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Traceability of on-machine measurements under a wide range of working conditions

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Traceable in-process dimensional measurement (IND 62 TIM)

Workshop, Braunschweig

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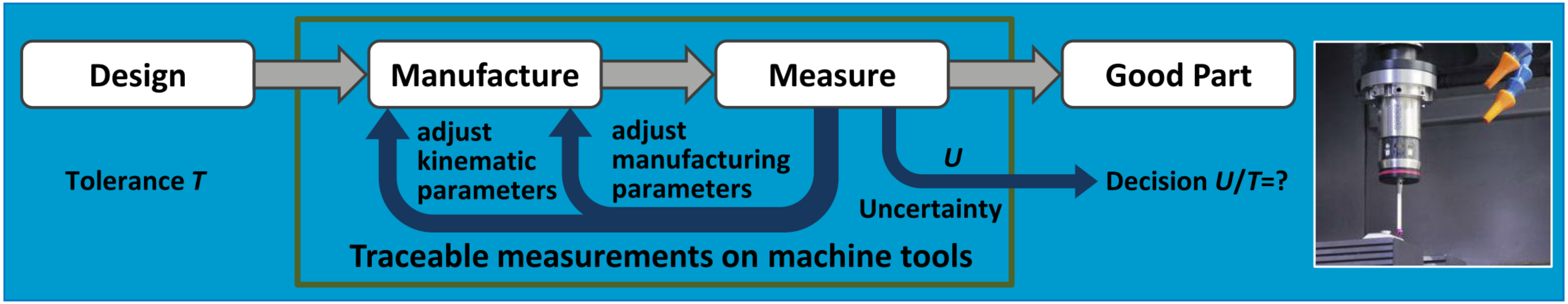
Introduction

Motivation: In-process measurement

→ Machining and measurement should take place on the same machine tool (MT)

- Need reliable and traceable measurements on MTs
  - Single part production:
    → Compensation of volumetric errors of the MT for higher accuracy
    → Task-specific measurement uncertainty e.g. via Monte-Carlo simulation
  - Serial production:
    → Task-specific uncertainty can be determined by calibrated artefacts
    → Task-specific error correction possible

→ Reliable and traceable measurements of workpieces in one and the same clamping on machine tools



Overview

- Simulation of environmental temperatures with the help of a mobile climate simulation chamber
- Measurement of the volumetric errors of a 5-axes machine tool with the help of a tracking laser interferometer
- Determination of thermally induced changes in a machine tool’s geometry
- Volumetric error correction and measurement of residual errors of a machine tool
- Establishment of an uncertainty budget for on-machine measurements using test workpieces
- Assessing the fitness for purpose of on-machine measurements

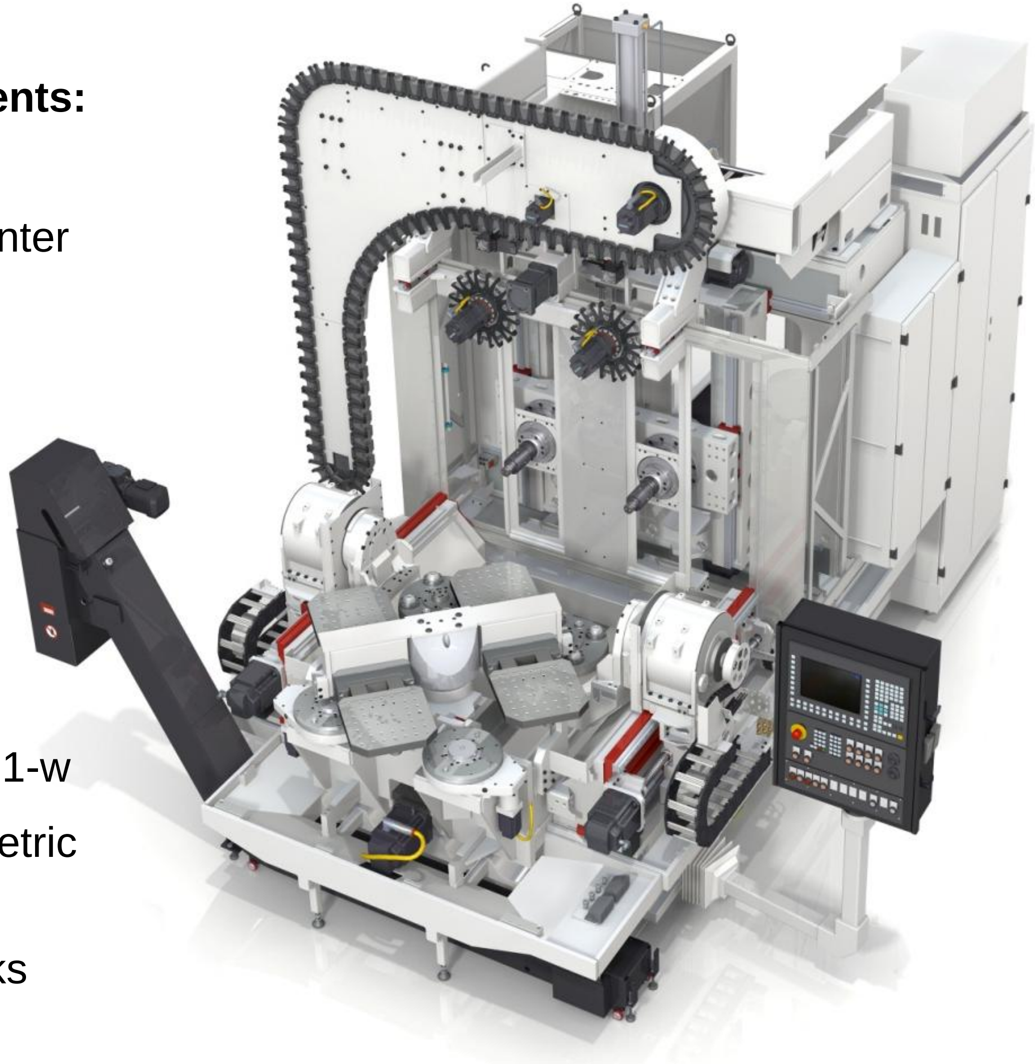
Climate simulation chamber

- 5 x 10 x 6 m^3 (H x L x W)
- Range: 15 to 45 °C
- Inhomogeneity: Up to 2 K (vertical)
- Stability: ± 0.5 K (system oscillation)

Machine tool: MAG SPECHT 500 DUO+

Machine tool used for the measurements:

- Horizontal dual-spindle machining center
- Three linear axes X, Y, Z
- Three rotational axes A, B1, B2
  (only A and B1 were used)
- Two working spindles S1, S2
  (only S1 was used)
- Working volume:
  630 mm x 730 mm x 860 mm
- Kinematic chain: t1-(C1)-Y-X-b-Z-A-B1-w
- Fanuc controller, with ability of volumetric error correction
- Application: Machining of motor blocks



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Temperature profile

Mapping of the volumetric errors of the MT at the temperatures:

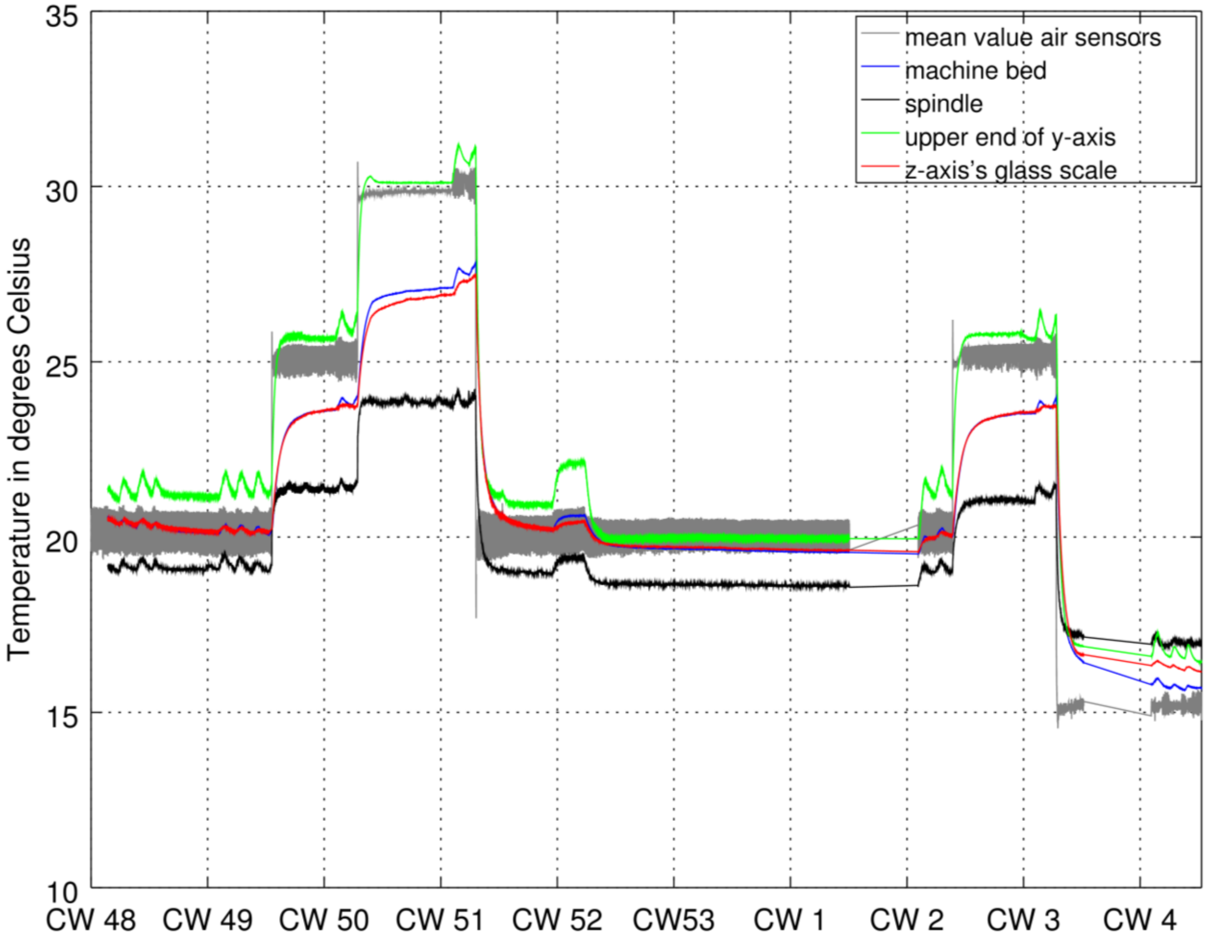
- 15 °C
- 20 °C
- 25 °C
- 30 °C

Mapping of residual errors:

- 20 °C
- 25 °C

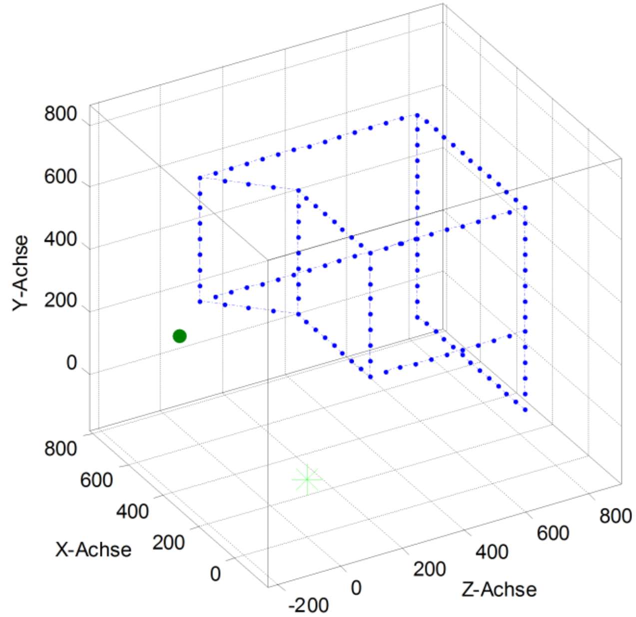
Production of test workpieces:

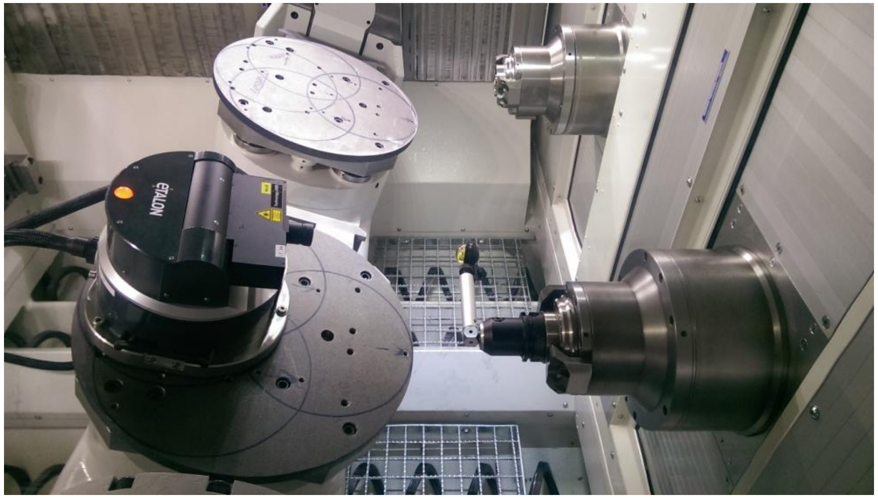
- 20 °C
- 25 °C

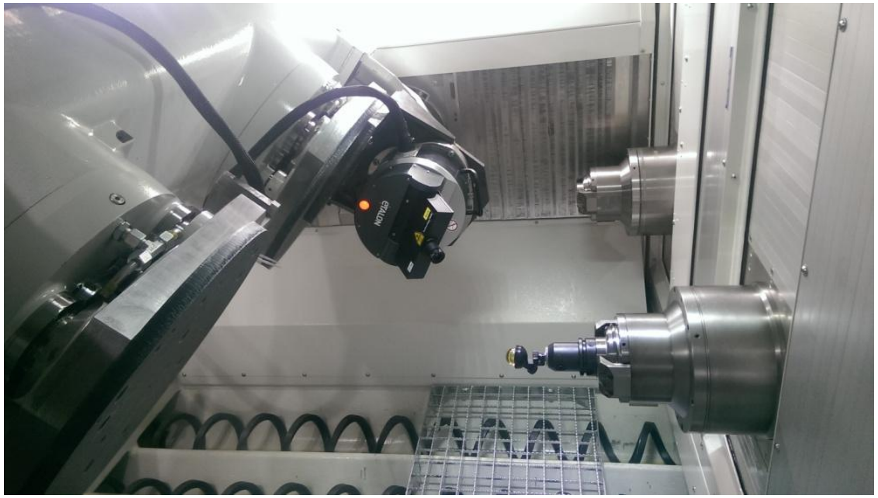


Procedure for mapping geometric errors

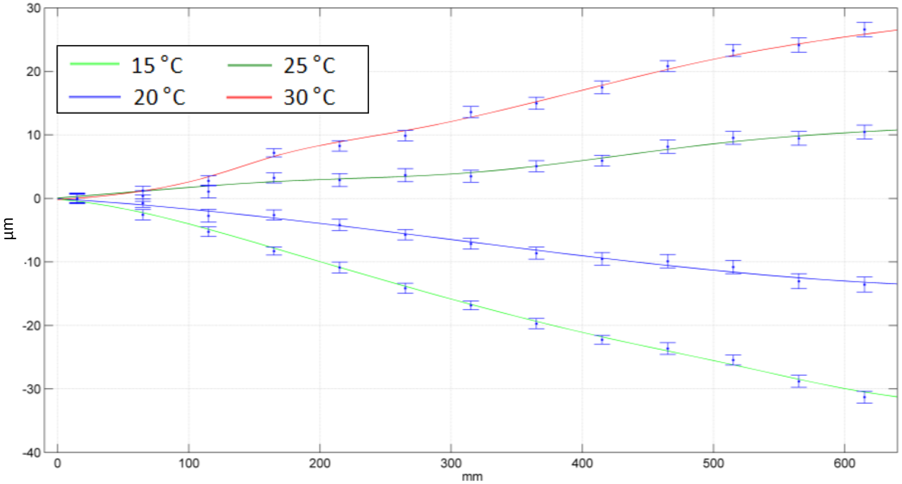
- Determination of volumetric errors via sequential multi-lateration using laser measurements
- Rigid body error model according to ISO 230-1
- 21 parametric errors for the three linear axes
- 20 parametric errors for the two rotational axes
- Estimation of uncertainties by Monte-Carlo simulation
- Calculation of a 3d-correction table for discrete grid points in the working volume



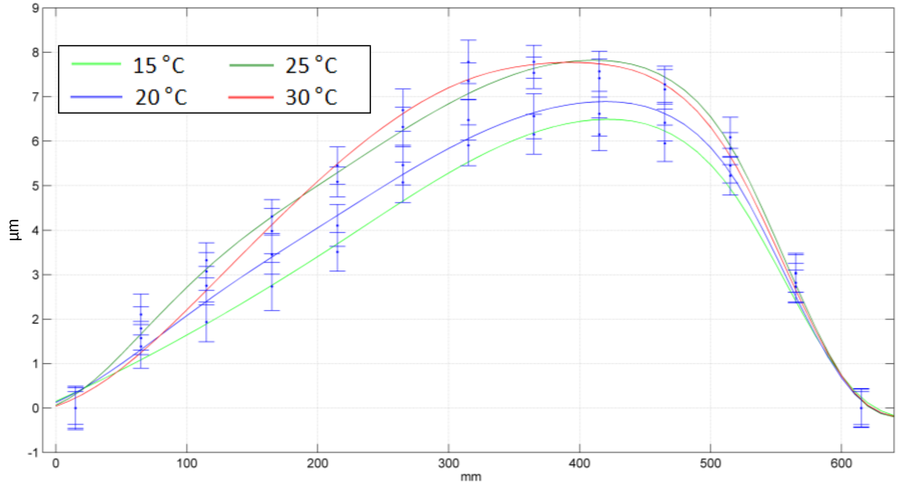




Volumetric error mapping: Results



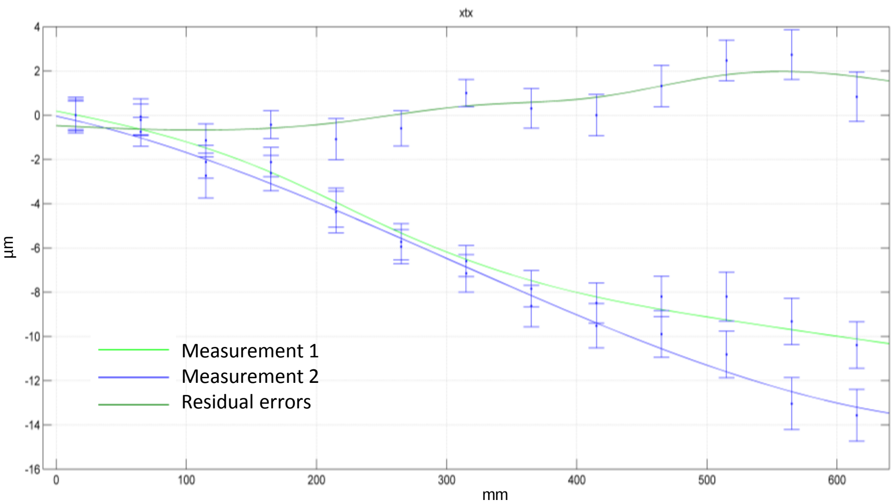
Positioning error E_{XX} of x-axis



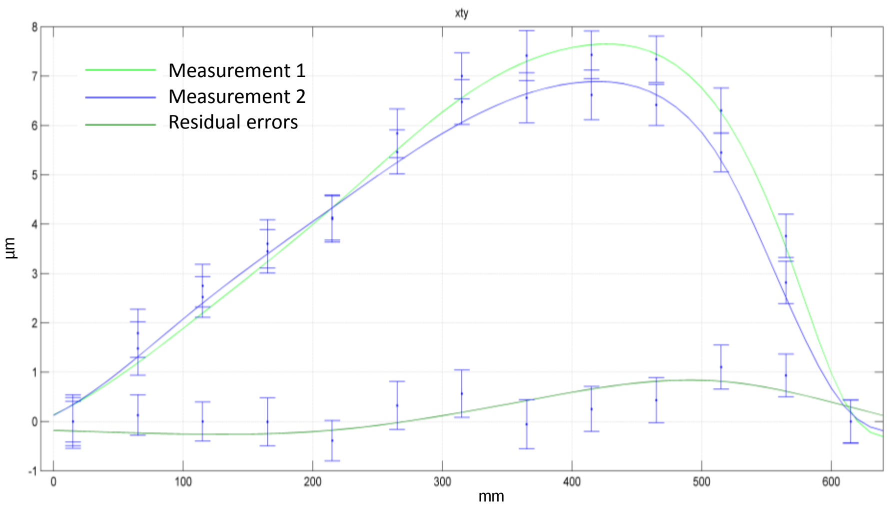
Straightness error E_{YX} of x-axis in y-axis direction

- Geometry errors vary with temperature
- Position and squareness errors are dominant errors and strongly affected by temperature effects
- Position errors are mainly influenced by thermal expansion of glass scales
- Straightness and rotational errors are less prone to temperature effects

Volumetric error compensation for 20 °C



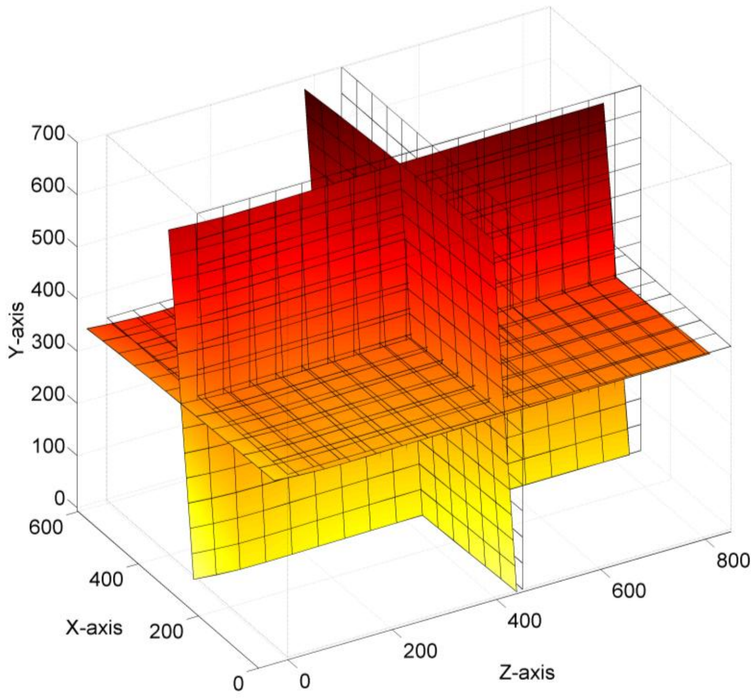
Positioning error E_{XX} of x-axis



Straightness error E_{YX} of x-axis in y-axis direction

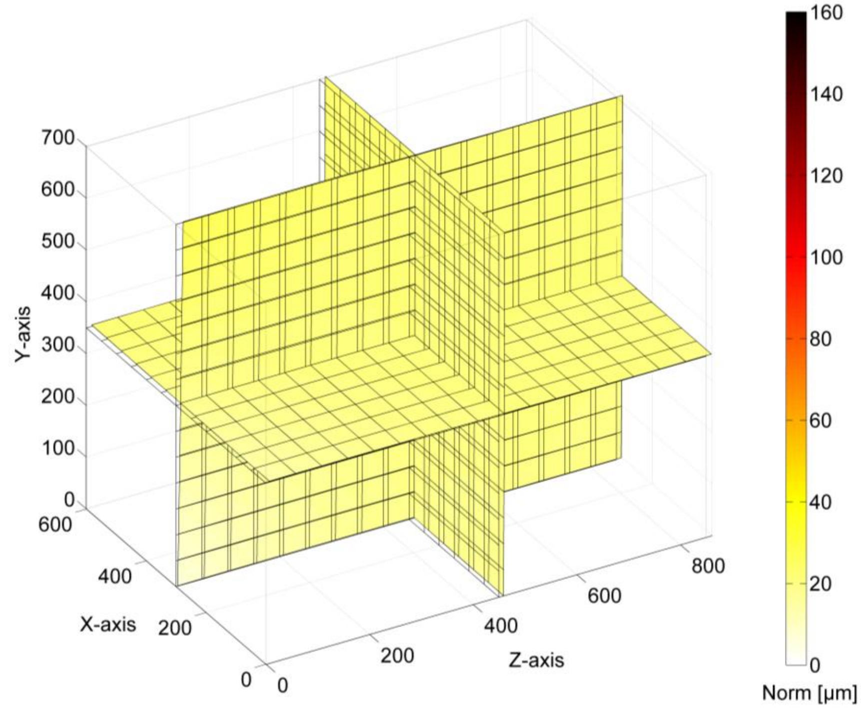
- Volumetric error correction could be validated
- Residual errors are still present:
  - Rigid body error model not completely fulfilled
  - Hysteresis effects
  - Environmental temperature and MT temperature not completely stable
  - Temperature in the working volume not exactly known

Volumetric error compensation for 20 °C



Without volumetric compensation

Squareness and position errors are dominant.



With volumetric compensation

Maximum error could be reduced by 80 %. (from about 150 µm to 30 µm)

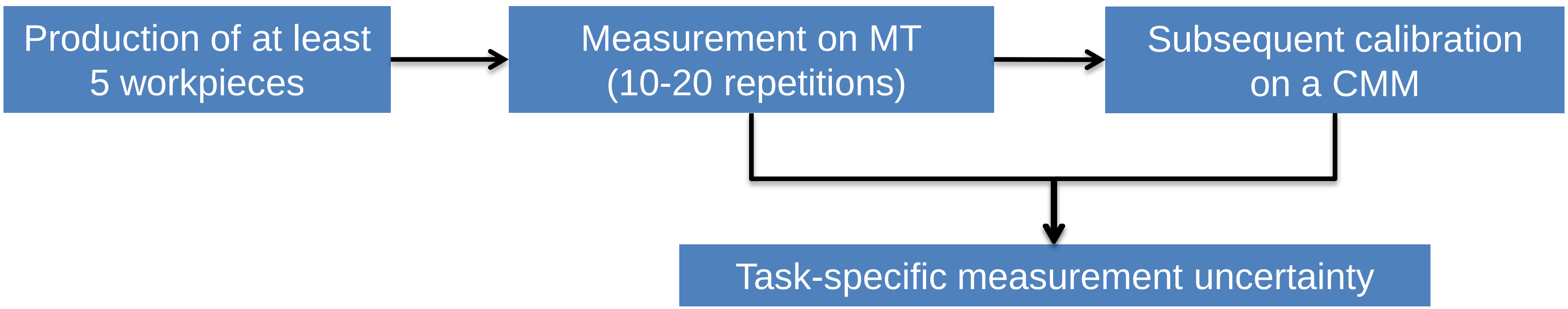
Fitness for purpose

Situation

- Workpiece is produced and measured on a MT
- Is the measurement on the machine tool capable to ensure for the workpiece the compliance of the tolerances?
- E.g. VDA 5: $U_{MP} \leq 0.15 \cdot Tol$

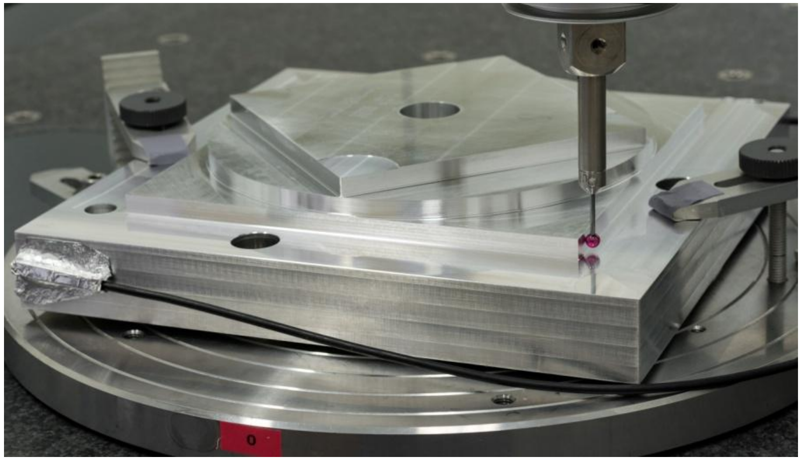
Strategy to determine task-specific uncertainties for serial production

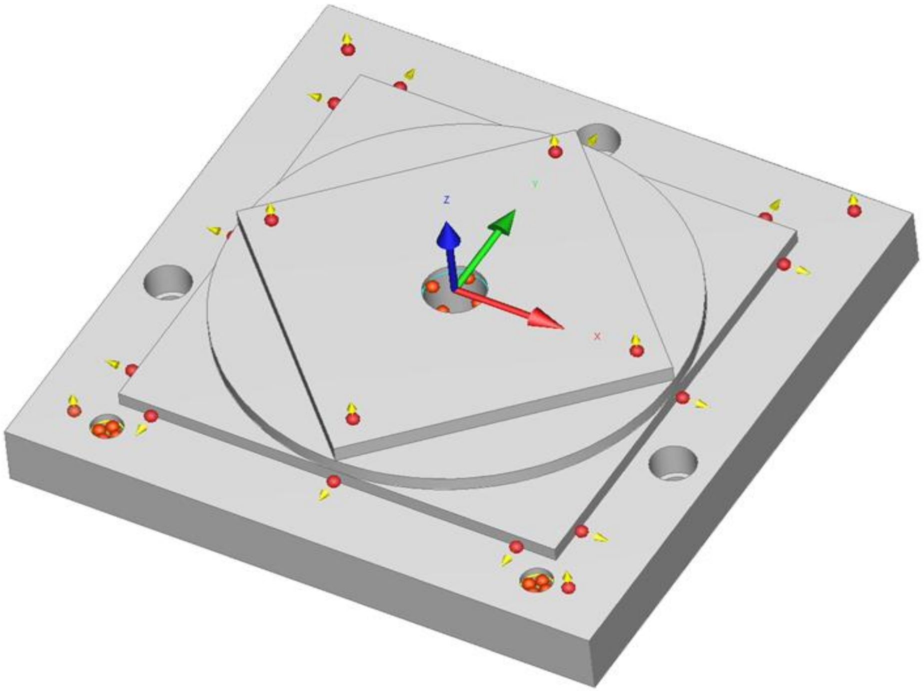
- Same measurement task for many parts in serial production
- Use calibrated workpieces
- ISO 15530-3 / VDA 5.1

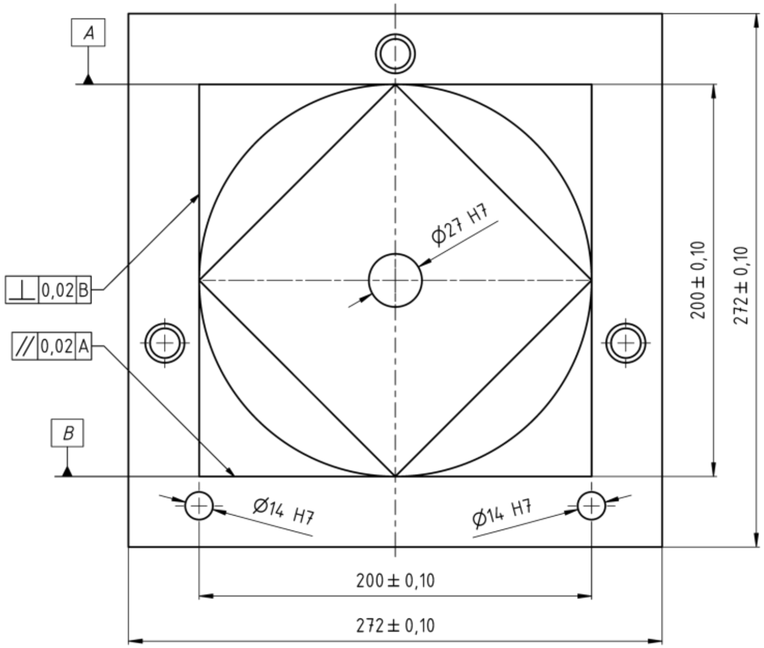


Workpiece replica material standard (WR-MS)

- WR-MS should allow typical measurement tasks normally performed on the MT
- Machining and measurements are done for two temperature levels (20°C, and 25°C)
- Without and with volumetric correction of the machine tool







Task-specific measurement uncertainty

- Manufacture a workpiece on the MT
- Repeat measurements on the MT N times ($N \geq 10$)

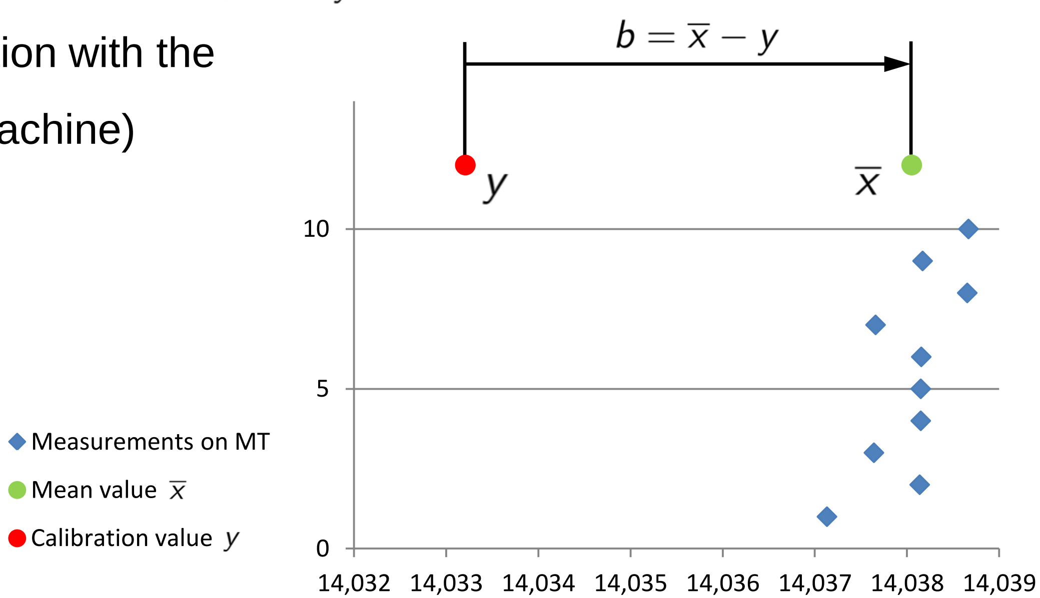
  → Get measurement results $x_1, x_2, \ldots, x_N$

  → Mean value $\overline{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$ and standard deviation $u_x = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \overline{x})^2}$
- Calibrate workpiece on a CMM

  → Calibration value and standard uncertainty: $y \pm u_y$

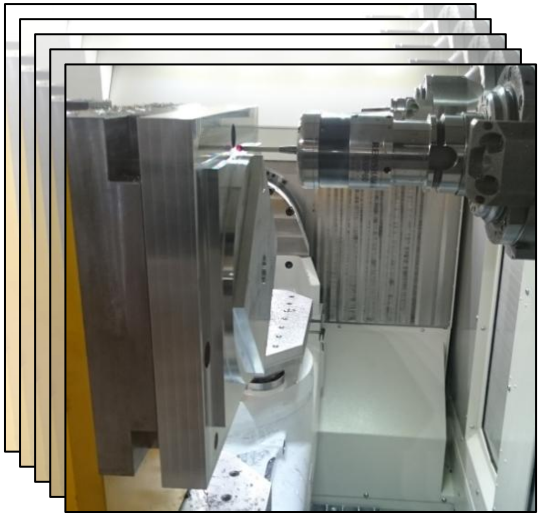
  (u_y was calculated by a simulation with the Virtual Coordinate Measuring Machine)

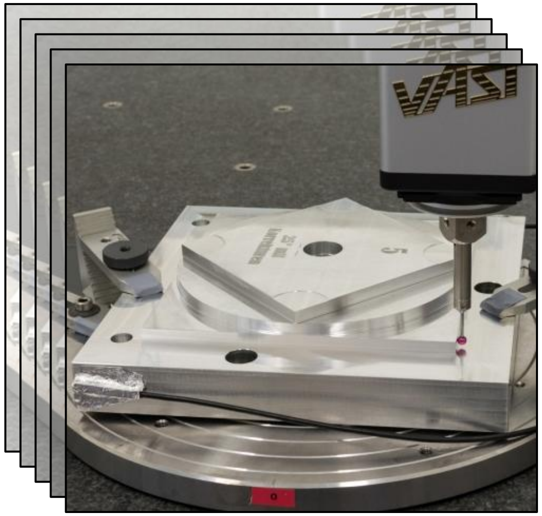
  → Systematic error: $b = \overline{x} - y$

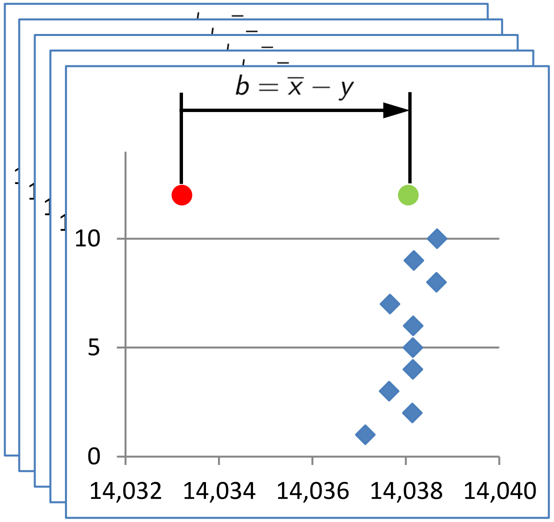


Task-specific measurement uncertainty

- Production and measurement of M parts $(M \geq 5) \longrightarrow \; \overline{x}_j,\; u_{x_j}\; y_j\; u_{y_j},\; b_j$ for $j = 1, 2, \ldots, M$







$$u_x = \max_{j=1\ldots M}(u_{x_j})$$

$$u_y = \max_{j=1\ldots M}(u_{y_j})$$

$$u_b = \frac{1}{\sqrt{12}}\left(\max_{j=1\ldots M} b_j - \min_{j=1\ldots M} b_j\right)$$

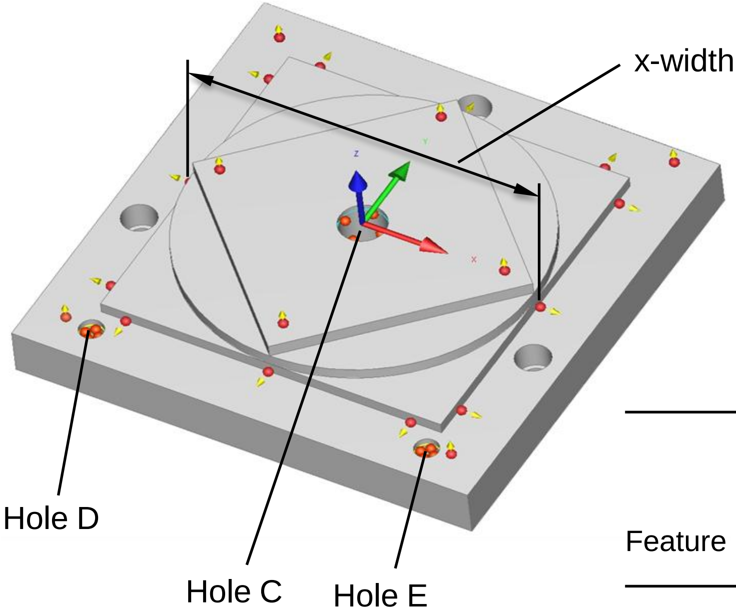
$$\overline{b} = \frac{1}{M}\sum_{j=1}^{M} b_j$$

Result for a measurement on the machine tool with measured value x:

$$x_{cor} = x - \overline{b}$$

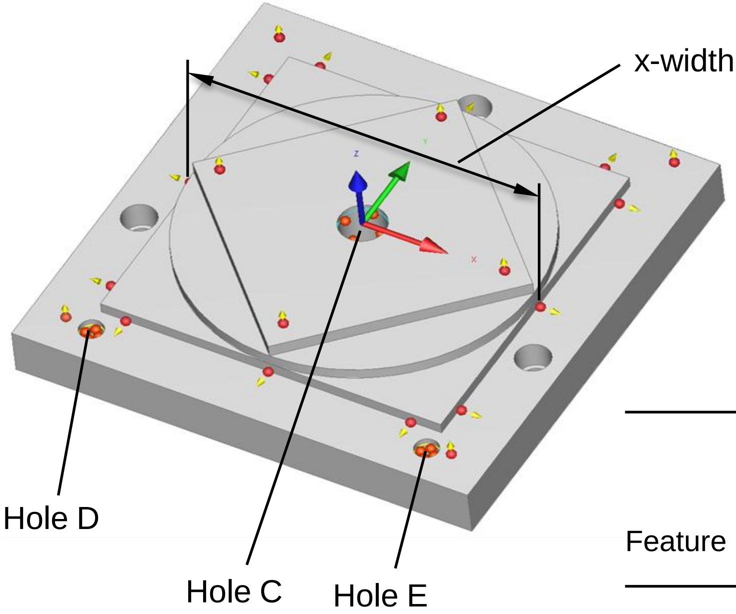
$$U_x = 2\sqrt{u_x^2 + u_y^2 + u_b^2}$$

Results: Task-specific measurement uncertainty



Feature	Nominal value [mm]	Tolerance *Tol* [µm]	*U* [µm]			
			20 °C, uncorrected	20 °C, corrected	25 °C, uncorrected	25 °C, corrected
x-width	202.5	200	5.5	3.7	7.4	4.4
y-width	202.5	200	5.5	3.8	6.0	5.3
Diameter C	27.0	21	2.8	3.0	5.3	3.1
Diameter D	14.0	18	1.7	2.0	1.9	2.0
Diameter E	14.0	18	2.0	2.3	3.3	2.2
Distance D-E	200.0	200	5.3	3.5	8.8	3.7
y-position D	-115.0	200	4.7	6.1	7.5	4.1
y-position E	-115.0	200	5.1	4.3	4.3	4.1

Results: Fitness for purpose



Feature	Nominal value [mm]	Tolerance Tol [µm]	$Q = \frac{U}{Tol} [\%]$ 20 °C, uncorrected	20 °C, corrected	25 °C, uncorrected	25 °C, corrected
x-width	202.5	200	2.8	1.9	3.7	2.2
y-width	202.5	200	2.8	1.9	3.0	2.7
Diameter C	27.0	21	13.3	14.3	25.2	14.8
Diameter D	14.0	18	9.4	11.1	10.6	11.1
Diameter E	14.0	18	11.1	12.8	18.3	12.2
Distance D-E	200.0	200	2.7	1.8	4.4	1.9
y-position D	-115.0	200	2.4	3.1	3.8	2.1
y-position E	-115.0	200	2.6	2.2	2.2	2.1

Summary

- Measurement of volumetric errors of a 5-axes MT under different, controlled environmental temperatures
- Monitoring the temperature dependent change of a MT geometry
- Measurement of residual errors
- Verification of temperature dependent volumetric error correction
- Determination of task-specific error correction and measurement uncertainty by the use of calibrated workpieces
- Assessing fitness for purpose for features of a test workpiece
- Demonstration of the general measurement capability of a MT

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