, which can be employed in manufacturing when using machine tools have been examined. Finally a coating on a soft copper-nickel base was chosen.



a) Circles standard **b) Rotated squares standard** **c) Prismatic standard**

Figure 6: NPL standards (before coating)

Finite Element Analysis

A finite element analysis has been carried out to assess the temperature variations within the standards, and the subsequent stress distribution and deformation due to thermal expansion or contraction. Six standards have been modelled: circles standard, squares standard, and prismatic standard all of solid construction and then of hollowed construction. It was assumed that the standard, initially at a uniform fixed temperature of 20 °C, was placed on a surface held at a fixed temperature (either 10 °C or 30 °C) in an atmosphere at a fixed temperature of 20 °C. A set of thermal models was used to estimate how long the standard took to reach an equilibrated temperature distribution, given that the lower surface of the standard was held at a fixed temperature and all other external surfaces exchanged heat with the atmosphere via natural convection. Once the equilibrium temperature distribution had been calculated for each standard and temperature, this temperature distribution was used within a stress analysis to calculate the effects of thermal expansion.

Reverse engineering of CAD

Reverse engineering is the process of measuring an object and then reconstructing that object as a 3D model. NPL outlined the procedure that they use to reverse engineer material standards designed and manufactured by NPL. As an example, the prismatic standard was used (Figure 6c). The objective was to correct, i.e. reverse engineer, the original CAD model, not to resemble the original design but the manufactured part. This requirement stems from the fact that the standards are required for high accuracy CAD comparison to in-process dimensional measurements taken directly in a shop floor manufacturing process.

Dimensional inter-comparison of the prismatic material standard

After calibration of the prismatic standard inter-comparison measurements were performed. The standard was calibrated on a tactile CMM of the Leitz Infinity type (maximum permissible error (0.3 + 1.0 L/1000) µm with L in mm). Calibration uncertainties were estimated using the Virtual Coordinate Measuring Machine (VCMM) software where a Monte-Carlo simulation with 8000 simulations was carried out. Finally an inter-comparison of measurements between 5 NMIs (NPL, Metrosert, CMI, LNE, and PTB) was performed. Within the inter-comparison the prismatic material standard was measured using tactile probes. The measurement results indicated that the aligning instruction needed some amendments, in order to obtain a better fit of the measurement results.

PTB – Multi Feature Check (TSEM-MS)

The Multi Feature Check (MFC) provides test features for several typical measurement tasks on machine tools and coordinate measuring machines. It is a modified copy of the eµmetron Multi Feature Check and is made from Zerodur®. In its basic structure the MFC is a cylindrical body with a length of 152.4 mm and a diameter of 100 mm. Several geometric features are incorporated in the cylindrical body like cylindrical and cone-shaped cut-outs, holes, and flat as well as inclined surfaces. The MFC provides test features of form (cylindricity, flatness, roundness), of dimensions (angle, diameter, distance) and of positions (inclination, parallelism, position of intersection points, squareness). It was designed for the mapping of task-specific measurement errors and the assessment of task-specific measurement uncertainties. Beside kinematic and thermo-mechanical error sources and errors due to the motion control and the control software of the machine tool are considered.

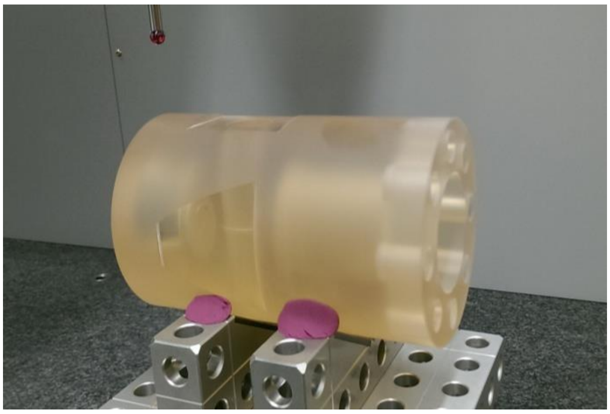


Figure 7: Multi Feature Check

The MFC has been calibrated on a CMM of type Zeiss UPMC850 CARAT (VAST probe-head). Task-specific measurement uncertainties were estimated for each calibrated feature by means of simulation according to the Virtual Coordinate Measuring Machine (VCMM).

CMI – Hyperbolic paraboloid (FF-MS)

Motivation

The design and manufacture of components with functional freeform surfaces in precision engineering placed great demands on applied metrological procedures and reliable evaluation of measured data and interpretation of obtained results. To establish the traceability of measurements, calibrated standards with sufficient precision, stability, reasonable cost and sufficiently small calibration uncertainty are used. Calibration standards of regular shapes (spheres, cylinders, step gauge blocks, ball plates, hole bars, hexapods, etc.) are well developed, while the traceability and quality control in freeform manufacturing are issues due to the lack of traceable verification standards. Therefore, a new traceable FF-MS Hyperbolic paraboloid has been developed, manufactured, calibrated and applied in industry within this project. The standard was designed specifically to investigate the performance of area-scanning measuring devices which are in use on machine tools.

Design

As the quality and relevance of a reference standard in CAD-based metrology is significantly influenced by the shape correspondence of the standard and its CAD representation, a geometrical-mathematical approach based on purposeful application of NURBS (non-uniform rational B-spline) and effective usage of its properties has been used to design a shape of FF-MS. Consequently, the CAD model of the standard is identical to its mathematical description. Moreover, the CAD model in NURBS representation can be easily modified according to the values measured on the physical standard. Application of this property on a suitably chosen CAD model of the standard resulted in the development of a calibrated CAD model of the standard.

From the metrological point of view, the surface of an hyperbolic paraboloid can be considered a freeform surface or a set of straight lines, parabolas or hyperbolas located on the freeform surface. It follows that there are different types of features to be measured such as surface points located on the freeform surface, points along 3D straight lines, points along 3D parabolas and points along 3D hyperbolas, see Figure 8.

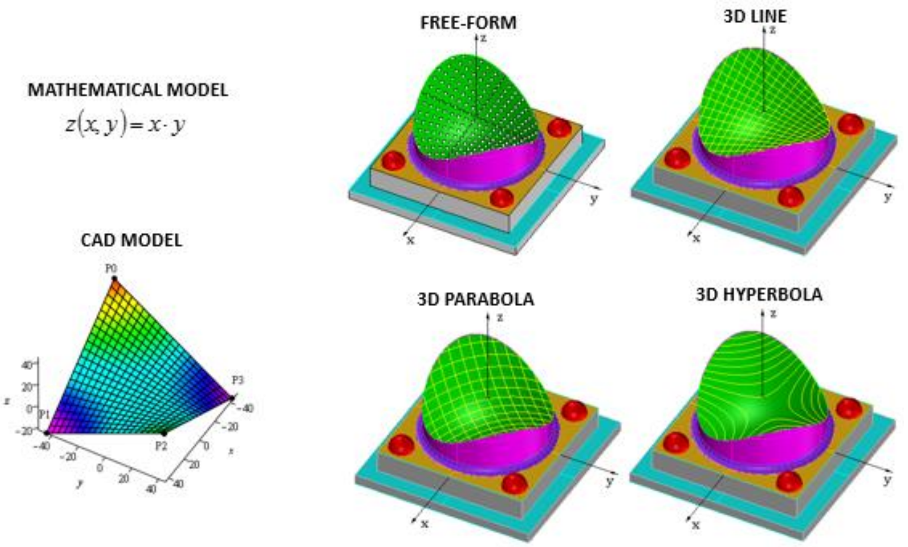


Figure 8: FF-MS Hyperbolic paraboloid

Manufacturing

The FF-MS Hyperbolic paraboloid (120 mm × 120 mm × 67 mm) has been manufactured by 3-axis milling on a CNC milling machine US20 by high speed cutting from steel EN X10CrNi18-9, see Figure 9.

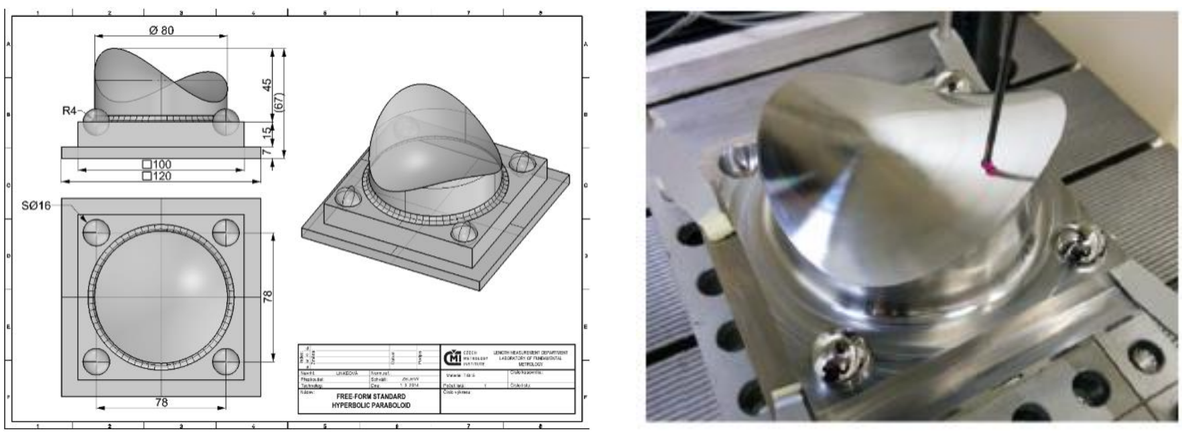


Figure 9: Technical documentation (left) and manufactured standard (right)

Calibration of the standard and calibrated CAD model development

During the calibration of the freeform artefact and its CAD model on a SIP 5 CMM (maximum permissible error (0.8 + 1.3L) µm), the standard was repeatedly measured without any changes of position in the clamping device. The environmental temperature was kept at (20 ± 0.2) °C. Colour maps of the deviations obtained by measurement of surface points and by measurement of points along curves located on the freeform surface are shown in Figure 10.

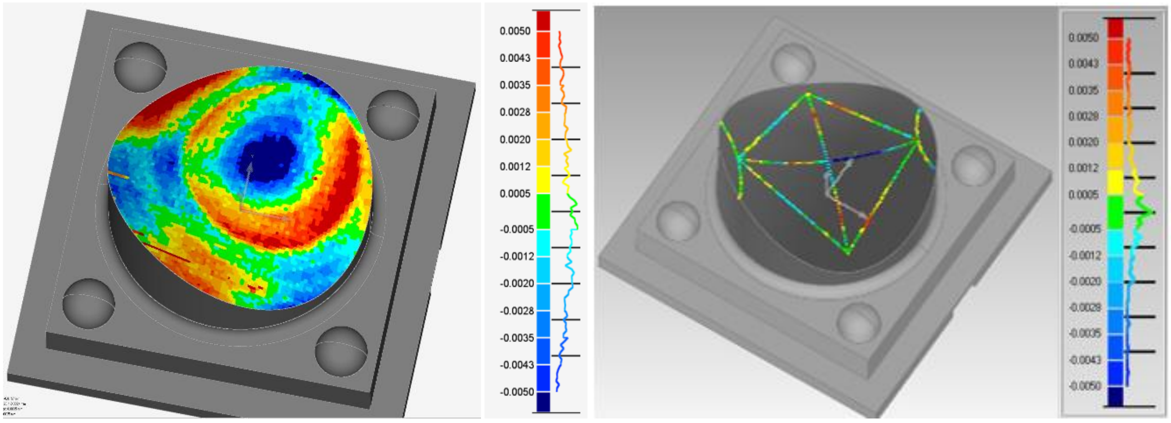


Figure 10: Colour map of the deviations of 5000 surface points located on the freeform surface (left) and along curves on the freeform surfaces (right)

The first step of the calibration consisted of determining the coordinate system. Here, three of the four spheres were used for the alignment of the standard and its coordinate system determination. During measurement, the repeatability of the coordinate system determination was influenced mainly by the sphericity of the spheres and the repeatability and measurement accuracy of the measuring device. After coordinate system determination of the standard, the calibrated CAD model of the standard was developed, see Figure 11.

Two basic prepositions for developing a successful procedure for a calibrated CAD model are as follows. (1) The freeform surface of the standard has to have an exact mathematical description in NURBS representation. Regarding the FF-MS, the surface of the hyperbolic paraboloid needs to be expressed as a uniform bilinear B-spline surface, therefore, this condition is fulfilled. (2) 3D modeller, based on NURBS representation, has to be used to create the CAD model without any simplification or approximation (Rhinoceros). Thus, the mathematical and CAD model of the surface are identical. Consequently, it is possible to use measured data as control vertices of the NURBS surface and to modify the CAD model according to the real physical form of the standard.

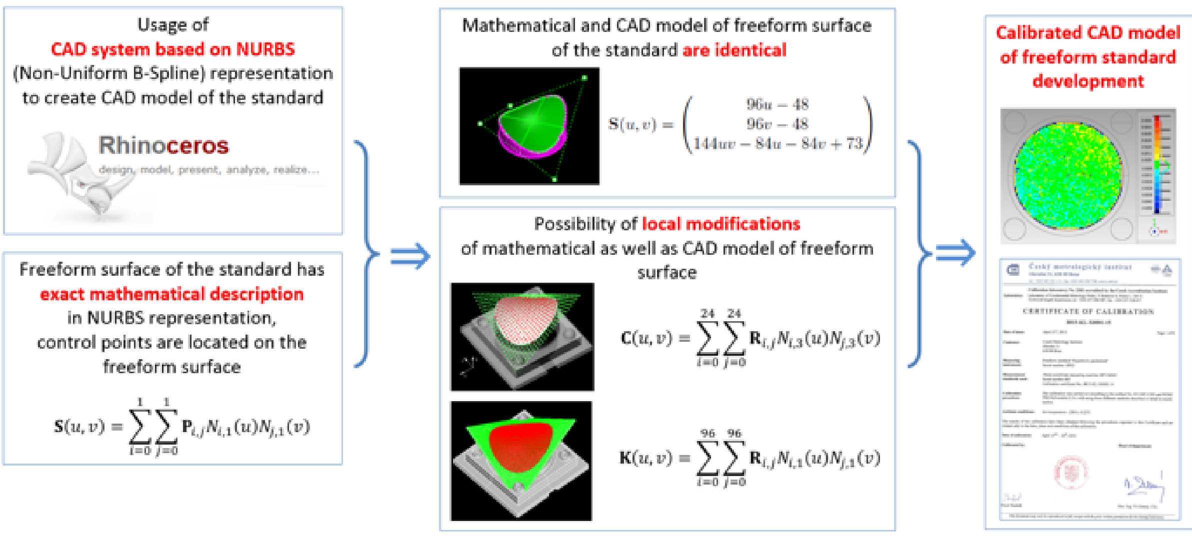


Figure 11: Process of calibrated CAD model development

VTT-MIKES – Roundness discs (R-MS)

Introduction

Roundness is an important feature for all rotating machines where smooth rotation of the rotors or even surface quality and even thickness of the end product is needed, such as paper machines, steel strip or sheet production, printing machines, engines and generators etc. In paper mills the roundness measurements are commonly carried out when the roll is located on a lathe or on a grinding machine, see Figure 12. Heavy rolls are rotating with their own bearings or they are supported by sliding pads. With these measurement setups it is difficult to avoid a rotational error of the centreline of the roll, and thus one- or two-point measurement methods cannot properly separate the rotational error of the centreline of the workpiece from its geometry. This is the reason for using a multi-point measurement devices in the paper industry. Most of them are based on the Ozono method, where the roundness is calculated from weighted sensor signals in a given configuration around the rotor.

Figure 12: Four-point roller measuring device of a grinding machine

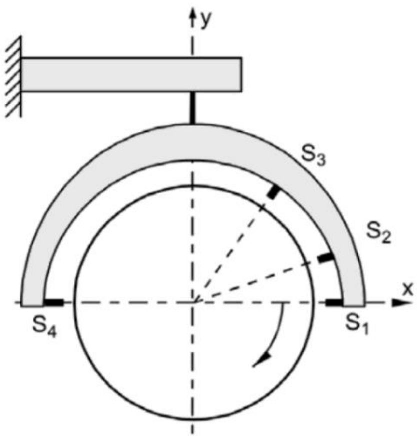


Figure 13: Orientation of probes [S1-S4] in a four-point measurement system

In modern machine tools for large scale rotors, i.e., paper mill or steel mill rollers, the reliability of the onsite measurement device is important also for the error compensation of the roller grinder or lathe. The control systems of the machine tools use the geometry information measured by the measurement device for the error compensation. Thus the measured geometry must be accurate to compensate for the error.

Development and testing of R-MS

In the project three R-MS were developed by VTT-MIKES and REG(Aalto) and their properties are shown in Figure 14**Error! Reference source not found.**. All standards are discs with the diameter of 500 mm to 550 mm. This is the largest diameter that can be easily measured in laboratories and not too small to be measured by in process roundness measurement systems in industry. The thickness of the discs is 30 mm to 54 mm which is enough for robustness and yet not too heavy to handle. The types and requirements of the selected standards are shown in Table 1 and Figure 14.

Name	Form	Roundness error / µm
Type A	round	0 to 2 µm
Type B	21 UPR	20 to 25 µm
Type C	asymmetric multiwave, 2 to 30 UPR	10 µm / undulation

Table 1: Properties of discs

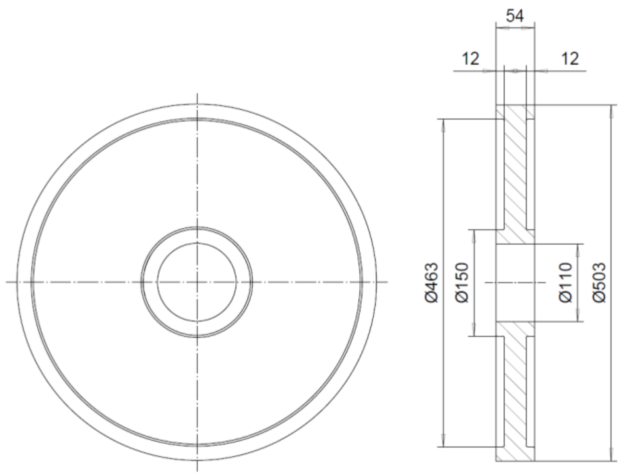


Figure 14: Drawing of the disc Type A

The type A standard is almost perfectly round. With a roundness error below 2 µm this standard helps to reveal errors like noise and thermal drift on the large measurement frame of the multi-point measurement systems. Type B was selected as it has one characteristic form of a 21 undulations per rotation (UPR) wave. The type C, asymmetric multi wave, consists of several waves. Standards of this type have previously been used and they are expected to work as an overall test standard. Previously only type C discs have been used in the calibration. However, by using multiple discs, different types of error sources can be evaluated.

The discs were calibrated by partners VTT-MIKES and Metrosert in laboratory conditions. The use of the discs was also tested by measurements in industrial conditions using a four point measurement device. The measurements showed that the discs are stable, portable and useful to give traceability to in-process measurements of rollers.

PTB – Workpiece Replica (WR-MS)

Introduction

The workpiece replica material standards (WR-MS) are designed as parts that are typically used for verifications of machining centres. They are based on the NAS (National Aerospace Standards) 979 cutting test and also known as diamond-circle-square standards. The aim of these material standards is to assess the performance of machine tools. However, many other designs may be used when appropriate.

Design and manufacturing

The workpiece replicas were machined from prepared aluminium blanks of the NAS standard. Figure 15 shows the CAD model of the workpiece replica. The squared base has a side length of 272 mm and the overall height of the standard is 60 mm. In the centre of the workpiece replicas is a borehole with a diameter of 27 mm. Additionally, two fitting holes with a diameter of 14 mm are located near to the lower left and the lower right corners of the squared base as a further quantity to be measured.

Calibration

Altogether 20 workpiece replicas were manufactured on the investigated machine tool at different temperatures using the mobile climate simulation chamber. After production of the workpiece replicas and on-machine measurement of the geometrical features they were calibrated on a ZEISS PRISMO ultra coordinate measuring machine with a VAST gold probe head. Task-specific measurement uncertainties were estimated for each calibrated feature by means of simulation according to the Virtual Coordinate Measuring Machine (VCMM).

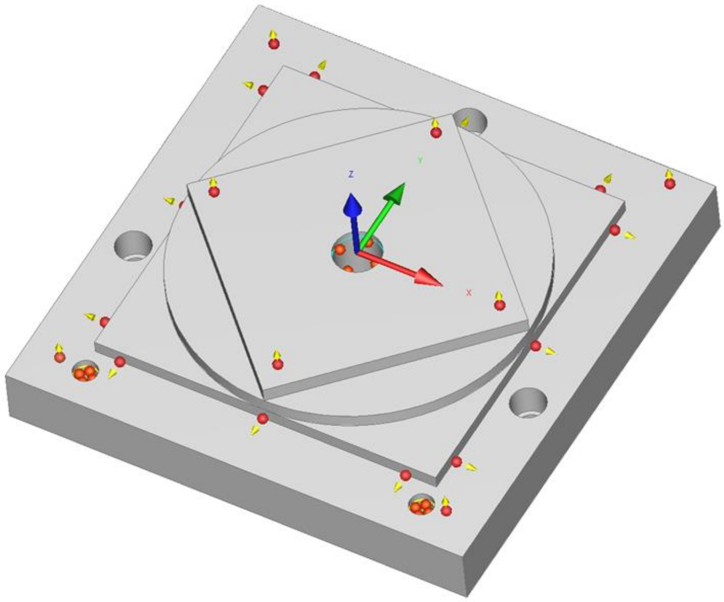


Figure 15: Workpiece replica material standard with probing points

Objective 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.

Conception and dimensioning

To improve the accuracy of machines under harsh surrounding conditions and to evaluate the measurement capability of machine tools, it is necessary to investigate the behaviour of the machines under different climatic and environmental conditions. REG(KIT) and PTB in cooperation with the industrial partners MAG IAS and Daimler discussed typical machine tool dimensions as well as the radiated heat during their operation in several workshops and meetings. The results can be summed up as follows:

- MT-Dimensions: 5.2 x 3.6 x 3.7 m³
- Heat emission: 24 kW

The inner dimensions (L x W x H) of the mobile climate simulation chamber were derived to 10 x 6 x 5 m³. REG(KIT) investigated typical environmental conditions in order to be able to calculate the conditioning devices and to estimate the final costs of the climate chamber: The temperature range to be simulated in the climate chamber was defined to be between 15 and 45 °C in order to cover all possible shop floor conditions worldwide. The density $\rho = 1.2041\ \mathrm{kg/m^3}$ and specific heat capacity $c_p = 1005\ \mathrm{J/(kg \cdot K)}$ we assumed to be invariable air properties. The temperature difference ΔT between the current and the set temperature was considered to be ≤ 10 K in order to be able to estimate the circulation of air through the air conditioning devices with simultaneous regard to possible draft effects. The resulting volume flow amount $\dot{V} = 7139.8\ \mathrm{m^3/h}$ was used as a characteristic reference value for the dimensioning process, of which a share of $300\,\mathrm{m^3/h}$ needed to consist of fresh air in order for a person to be able to be located inside the chamber. The final request for a sufficient cooling capacity demands the consideration of extreme operational conditions that are targeted with the temperatures $T_{\mathrm{inside,min}} = 15\ ℃$ and $T_{\mathrm{outside,max}} = 45\ ℃$. The consideration of Mollier's h-x chart and the boundary conditions result in a minimum cooling power of $P_{\mathrm{cool,min}} = 28\,\mathrm{kW}$ and the maximum power of $P_{cool,max} = 34\ \mathrm{kW}$.

The mobility aspect of the climate chamber was respected by choosing modular load-bearing elements that can be assembled and disassembled within one week with the support of a work platform. Perforated textile hoses were chosen for a homogeneous air distribution inside the climate chamber. In the final phase of the conception, REG(KIT) validated the system behaviour digitally with a computational fluid (CFD) simulation in order to avoid undesired system behaviour. The results of the simulation showed that an overall temperature homogeneity of 3 K can be achieved with the designed system.

Verification of the climate simulation chamber

After the final assembly and commissioning of the climate simulation chamber preliminary verifications have been carried out by REG(KIT), which have shown that a temperature change of 10 K (15 °C → 25 °C) can be reached within approximately 30 minutes with a maximum temperature inhomogeneity of 2.2 K, confirming the preliminary investigations via CFD simulation. In order to verify these results in the relevant temperature range, a validation experiment was designed with the aim of evaluating the performance of the subsystems of the climate chamber. The testing procedure includes realistic temperature changes of 5-10 K and temperature plateaus for the systematic evaluation of geometric errors. An important restrictive factor for the duration of the temperature plateaus is the machine specific through heating time. At this state of investigations a comparable estimation of geometric errors of machine tools requires that a stable thermal state is established in the machine tool. The outside of the assembled climate chamber can be seen in Figure 16a. Figure 16b shows the inside of the climate chamber with the inspected Machine Tool MAG Specht 500 DUO+.

a) Outside **b) Inside**

Figure 16: Climate simulation chamber

Temperature measurements

CMI and Metrosert in close cooperation with the REG(KIT) designed an applicable sensor network that monitors the environmental temperature in the chamber. The sensor network is based on the design layout as finalised by REG(KIT) and PTB. The sensor that was used for the validation of the climate chamber consisted of air temperature sensors at measuring positions surrounding the machine tool. Two different configurations of sensors were used simultaneously in order to maximise the density of information and to validate the interpolation algorithm that was developed.

- Temperature system provided by Metrosert/REG(KIT):
  The temperature system provided by Metrosert and installed and monitored by REG(KIT) consisted of 21 sensors which were arranged in 7 vertical lines of 3 sensors each close to the chamber's wall. The locations of the sensors are shown in Figure 17.

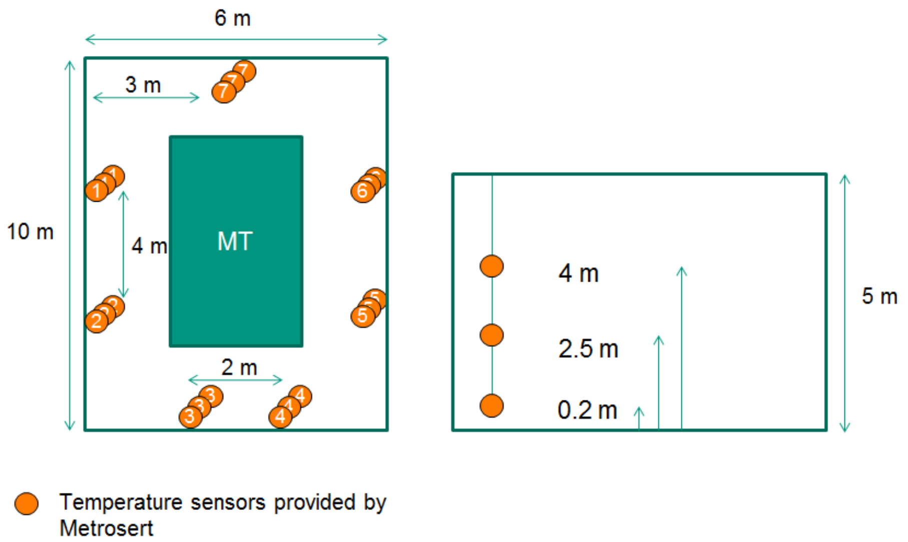


Figure 17: Spatial distribution of temperature sensors (Metrosert, (REG(KIT))

- Temperature system provided by PTB:
  The temperature system provided, installed and monitored by PTB consisted of 24 sensors which were arranged in 6 vertical lines of 4 sensors each close to the machine tool. See Figure 18 for the locations of the sensors.

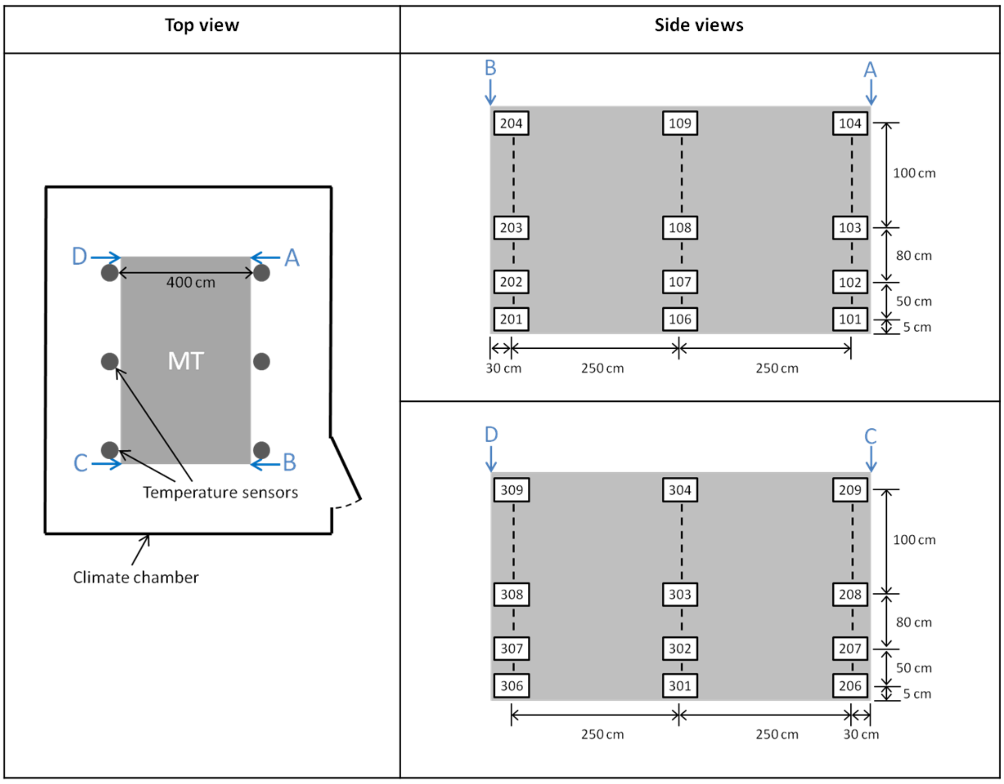


Figure 18: Spatial distribution of temperature sensors (PTB)

Working parameters

The verification of the climate simulation chamber was carried out by REG(KIT). The evaluated temperature homogeneity is based on the consideration of three different height levels in the climate chamber with iterative temperature change steps. The measurements showed a maximum temperature inhomogeneity of about 2 K. The specified heating/cooling performance of ±3 K/h was reached without any negative observations. The biggest temperature gap between 15 °C and 45 °C was reached within 2 hours, which results in a heating performance of +15 K/h. The cooling performance of the climate chamber was verified with a temperature drop of 10 °C from 25 °C to 15 °C. This temperature area was chosen because of the circumstance that the outside temperature has no supporting effects, as the shop-floor temperature was around 25 °C. The described temperature drop was reached 45 minutes after the temperature change was initiated, which resulted in a cooling performance of -13.3 K/h.

Spatial temperature interpolation

With the design of the testing procedure it was necessary to develop an interpolation algorithm in order to reliably determine the temperature distribution throughout the considered space. CMI in collaboration with PTB developed an interpolation method to mathematically model the spatial environmental conditions of a predefined space and of the environmental parameters. The solution is based on isogeometric analysis whereby the medium, interface and boundaries of the space are considered. CMI and Metrosert in collaboration with PTB and REG(KIT) then conducted experimental verification of the mathematical model by interpolating the spatial environmental conditions.

The applied interpolation method “Kriging” is a statistical method of interpolation, which is based on stochastic processes and assumes the stationarity of the measuring points. Stationarity in this context means that the measurands of adjacent measuring points are more similar than those of distant ones. The advantage of Kriging methods is that the estimation is unbiased. These methods are very flexible and the interpolation result is fully controllable by several parameters. In contrast to tri-linear interpolation the measuring points can be positioned arbitrarily.

Verification measurements

After the implementation of the algorithm a validation procedure was applied. For this purpose two different sensor networks were used (see aforementioned configurations):

1. **Verification using REG(KIT) temperature data**
   For the verification of the interpolation model the data of the 7 lower and 7 upper (height 0.2 m, and 4 m, respectively) temperature sensors were used for the interpolation, while the temperatures at the locations of the 7 sensors at a height of 2.5 m were interpolated. Comparison with the measured data at these positions allowed us to conclude about the validity of the used interpolation model. The following Figure 19 and Figure 20 show the maximum estimation error and the mean prediction error for the interpolated temperatures.

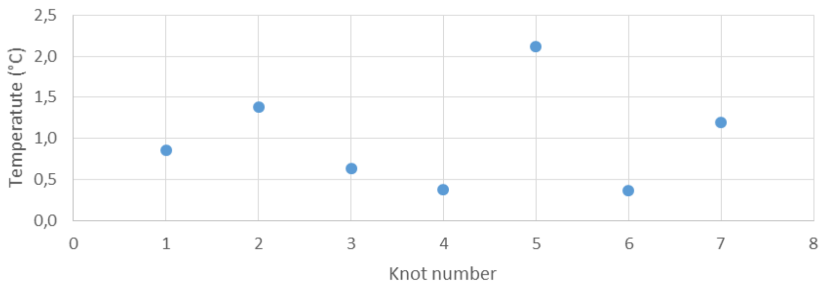


Figure 19: Absolute value of the maximum estimation error, REG(KIT) experiment, 20 °C, height of 2.5 m

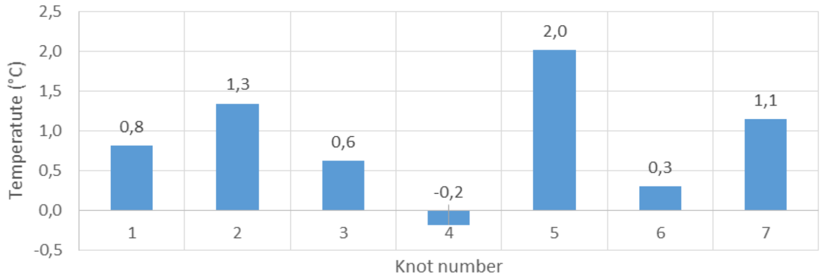


Figure 20: Mean prediction error, REG(KIT) experiment, 20 °C, height of 2.5 m

2. Verfication using PTB temperature data

For the verification, the data of the 18 temperature sensors at heights 5 cm, 55 cm, and 235 cm were used for the interpolation, while the temperatures at the locations of the 6 sensors at a height of 135 cm were interpolated. The maximum estimation error and mean prediction error for the interpolated temperatures are pictured in Figure 21 and Figure 22.

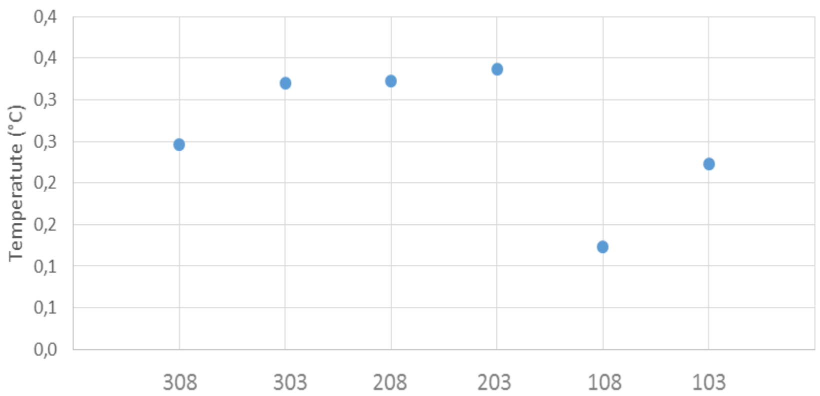


Figure 21: Absolute value of the maximum estimation error, PTB experiment, 20 °C, height of 1.35 m

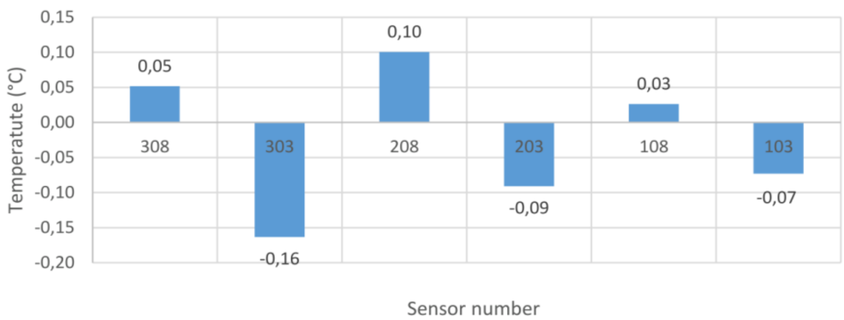


Figure 22: Mean prediction error, PTB experiment, 20 °C, height of 1.35 m

Considering the great temperature fluctuations and distances between the sensors the result of the verification has shown minor differences between the two applications of the interpolation method. The precision of the algorithm can be enhanced by applying different methods of correction. The interpolation uncertainty however was in accordance with the assumed total uncertainty budget.

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

The standards developed within this project are provided to ensure the traceability of dimensional on-machine measurements to the definition of the metre. Therefore procedures have been developed that are qualified and adequate to be used for implementing acceptance tests, re-verification, volumetric and task-specific error mappings, and error corrections to optimise on-machine measurements and finally the machining process. Therefore various machine tool conditions that are influential to the measurement accuracy and to the traceability of the measurements, such as the heat generated from the machining process, environmental factors, dynamic forces and other systematic errors have been considered besides kinematic error contributions. This will help the industrial end-user of machine tools as well as the machine tool manufacturer to assess or even to improve the specific measurement accuracy and to verify the measurement performance of the machine tools at regular intervals. This section provides an overview of the developed procedures and their verification tests.

Evaluation of a machine tool using the Multi-Feature Bar

The Multi-Feature Bar (MFB) calibrated by reversal technique was used by LNE to map the geometric errors of the 3 linear axes of the Mikron UCP710 5-axis machine tool (Figure 24). Hence, a high-accuracy 3D touch probe trigger was integrated in the Mikron MT. A specific interface was developed by LNE to collect real time raw data provided by the 3D probe trigger, as well as the linear and rotary encoders of the Mikron MT (Figure 23). An additional procedure was also developed to acquire the machine zero point by counting distance-coded reference marks. The developed interface was used instead of the industrial computer numerical control (CNC) of the Mikron MT to avoid collecting data with any pre-existing error compensations and uncontrolled processing. The interface ensures the measurement procedure with regards to the following steps:

1. acquisition of the machine tool zero point,
2. collection of the absolute MT coordinate (X, Y, Z, A, C) in real time (f = 33 kHz, resolution = 10 nm) and directly on linear and rotary encoders,
3. collection of the touch probe trigger ($U_{(k=2)}$ = 0.25 µm with a feedrate equal to 240 mm/min^{-1}),
4. record of the data,
5. fetch recorded data on the hardware device.

All the data are recorded only when the touch probe trigger is activated.

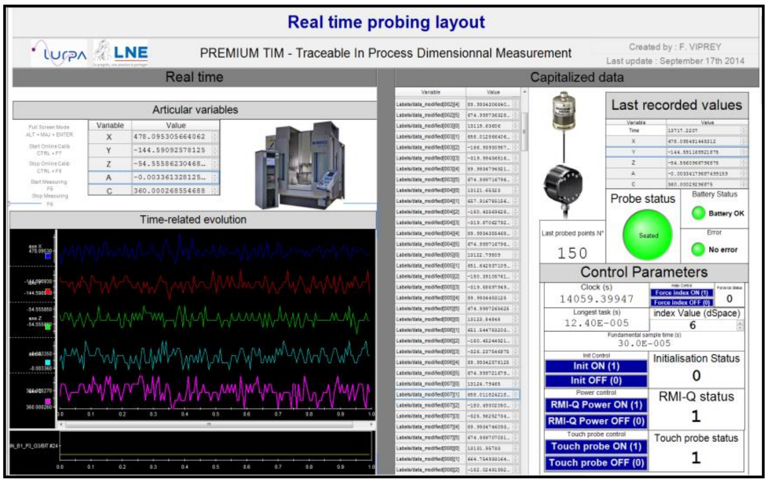


Figure 23: Developed end user interface

By using a developed geometric error model, and some particular positions of the MFB (Figure 24) and the position of a datum sphere (Figure 25) it is possible to extract geometric motion errors of the machine tool.

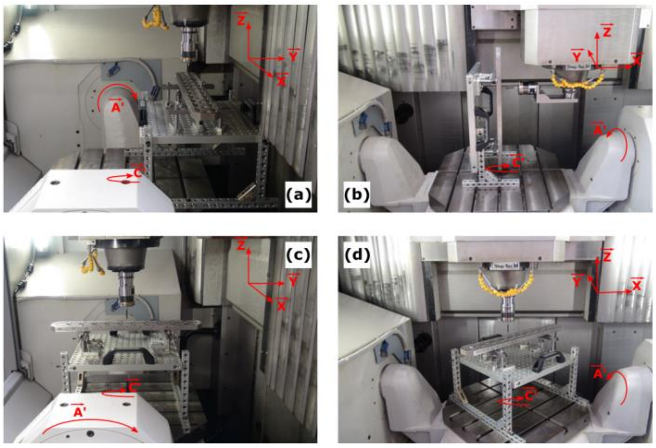


Figure 24: Error mapping of Mikron UCP710 MT by using the MFB: (a) along the X-axis, (b) along the Y-axis, (c) along the Z-axis, (d) along the XY plane diagonal

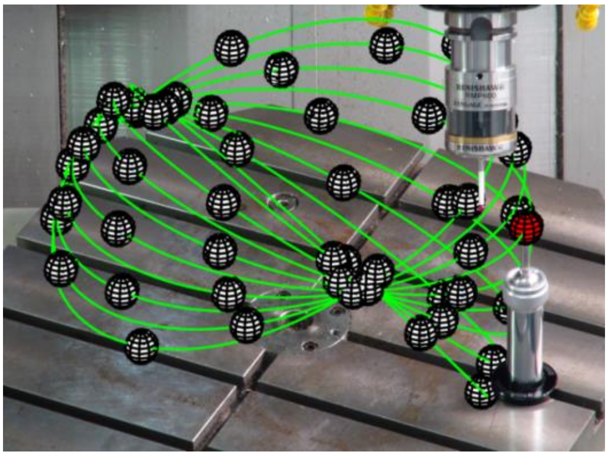


Figure 25: Error mapping of Mikron UCP710 MT using a datum sphere

For verification LNE compared the geometric errors that were identified using the MFB and a datum sphere to the errors that were identified with the established method of using tracking laser interferometers, and to a virtual machine tool that was developed by LNE, too. This virtual machine tool facilitates the simulation of the effect of geometric errors in the workspace, and the testing of the identification process. Finally, this virtual machine also considers the compensation process of these errors.

Fast machine tool verifications using a ball-bar

Uncalibrated ball bar

UM developed a procedure to check the accuracy of the linear scales of a machine tool using an uncalibrated ball bar standard. The length of the ball bar is measured parallel to each one of the three axes. If all three measurements are the same, the probability is very high that the scales are all performing well. If on the other hand one scale or all three scales are giving different readings, it is obvious that there is a scale problem. Prior to evaluating the scales, all squareness and roller errors should have been corrected for, as they can effect this evaluation in some complex ways.

To check the scale of a single axis the ball bar is measured in two different positions parallel to the corresponding axis. For example, for evaluating the Z axis scale (Figure 26), the ball standard is set straight up vertically. The vertical ball standard is usually measured in two positions in each of two diagonal corners at the extremes of the machine envelope.

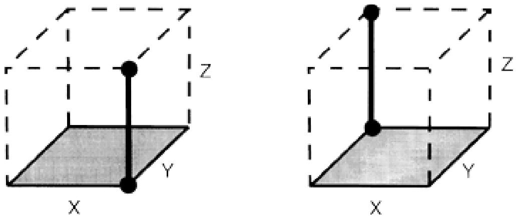
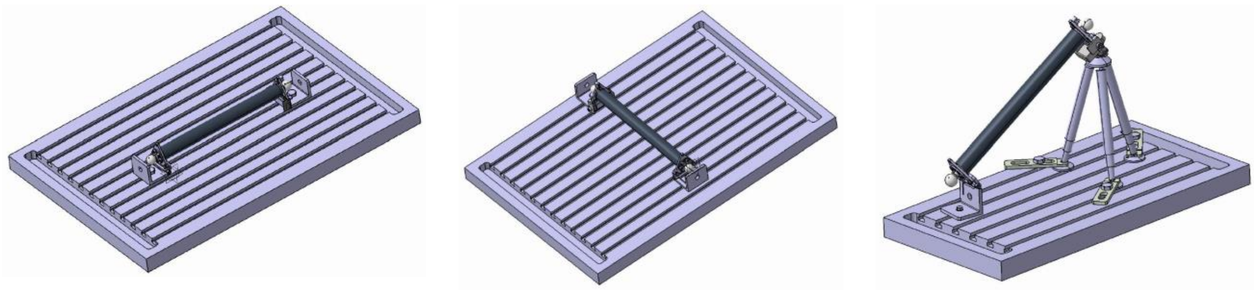


Figure 26: Verification of the Z-Axis scale

Calibrated ball bar

UM additionally developed a procedure for checking geometric machine tool errors in three linear axes. This verification procedure enables end users to determine whether the maximum measured length error is smaller than the maximum permissible length error (MPE). The ball bar standard is measured in at least three settings (Figure 27). For evaluating the X and Y axes scales, the ball bar is set horizontally and placed parallel to the corresponding axis. For evaluating the Z axis scale, the ball bar is mounted with one side to the machine table and with the other side to a tripod, which is also mounted on the machine table. With this combination, the ball standard can be positioned in any direction in the machine working space. The measurand is the distance between ball centres of the ball standard. Measurement is performed by probing four points by a 3D touch probe on each of the two ceramic balls and by evaluating their coordinates. Measurements are repeated several times in each ball bar position. After that, the distance between ball centres is calculated and compared to the calibrated ball bar length. A measurement uncertainty of U<5 µm was verified by applying the developed ball bar and the procedure on the milling machine tools.



a) X-Axis **b) Y-Axis** **c) Space diagonal**

Figure 27: Positions of the ball bar

Volumetric error mapping of machine tools in a wide range of working conditions

A significant part of the overall geometrical errors of machined work-pieces is induced by the effects of temperature. Thermo-mechanical errors of a machine tool are caused by environmental influences like the shop floor temperature and also by internal influences such as the heat generated by the machining process.

In order to identify changes in a machine tool's structure due to varying environmental temperatures, the mobile simulation chamber designed by REG(KIT) within this project was used. The investigated machine tool was a SPECHT 500 DUO+, a 5-axis dual-spindle machining centre belonging to the industrial partner MAG IAS. PTB measured the geometric errors of this machine tool in a temperature range between +15 °C and +30 °C in steps of 5 K. All kinematic errors of location and orientation of the three linear and the two rotational axes (one rotary table and one swivel axis) according to the standard ISO-230 Part 1 were mapped via sequential multi-lateration using a tracking laser interferometer. Preliminary investigations revealed, that considering the specific kinematic of the SPECHT 500 DUO, a tracking laser interferometer is much better suited for the mapping of machine errors in comparison to a 3D hole plate, which in this particular case makes it necessary to use very long extensions and/or styli when measuring the plate. For the investigation of the geometrically and thermally caused machine deformations, the applied test procedure has to be invariant with respect to changes in temperature. As the tracking laser interferometer is equipped with a weather station for compensating the influence of the air temperature and pressure, this condition is sufficiently fulfilled. Therefore the geometric errors of a machine tool at different temperatures could be measured.

The main results of these measurements at varying temperatures are: Position errors due to thermal expansion of the glass scales and squareness errors were the most dominant errors of the linear axes. In comparison to the position and squareness errors, straightness and rotational errors were less prone to temperature effects. The machine tool's highest precision under no load was determined at 25 °C when using the machine-specific error compensation. Temperature effects on the geometric errors (six degrees of freedom) of the rotational axes were negligible due to their active cooling. The most prone temperature influence on the rotational axes was determined for their location errors.

In the next step, these measured errors were numerically compensated for by the controller of the machine tool, leading to a temperature-dependent volumetric error compensation of the machine tool. Measurements of the residual geometric errors of the machine tool were performed at the temperature levels 20 °C and 25 °C. Therefore, it was demonstrated that the effect of the ambient temperature could be significantly reduced and that the overall accuracy of the machine tool could be increased. The maximum volumetric error was reduced by about 80 percent, from 147 µm to 28 µm (Figure 28).

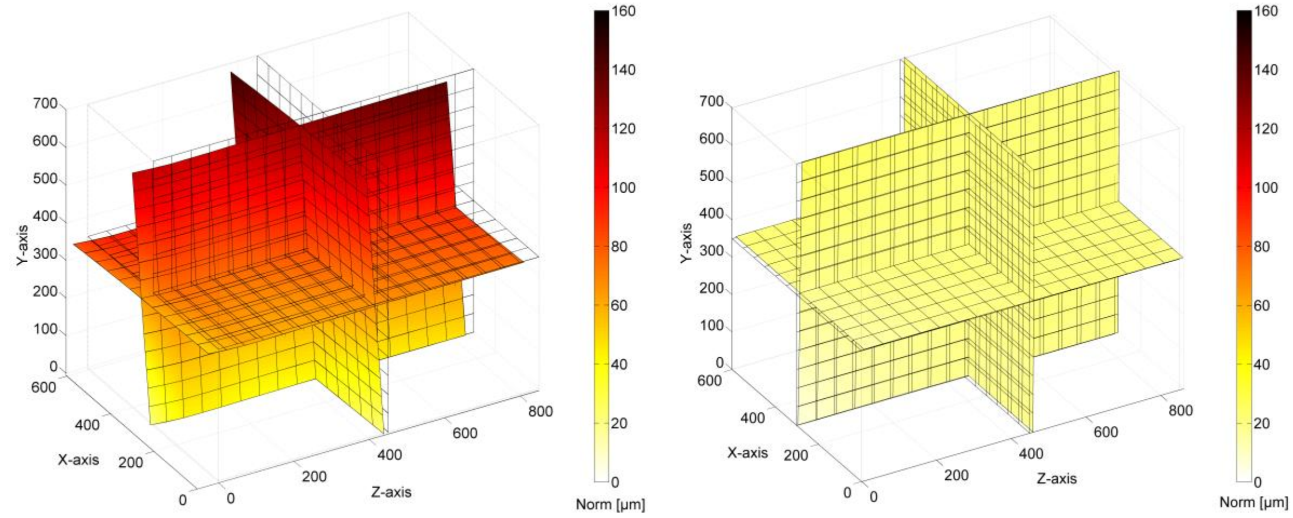


Figure 28: Geometric errors of a MT without (left), and with compensation (right), respectively

On-line compensation model for thermal machine tool errors

IK4-Tekniker in cooperation with CEM developed a parametric linear state-space model for the thermal compensation of a vertical large-scale machine tool in shop floor conditions (Figure 29). This is a mathematical model in which a number of inputs, outputs, and state variables are related by a series of first order differential equations that are combined in a single pair of differential equation matrixes in which variables are expressed as vectors. This time domain approximation is compact and convenient to analyse systems with multiple inputs and outputs. The state variables comprise the smallest set of variables that can be defined by the system in any time instant when the initial value of these variables and the applied input are known.

Influence of temperature variations on multi-lateral error mappings

Volumetric error mappings by sequential multi-laterations using laser interferometers requires the machine tool to repeat at least four times the same measuring point cloud. If perfect machine tool repeatability is achieved and the measurements would not be affected by environmental influences the residuals of sequential multi-lateration mathematics fits to 0. However since this is never achieved, misfit histograms are used as a suitable estimator of the measurement quality. IK4-Tekniker supported by CEM investigated how to reduce the misfit of a whole measuring process in order to reduce the uncertainty of volumetric performance assessments. The investigations concerned different influences such as repeatability of the machine tool, correction of refractive index, laser beam stearings, retro-reflector induced errors, temperature variations (Figure 30), etc. over a wide range of working conditions, machine types and sizes.

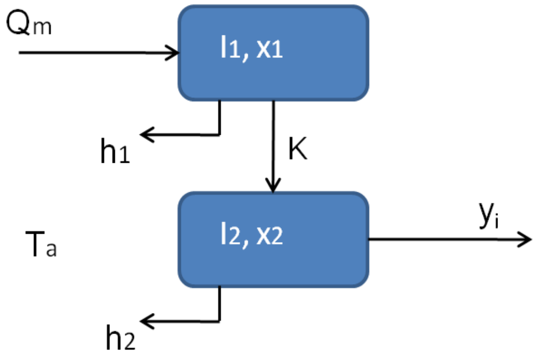


Figure 29: Parametric lumbed model of a vertical machine tool

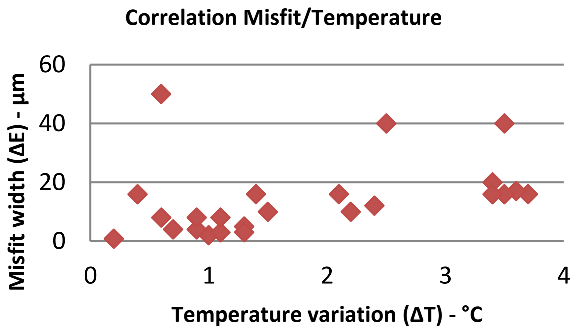


Figure 30: Misfit of measurements in a function of temperature variations

Verification of tactile and area-scanning on-board metrology systems

CMI developed a procedure for checking optical area-scanning on-board metrology systems as well as tactile probing systems using the developed freeform material standard (hyperbolic paraboloid). Due to the special geometrical properties of the surface of a hyperbolic paraboloid, the measured points can be placed along the whole freeform surface or along curves (3D lines, 3D parabolas or 3D hyperbolas) located on the freeform surface (Figure 31). In the case of using a tactile scanning probe, the scanning paths can be arranged, for example, in the direction of the x or y-axis as shown in Figure 32. Consequently, the recommended metrology strategy depends on the measured feature. Finally, the normal distance of the measured points from the reference CAD model is evaluated.

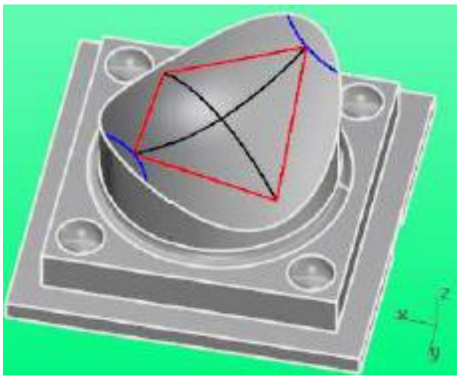


Figure 31: Geometrical features located on a freeform surface: 3D lines (red), 3D parabolas (black) and 3D hyperbolas (blue)

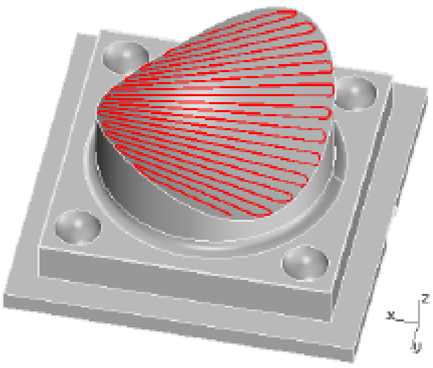


Figure 32: Metrology strategy for freeform measurement with a tactile scanning probe

Influences on the machining process

Errors associated with translating CAD to CNC

Modern CNC (Computer Numerical Control) machines allow parts to be machined directly from CAD (Computer Aided Design) models. This not only has the effect of reducing the cost of manufacture through saved time but it also removes the need for a trained operator to spend extended periods of time setting up and writing a “machine program” to produce the part. However this is not without its own cost, the lack of human input means there is no in-process inspection and correction of the machine tool.

A good knowledge of the machine to be used allows the designer to design parts that are of high quality and produced easily. This knowledge also allows for sensible settings to be used in the CAM (Computer Aided Manufacture) software when producing the APT (Automatically Programmed Tool) code for the CNC machine to follow. NPL explained some of the geometric errors associated when translating CAD models into CNC code. As there will always be pressure to produce parts quicker and for less cost but with many of the errors in CNC produced parts from CAD models being avoidable with a good understanding of the system as a whole, the time spent to gain this understanding will be easily recovered in the reduced scrappage of poorly produced parts.

Dynamically monitoring machine tools

As an alternative to measuring the work piece it is possible to use optical techniques to track the movement of the cutting head within the machine tool. Using these methods it is possible, with a higher level of accuracy, to calculate the size and shape of the work piece being produced. NPL addressed a list of some of the possible techniques, including static and dynamic approaches, including contact and non-contact techniques. However, these methods are not a complete solution. The conditions within a machine tool do not lend themselves well to optical measurement methods due to line of sight problems, complex heat distributions, high levels of dirt and debris and several unknown variables. The initial expense of employing a robust in-process inspection system will be offset by the savings made in removing the need for highly trained inspection personnel and a reduction in the scrapping of incorrect parts.

Thermo mechanical stability

In order to investigate the influences of the clamping force as well as the heat induced by the machining process, NPL machined and measured blocks of steel and aluminium on a milling machine. With this aim, the distances between reference spheres mounted on the workpieces were measured before and after the milling process using a 3D optical scanner. The results obtained can be used for estimating temperature-related measurement uncertainties.

Evaluation of measurement uncertainty for harmonic amplitudes for a roller measurement

Evaluation of measurement uncertainty for industrial measurements of rollers was done using Monte Carlo simulations by VTT-MIKES and REG(Aalto). REG(Aalto) brought knowledge of the error sources, industrial conditions and valuable input was also got from Rollresearch. The measurands are the harmonic amplitudes of the roundness measurement of a roller in typical industrial conditions.

The output from the Monte Carlo simulation is shown in Figure 33 and Figure 34. The first result shows clearly that the hybrid method is insensitive to a centreline movement of ±10 µm. The maximum deviation of the amplitudes was less than 0.05 µm. This is a good result but the main goal was to evaluate the uncertainties in typical industrial conditions. The assumed standard uncertainties are 0.3 µm for probe errors, 0.5° for probe alignment and 0.5 °C for temperature change. The main result is shown in Figure 34 where the different standard uncertainties are shown as error bars.

With the present assumptions the four-point hybrid algorithm works well. It is also concluded that the dominating uncertainty contribution for a four-point measurement instrument is the positioning of rods of the probes S_2 and S_3. A third result is the insensitivity to probe error. More detailed results will be submitted for publication in the journal Precision Engineering.

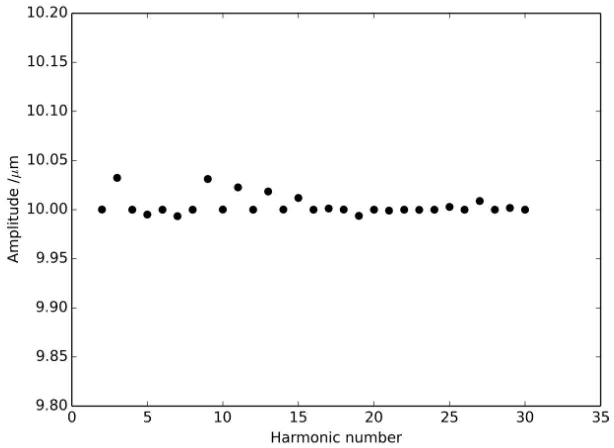


Figure 33: Output from Monte Carlo simulation with centreline movement as the only uncertainty source

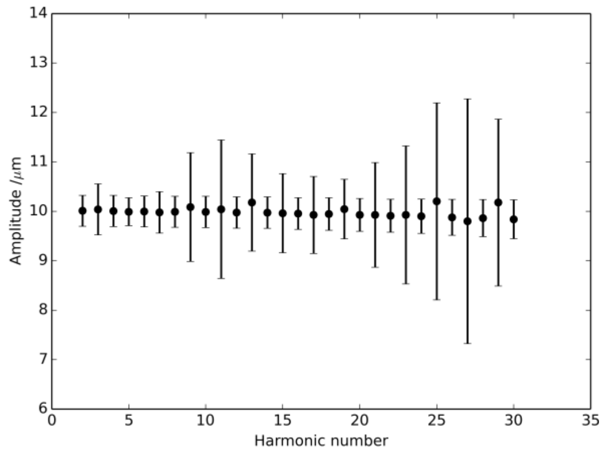


Figure 34: Output from Monte Carlo simulation showing the calculated standard uncertainties as error bars. The simulation was run with error sources representing typical industrial conditions.

Objective 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.

To demonstrate that the developed material standards and procedures are suitable for machine tool verification in a hostile environment several experiments were performed under shop-floor conditions. For these experiments the unfunded partners and collaborators such as e.g. EMO Orodjarna, Gorenje Orodjarna, and MAG IAS provided different CNC machine tools or measurement facilities. Additionally, the applicability of the climate simulation chamber to investigate the thermo-mechanical behaviour of machine tools was demonstrated.

Verification of machine tool measurement performance

Fast verification of tactile on-machine measurements

UM together with EMO Orodjarna and Gorenje Orodjarna carried out experimental measurements to verify that the ball bar is suitable for verifying the measurement performance of machine tools. The measurements were performed under three different environmental conditions (temperatures 20 °C, 22 °C, and 25 °C) on a Hermle C50 milling-centre, and under quite constant conditions (temperature 25 °C) on a Famup MC 120 milling machine at EMO Orodjarna. The main purpose of changing the environmental conditions was to demonstrate the thermal stability of the developed material standard. By means of performed measurements the fitness for purpose of the ball bar and of the developed procedure were confirmed. It was found that the ball bar is suitable for verifying machine tools with a target uncertainty U < 5 µm at various temperatures. The uncertainty that was confirmed by the calibration procedure was confirmed by tests at different ambient temperatures and with a repeatability test. Since the machine tool had built-in temperature corrections, the expansion of the standard was checked, as well. No significant expansion was observed. The length changes were within the standard deviation of repeatable measurements. Therefore, it can be confirmed that the standard can be used in harsh environmental conditions within the expected uncertainty of measurement.

Verification of optical on-machine measurements

NPL developed a procedure to assess the performance of a machine tool using the NPL TSEM/TSMU-MS prismatic material standard and a fringe projection system. This procedure does come with a caveat, that the material to be measured should be suitable for measurement using a fringe projection system. It is well known that optical contactless metrology systems do not perform well when measuring the highly shiny surfaces, which are often produced when materials are milled or cut. With this in mind, it is important to select a material that, when machined, produces an optically compliant surface for inspection with a fringe projection system. Should a non-optically compliant surface be used, or a fringe projection system is unavailable, a suitable alternative inspection tool can be employed following the same inspection and comparison procedure.

Furthermore, NPL carried out measurements in industrial type environments on machine tools using standards. The work reported is based on the industrial demonstration of the project’s outputs and the involvement of end-users in their implementation under laboratory and/or shop floor conditions. The chosen experiments demonstrate different applications using the material standards manufactured in the project. A good practice guide details worked examples relating to the measurement and analysis of data from the NPL Prismatic Dimensional Material Standard.

Identification of the geometrical errors of an industrial machine tool

LNE has used their Multi-Feature Bar (MFB) and its measurement procedure to identify the geometric errors of an industrial machine tool in shop floor conditions; to demonstrate the influence of temperature and hygrometry on machine tools and the usefulness of the MFB. Therefore the geometric errors of the same shop floor machine tool (Mikron UCP710) were determined on two different days (one in July and one in December) with a temperature spread of approximately 7°C on the shop floor. The results of the X-axis measurements are given in Figure 35 (errors as a function of the X-axis-position). The position error is given in the first row. The straightness errors in the Y- and Z- direction are given in the second row, and the rotational errors around the three axes (X->A, Y->B, Z->C) are given in the last row. These measurements obtained with different temperatures allow for the compensation of the geometric errors on the machine tool according to the evolution of the temperature in the manufacturing shop floor.

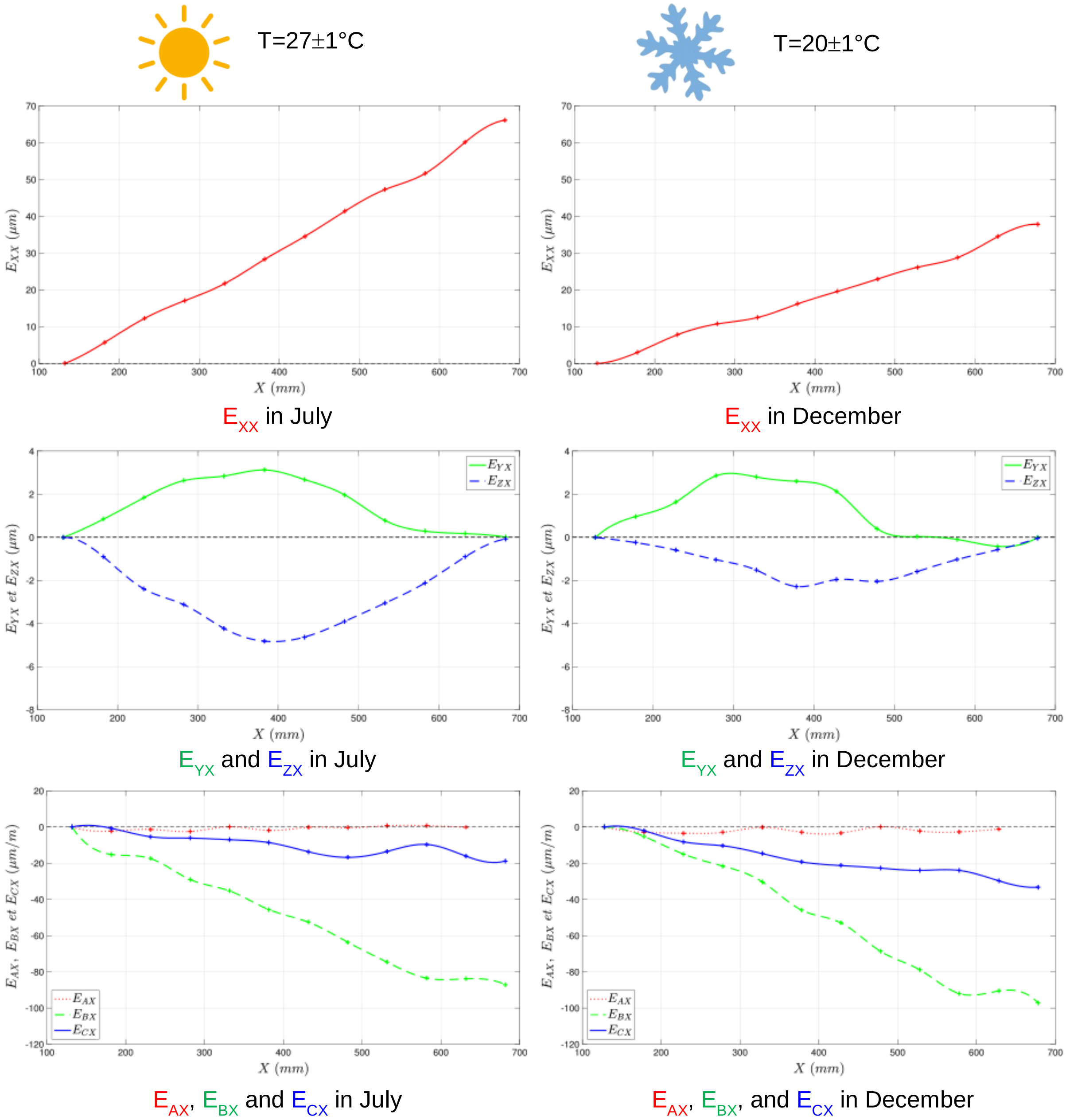


Figure 35: Impact of temperature on the extraction of the geometric errors of an industrial machine tool

Fitness for purpose assessment of on-machine measurements

If a machine tool is used for in-process measurement, the measurement accuracy of the measuring process has to be verified to be sufficient to guarantee compliance with the tolerances for the measured features. When assessing this fitness for purpose, you have to take into account that the measurement results are not only affected by kinematic errors and the environmental temperature but also by other error sources such as loads, dynamic forces, motion control and control software as well as heat sources from the machining process. In order to estimate the task-specific uncertainty for the measurement of certain features on a workpiece, such workpieces were produced and adjacently repeatedly measured on the machine tool in the same chucking by the partner MAG IAS (Figure 36). The workpieces were subsequently calibrated at PTB on a coordinate measuring machine (Figure 37). On the basis of the deviation from the calibrated values, PTB determined the task-specific measurement uncertainties for the measured features. Uncertainty contributions for the measuring process come from the repeatability and systematic errors of the machine tool measurements, and from the calibration uncertainty.

The production and measurement of the workpieces was done at environmental temperatures of 20 °C and 25 °C where again the mobile climate simulation chamber was used to generate stable environmental conditions. For both temperature levels five workpieces were produced without volumetric error correction, and another five workpieces with volumetric error correction. The comparison with the calibration values showed, that the maximal measurement uncertainty of the performed length measurements on the test workpieces could be reduced by the volumetric correction from 6 µm to 4 µm at 20 °C, and from 9 µm to 4 µm at 25 °C, respectively.

Figure 36: On-machine measurement of a workpiece replica

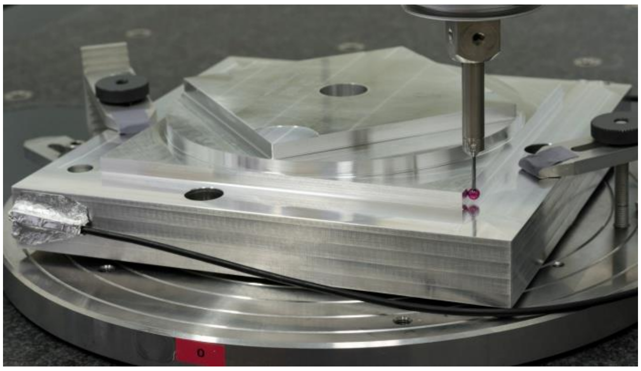
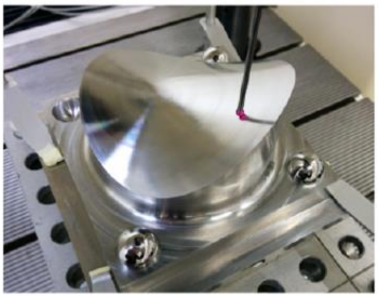


Figure 37: Calibration of a workpiece replica

With the help of the task-specific uncertainties, fitness-for-purpose can be assessed. Typically the extended measurement uncertainty of the measuring process should not exceed 15 % of a feature's specified tolerance ($U_{MP} \leq 0.15 \cdot T$). In this way, it was ensured that the measurement process on the MT is suitable for measuring the workpiece to be manufactured.

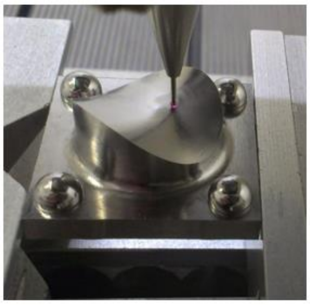
Comparison of different technologies used in freeform measurement

Three different forms of FF-MS Hyperbolic paraboloid (Figure 38) have been used in applications by CMI. The variability of standards allows us to investigate a wide range of measurement systems, e.g. the tactile measurement of surface points, tactile measurement with an active scanning probe, tactile measurement on a CNC, computer tomography, optical 3D scanner and laser scanner, see Table 2. The results obtained by CMI are summarised in Table 3.



120 mm x 120 mm x 67 mm
steel EN X10CrNi18-9

Ø 80 mm
polyurethane aluminium



30 mm x 30 mm x 15 mm
titan grade 5

Figure 38: FF-MS used in applications

Measurement technology	Measuring machine
Tactile measurement of surface points	SIP CMM 5
Tactile measurement by active scanning probe	ZEISS PRISMO
Tactile measurement on CNC	CNC Deckel Maho DMU 50+ Renishaw OMP 400
Computer tomography (CT)	Werth Tomoscope HV 500
Optical 3D scanner	ATOS Triple Scan
Laser scanner	FARO Quantum Arm+Laser Scaner V3

Table 2: Measurement technologies in FF-MS applications

	Measurement technology	Measuring machine	Measurand	Measurement uncertainty
PILOT	Tactile on CMM	SIP	Deviation of surface point from reference model	U_L = ± 1.6 µm
LAB 1	Tactile on CNC	Renishaw	Deviations of measured points from CAD	U_L = ± 1.5 µm
LAB 2	Optical 3D scanner	ATOS Triple Scan	Deviation of pilot data from STL	U_L = ± 2.8 µm
LAB 3	Laser scanner	FARO Arm	Deviation of pilot data from STL	U_L = ± 40 µm
LAB 4	Computer tomography	Werth CT	Deviation of pilot data from STL	U_L = ± 4.1 µm
LAB 5	Tactile active scanning probe	ZEISS	Deviations of measured points from calibrated CAD	U_L = ± 1.0 µm

Table 3: Comparison of different measurement technologies

Industrial roundness measurements

Tests with the manufactured calibration disc type C were carried out at three sites: with the four-point roller geometry measurement device (RollCal 3) at an industrial partner (IP), with the four-point measurement device (own model) at REG(Aalto) and with the CMM (Legex 9106) at VTT-MIKES (Figure 39). The deviation of the harmonics 3 to 30 between the different measurement devices are less the than 1 µm. The deviation of the second harmonic between the measurement devices is 1 µm and 2.3 µm (amplitude of the 2nd harmonic: VTT-MIKES 7 µm, REG(Aalto) 8.1 µm and IP 9.3 µm). The cause for this could be tracked down to the coupling between the disc and its shaft. A cure for this has already been designed and manufactured.

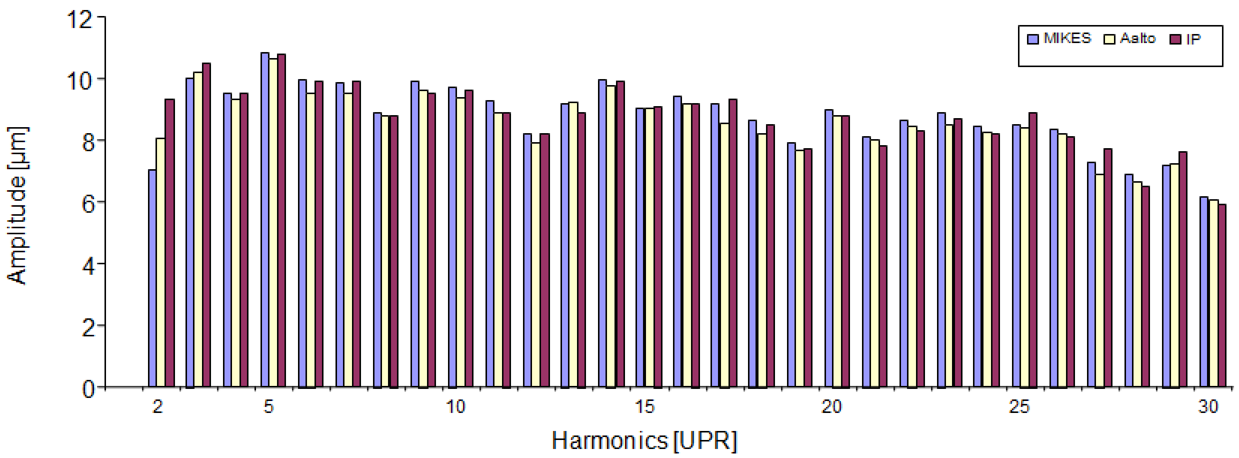


Figure 39: Comparison of the measurement results of the harmonics of the calibration disc type C made at three different sites

Summary and conclusions

- An exemplary set of thermally invariant material transfer standards for the verification and error mapping of machine tools has been fully developed and successfully produced. Although reference standards for machine tools have been previously used, the design of the standards that have been manufactured within this project are unique as they are designed to access manufacturing errors when complex forms are being machined in hostile environments.

- Procedures for checking machine tool accuracy as well as for ensuring reliable and traceable on-machine measurements were developed. They comprise procedures for:
  - Mapping the geometric errors of the linear axes using the developed Multi-Feature Bar
  - Fast machine tool verification using the developed ball-bar
  - Volumetric error mapping
  - Assessing task-specific measurement uncertainties as well as fitness-for-purpose of tactile on-machine measurements using a workpiece replica material standard
  - Verification of area-scanning on-board metrology systems using the developed freeform material standard
  - Evaluation of the measurement uncertainty for harmonic amplitudes for roundness measurements. This procedure led to the first task-specific uncertainty evaluation ever done in industrial roller measurements.

- The applicability of the developed material standards and procedures under harsh environmental conditions was verified by several measurements carried out under shop floor conditions.

- With the design and assembly of the mobile climate simulation chamber a system is now available for the systematic determination of thermal influences on the shop floor. Its industrial use is made possible by its modular structure relating to the wall elements and additionally purchased coldwater pipes that allow the flexible placement of the heat exchanging elements according to the boundary conditions on the shop floor or outside of it.

4 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.

5 Website address and contact details

A public website is available at: www.ptb.de/emrp/tim.html

The contact person for general questions about the project is Klaus Wendt, Dr.-Ing. (klaus.wendt@ptb.de).

6 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**.