Challenges and Solutions for Thermal Compensation of Machine Tools

EUSPEN SIG 2024 Eindhoven

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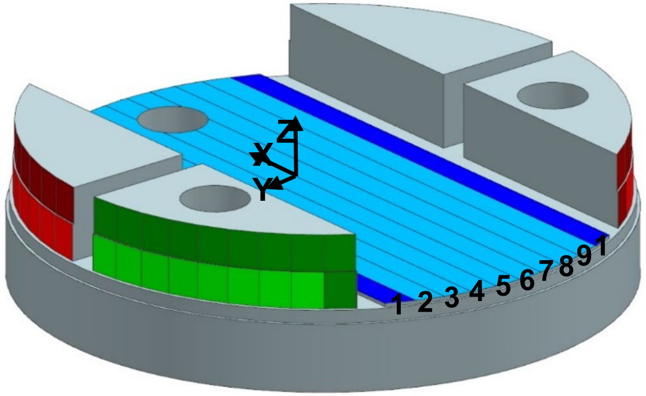
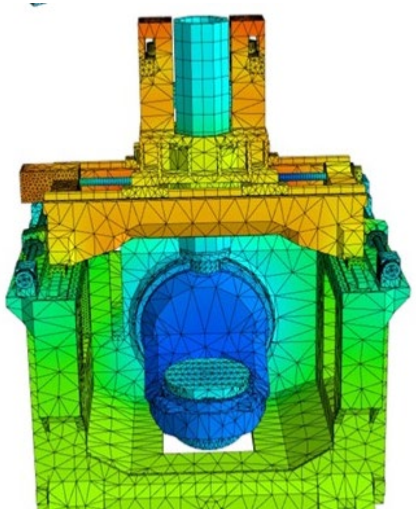
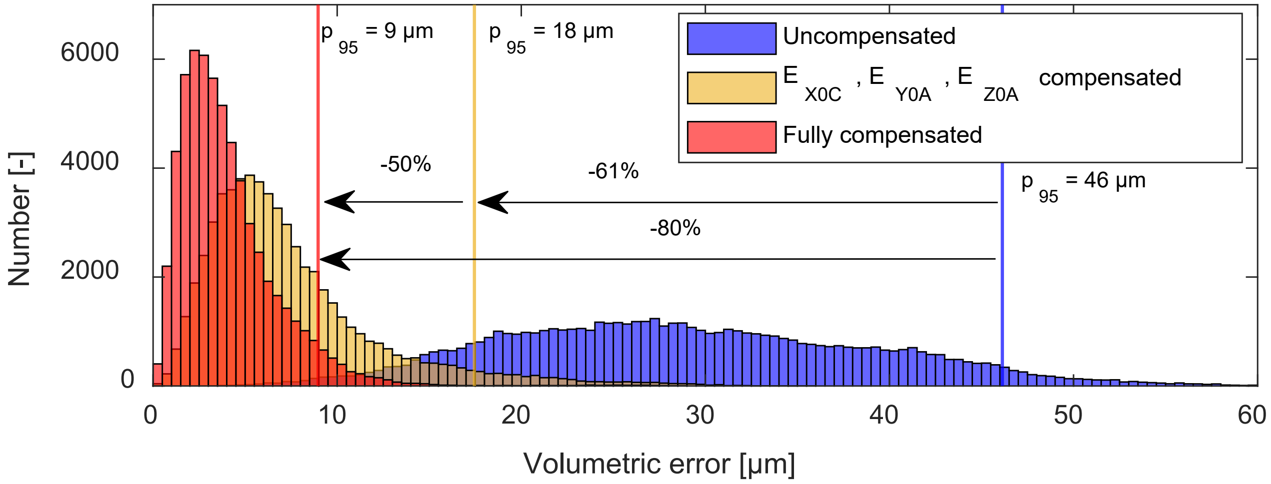
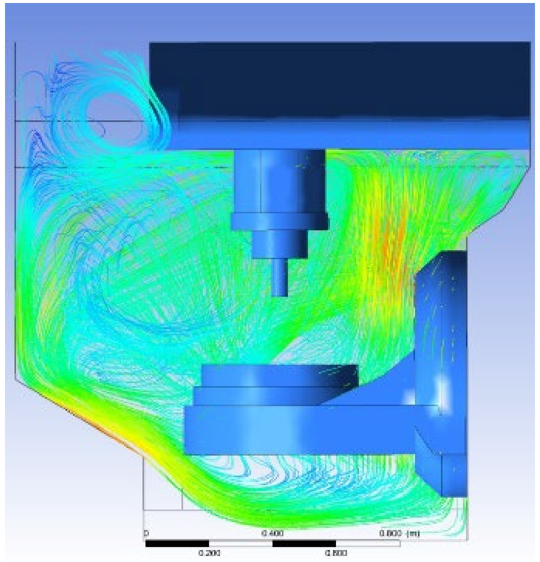
14.03.2024

- Introduction
- Cooling aspects – fluidic topics
- Thermal compensation of different machine tools
- Thermal behavior in cutting operation
- Federated learning of thermal behavior
- Conclusion



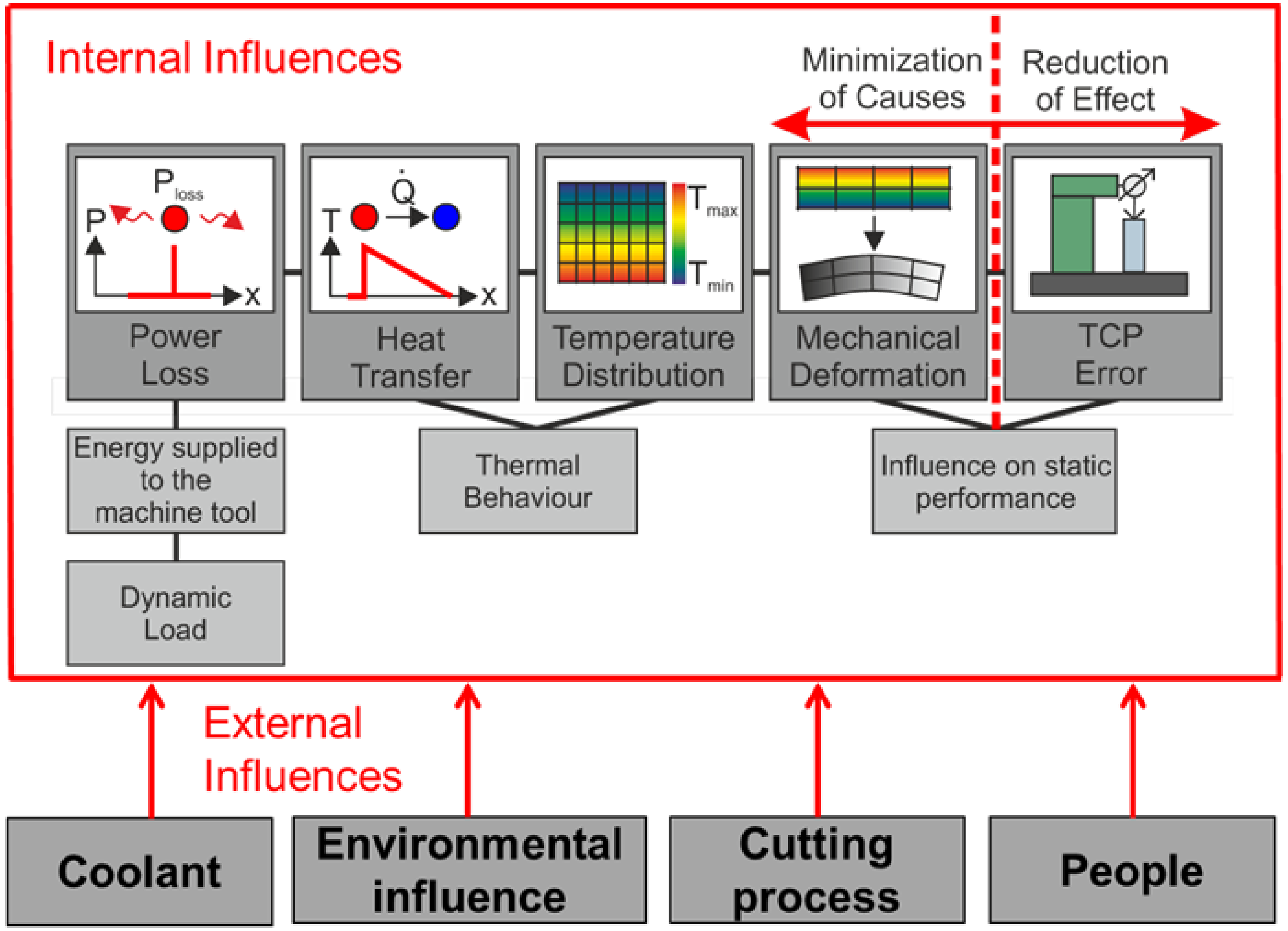






Thermal influences on machine tools

inspire



Standard regarding thermal issues:

ISO 230-3:2020 → Environment

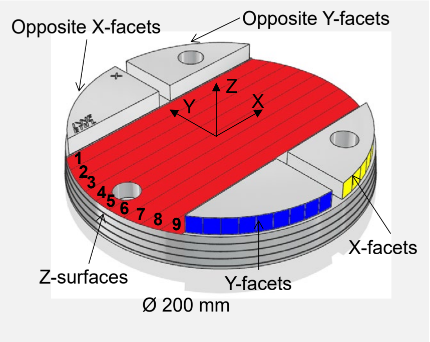
→ Spindle

→ Linear Axis

→ Rotary Axis

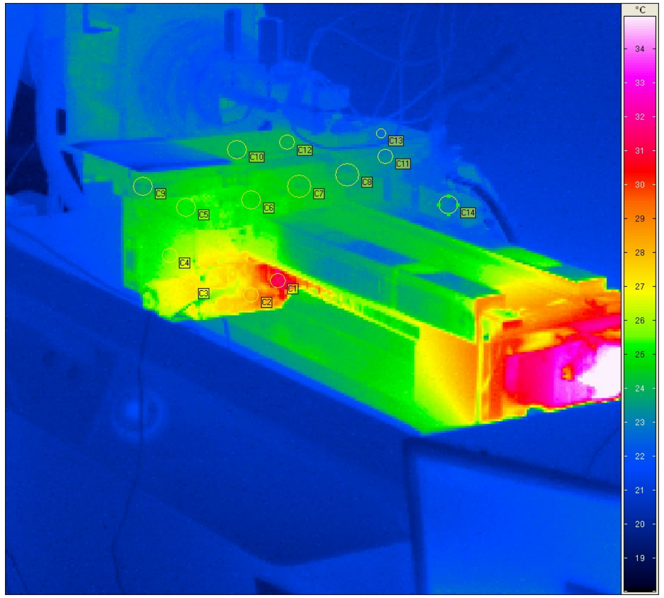
Standard regardin

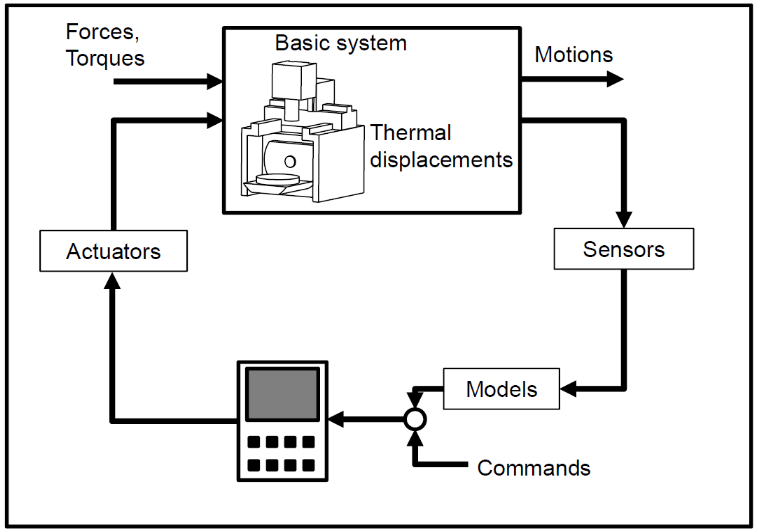
ISO 10791-10:2022: →

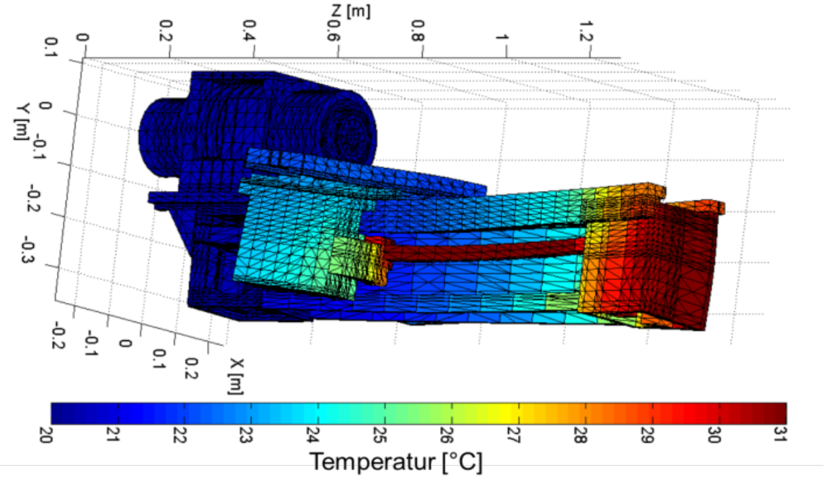


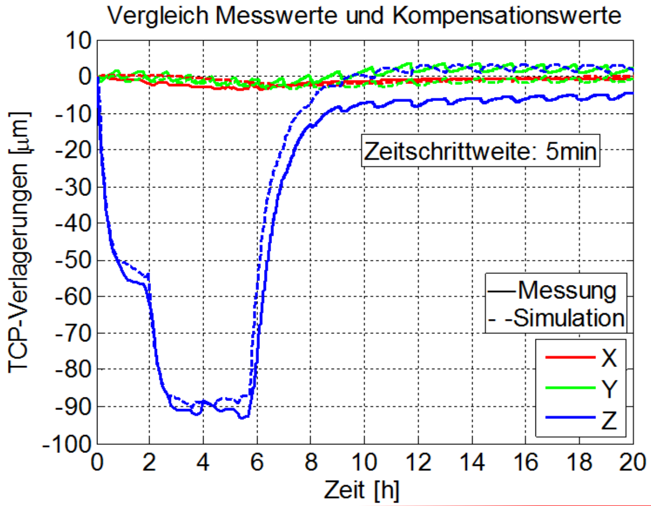
Compensation
Motivation for thermal compensation

- Conventional view: Resource based
  - Thermal stability can only be reached with cooling and air conditioning
  - Enhancement of work piece accuracy and yield only with warm up cycles
    ➔ energetic efforts necessary
- Advanced view: Knowledge based
  - Optimization of work piece accuracy without additional utilization of energy
  - Countermeasures by control and existing actuators
  - Mastering of thermal behaviour (knowledge based)
- Combination of accuracy and sustainability: **don’t move heat around**









Thermal compensation strategies

Sensor technology	Modelling	Actuator Technology
NC-program	Physical field equations	Cooling, heating
Power intake of components	Reduced physical field equations	Axes of machine
Temperature measurements	Thermobalance models	Additional axes
Elongation measurements	Phenomenological models	
Position measurements	AI approach, neural networks	

Challenges and Solutions for Thermal Compensation of Machine Tools

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- **Cooling aspects – fluidic topics**
- Thermal compensation of different machine tools
- Thermal behavior in cutting operation
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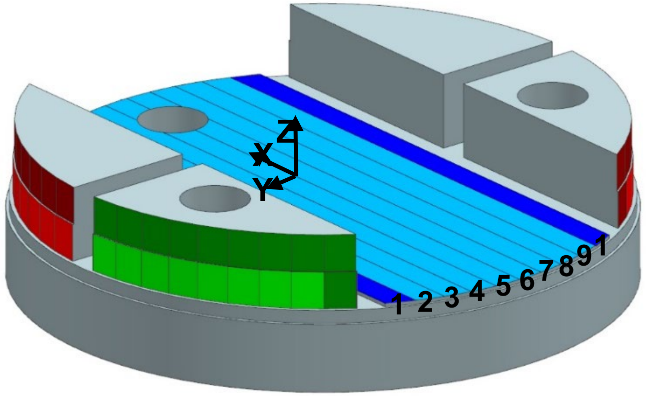
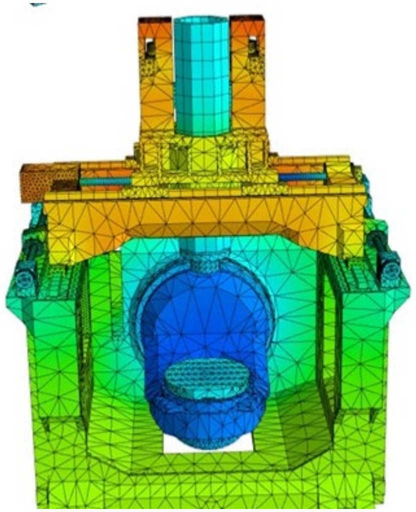
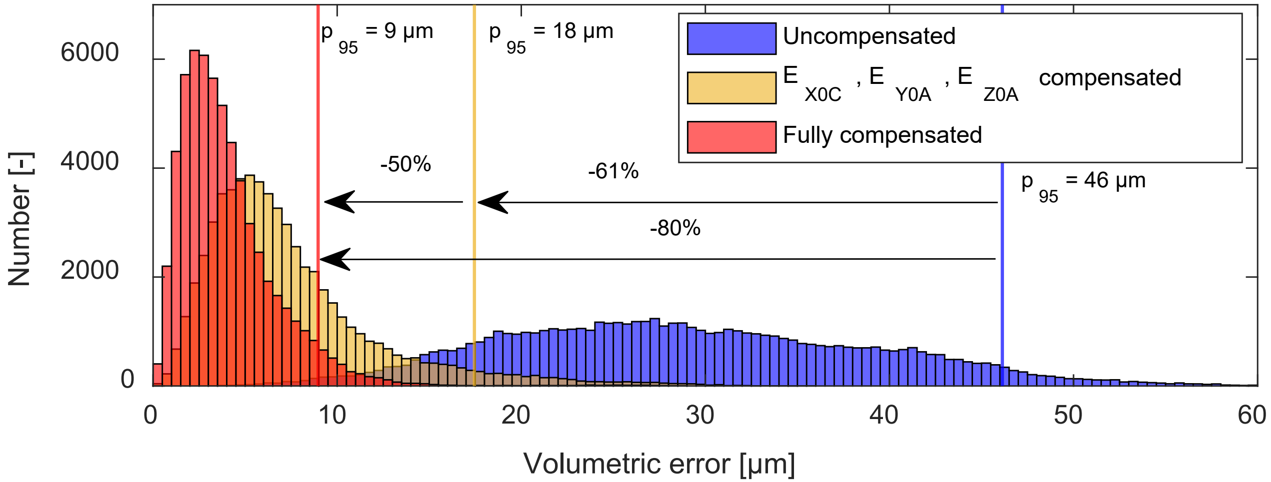
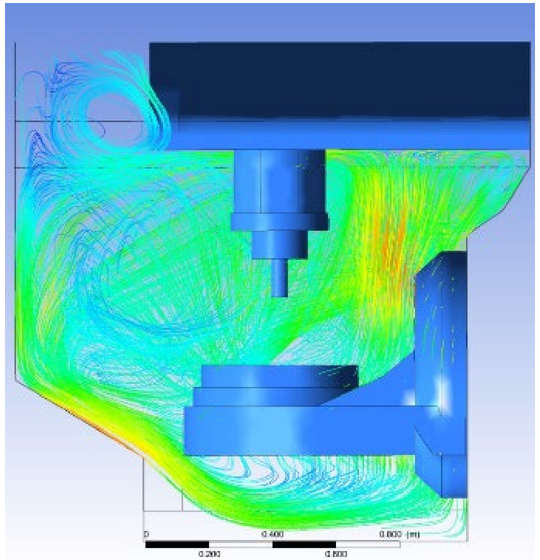
- Conclusion







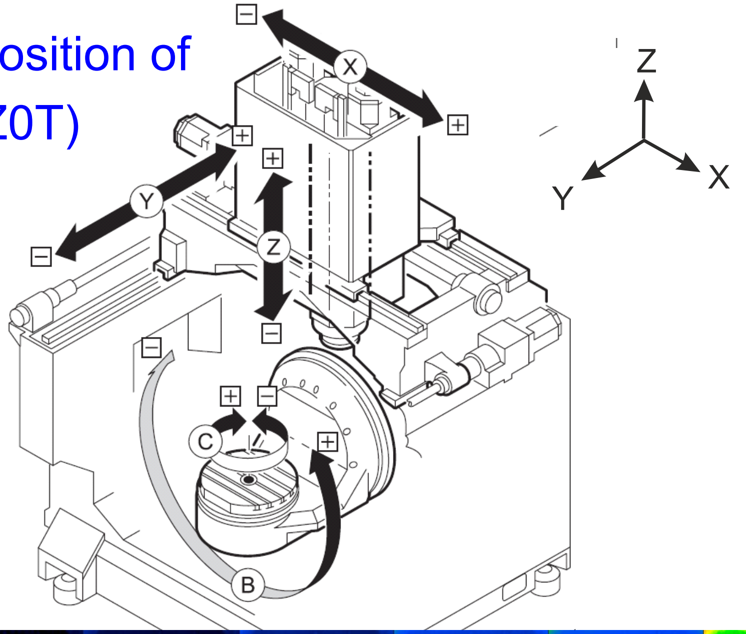


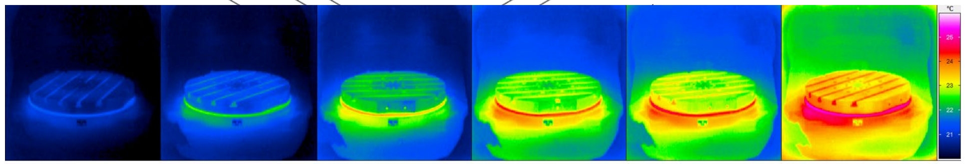
ETH zürich

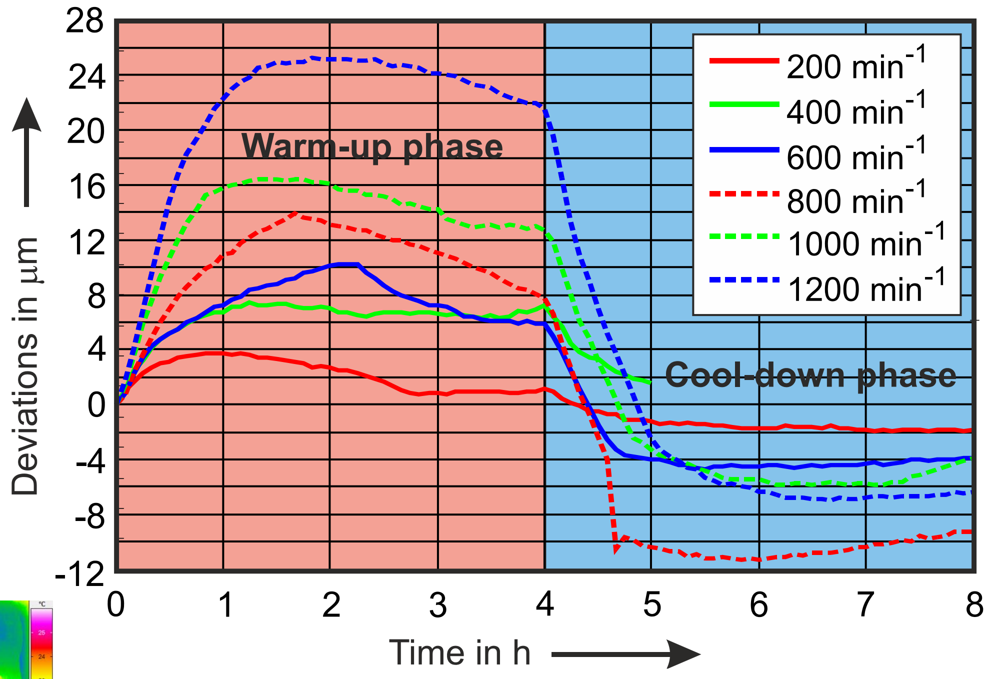
IWF
Institut für Werkzeugmaschinen und Fertigung
Institute of Machine Tools and Manufacturing

Influence of rotary axes: example

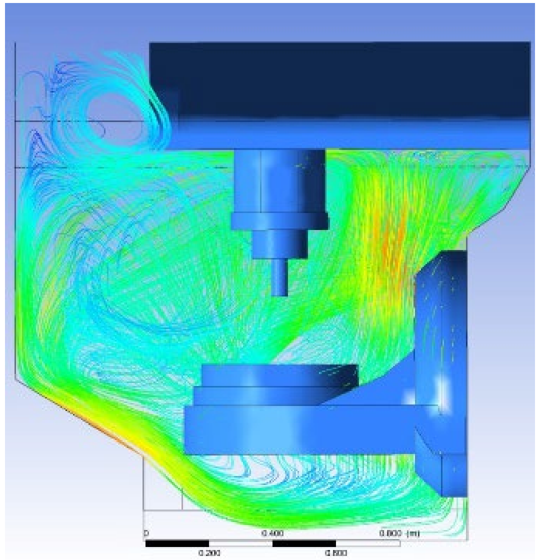
Z-Position of T (Z0T)



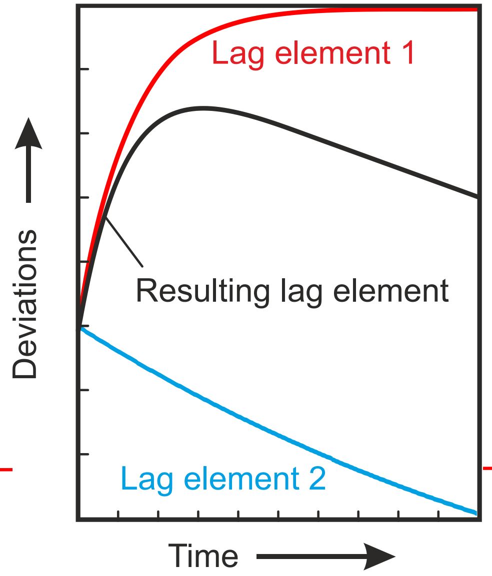

t=5 min t=10 min t=60 min t=100 min t=180 min t=240 min



- Measurement of location errors at 6 different rotational speeds
- 4h warm up phase / 4h cool down phase



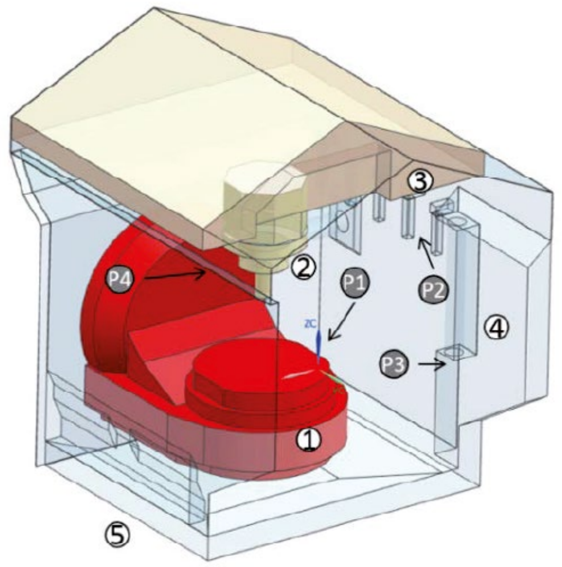
- Combination of two lag elements
- Heterogeneous heat input causes bimetal effect
- Heat conduction in the structure leads to a homogenization of the temperature contribution (lag element 2)
- Decrease of the thermally induced error



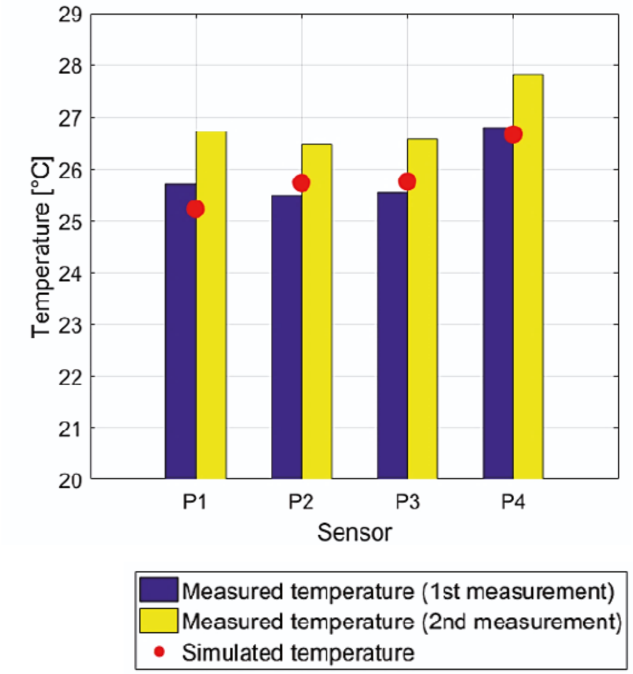
2nd lag element is the influenced by convective heating of the spindle

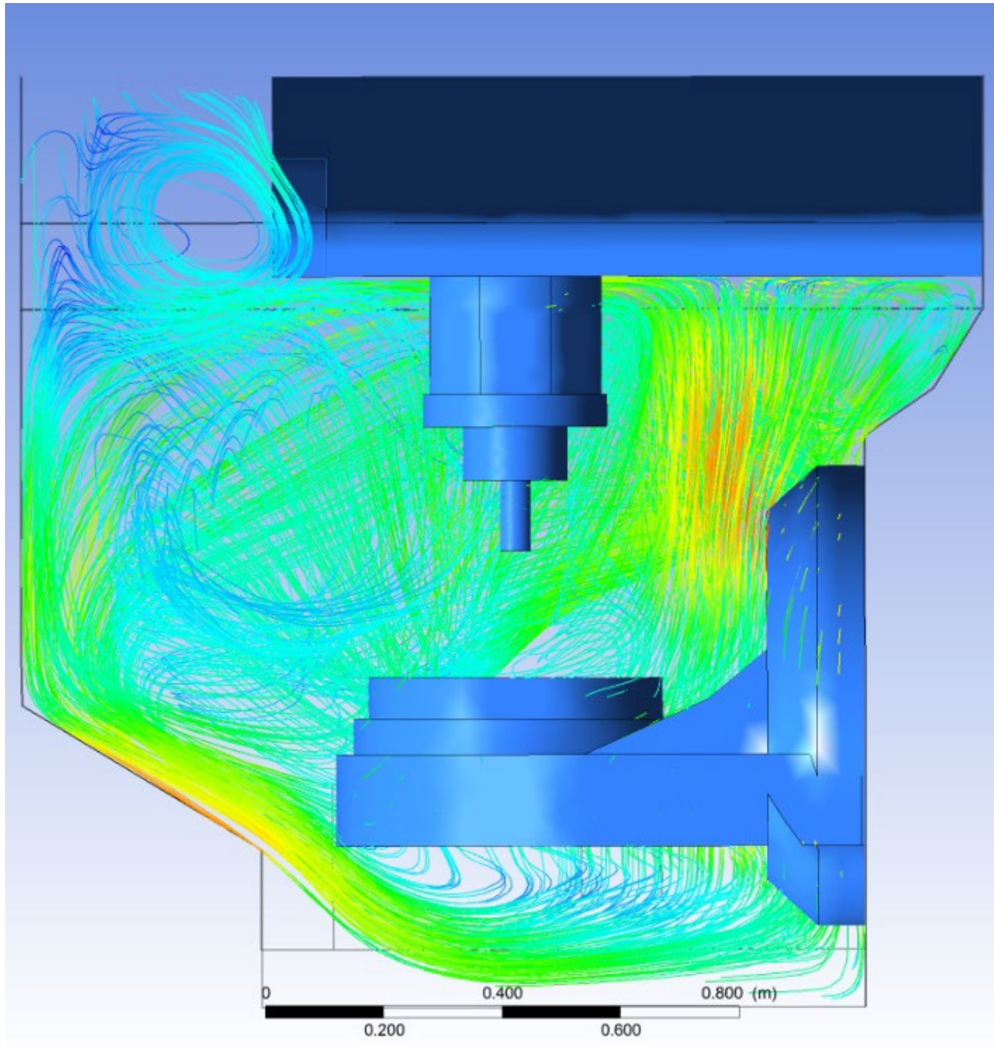
CFD simulation of enclosures: 5-axis machine tool

- CFD simulation of air flow due to convection inside a machine tool enclosure
- Heat generation with C-axis rotation and temperature measurement on wall of enclosure
- Understanding of the machine behavior only possible with fluiddynamics influence (aerodynamic and coolant)
- Sensor placement by CFD



P1, P2, P3, P4: temperature sensors

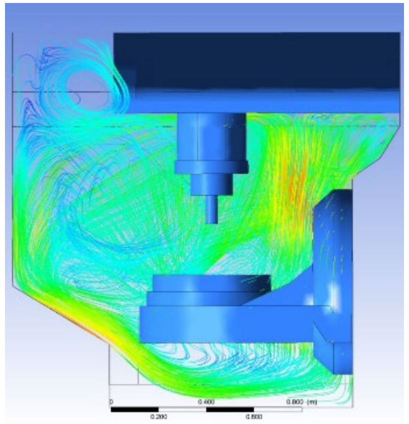


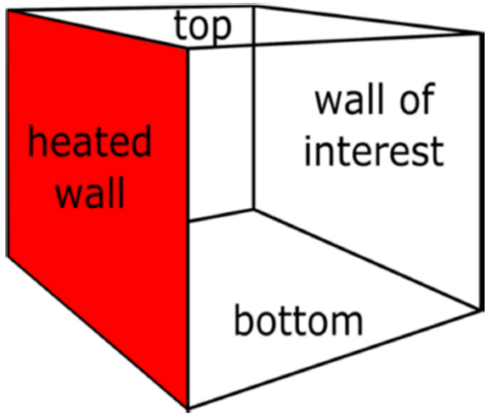


Fluidic topics
Meta models for hollow spaces in machine tools

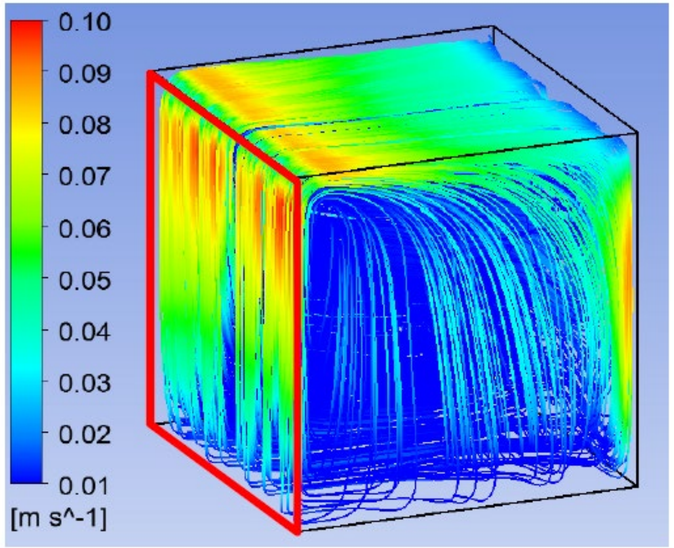
- Naked machine tools behave different than enclosed ones
- Realistic boundary conditions required
- Efficient way to calculate the heat transfer coefficient *h* in an enclosure without doing CFD simulations

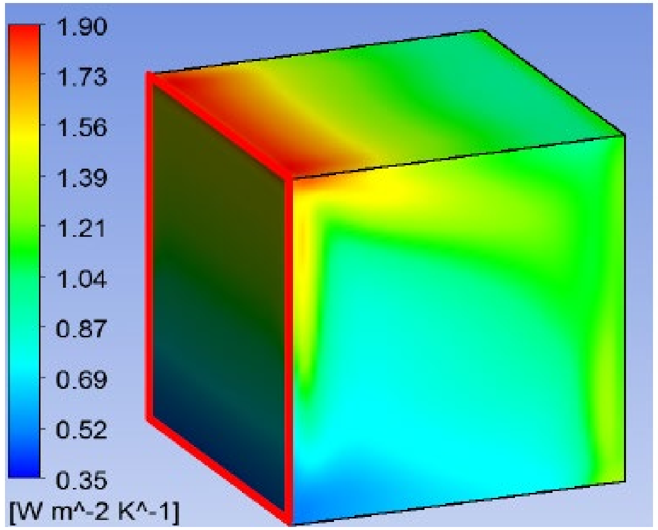
$$
\begin{aligned}
h = \; & b_1 + b_2 \cdot T_h + b_4 \cdot T_e + b_6 T_b \\
& + b_3 \cdot T_h^2 + b_5 \cdot T_e^2 + b_7 \cdot T_b^2 \\
& + b_8 \cdot T_h \cdot T_e + b_9 \cdot T_h \cdot T_b + b_{10} \cdot T_e \cdot T_b
\end{aligned}
$$

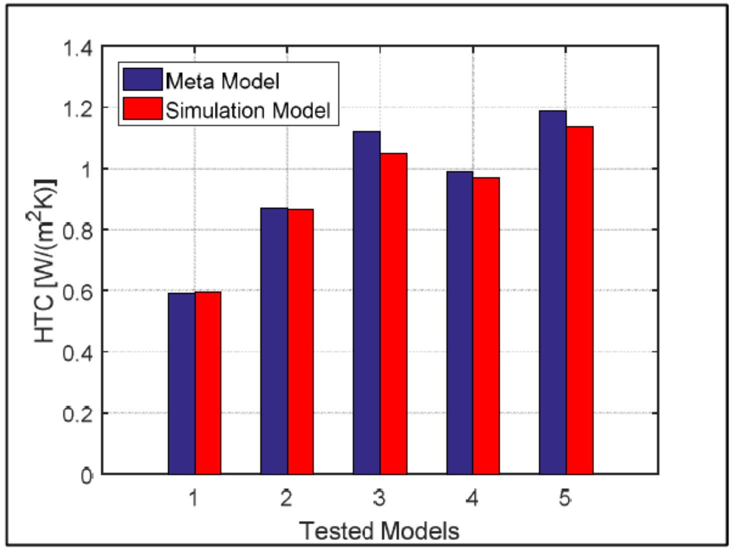




Pavlicek 2019

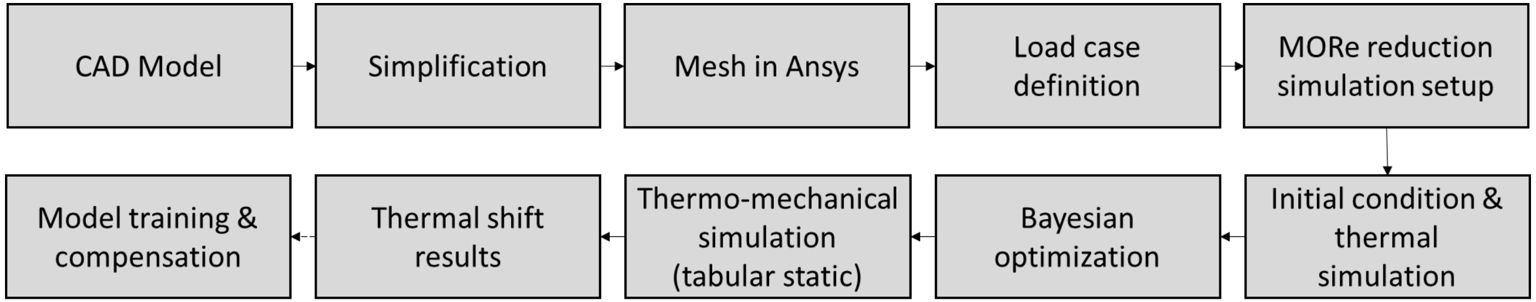






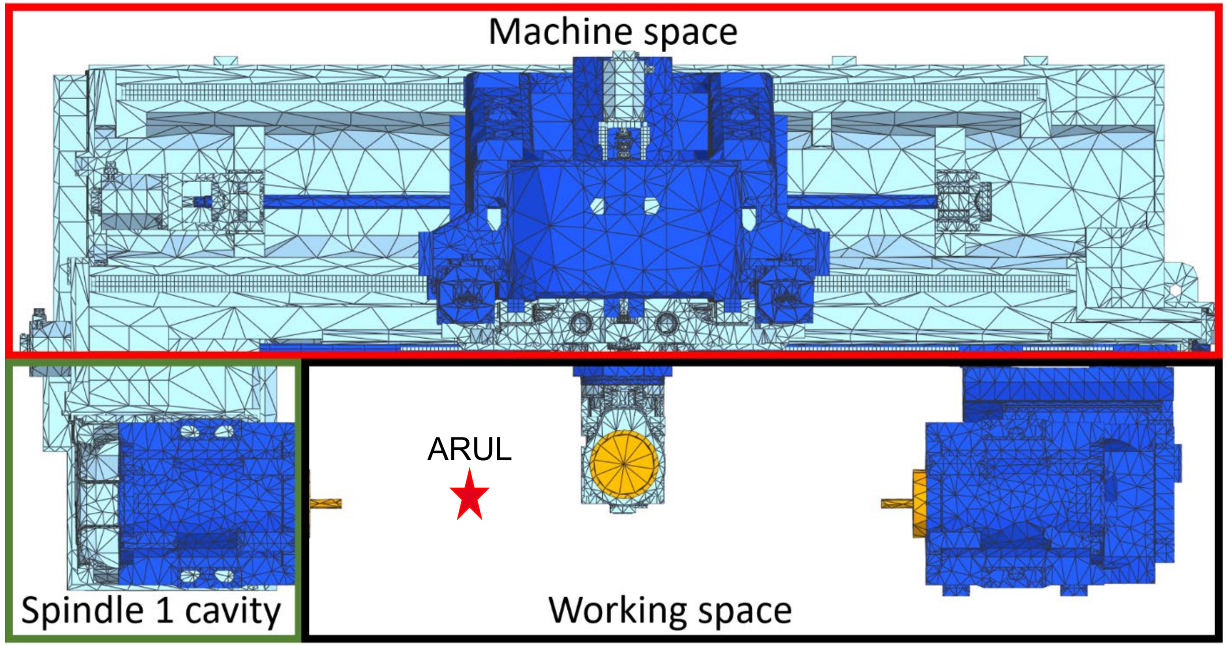
Solution for hollow spaces

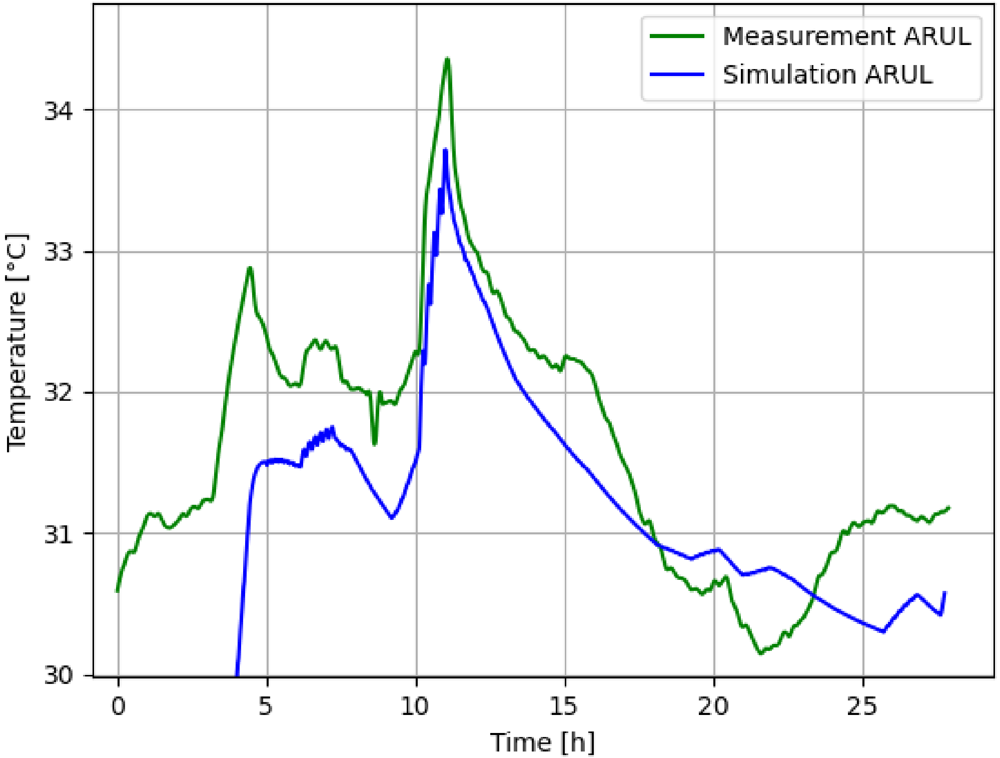
- Lumped capacitance model for hollow spaces
- Per surface constant heat transfer coefficients (HTC)
- Different HTC to different surfaces
- Bayesian optimization of HTC within physically relevant boundaries



- Temperature within working area (ARUL-sensor).
- Simulation with lumped capacitances

Lang 2023





Fluid flow – CFD simulations - ANSYS CFX boundary conditions

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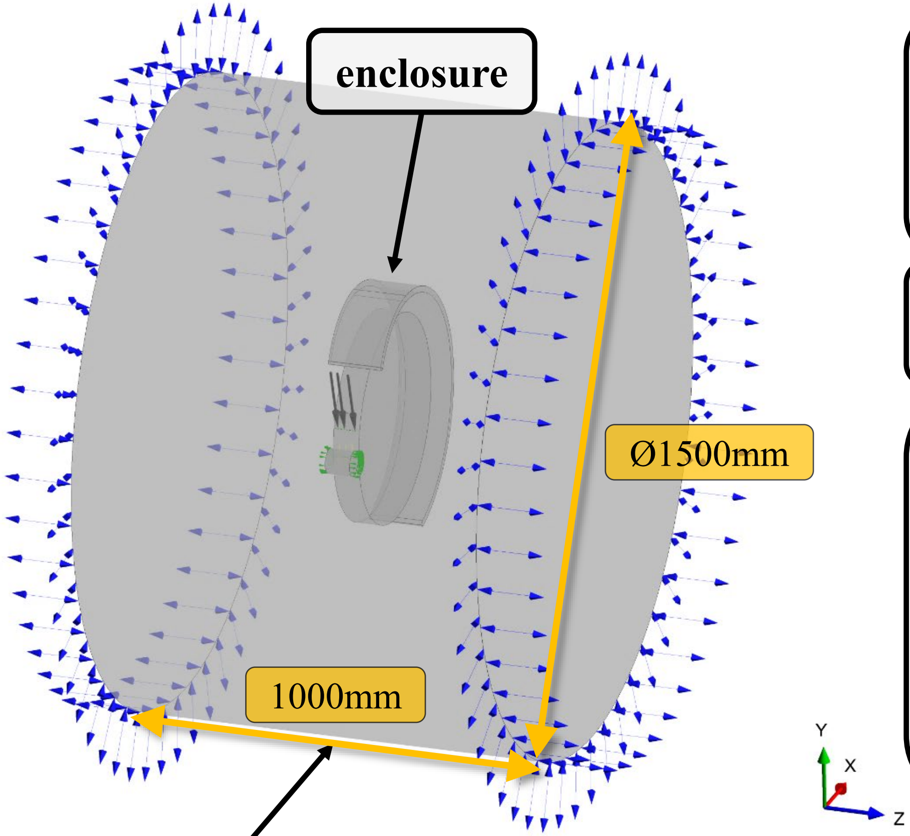


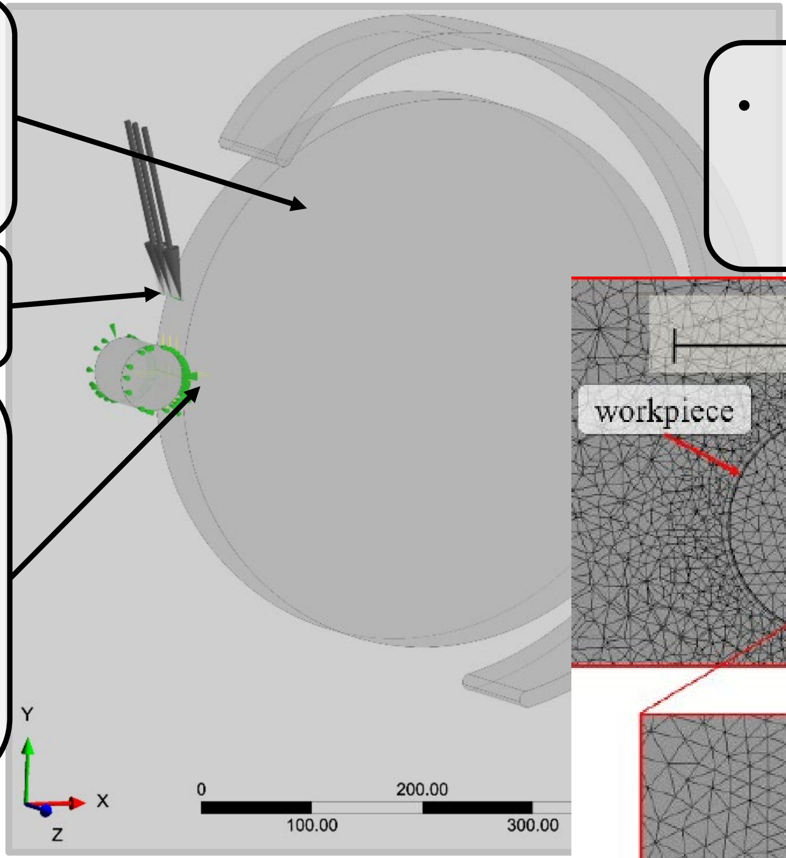
opening

coolant
based on water properties
<u>measured and adapted:</u>
contact angle = 51° (on steel)
surface tension = 39 mN/m
dyn. viscosity = 1.2275 mPa · s

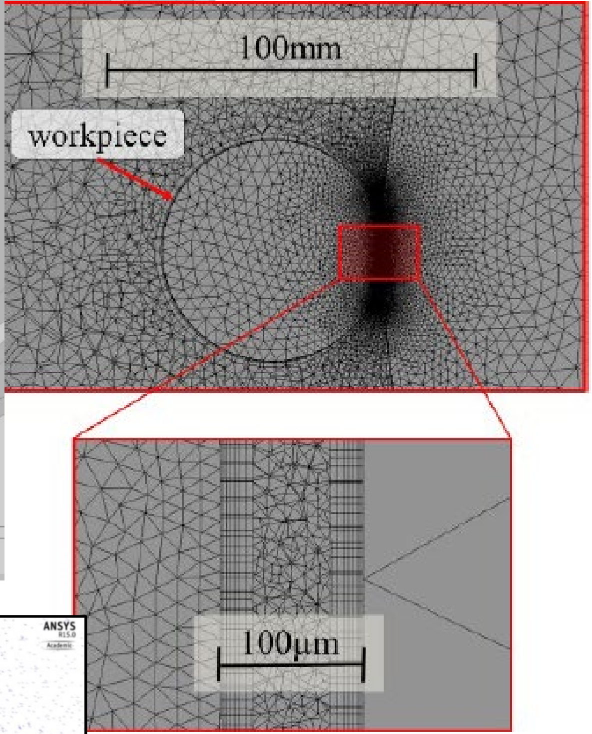
grinding wheel (wall)
no slip condition,
adiabatic
1910/min
63mm · Ø500mm

nozzle exit (inlet)
mass flow rate, coolant

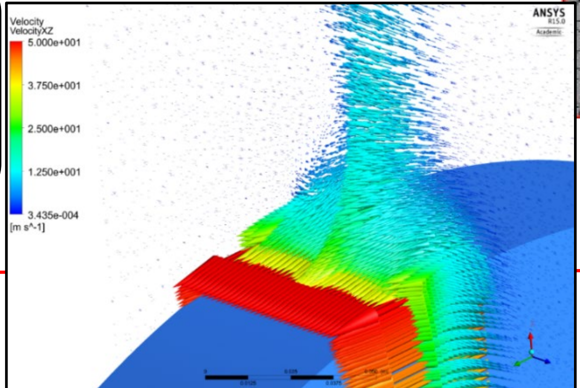
grinding gap (interface)
no slip condition
heat source: 600W
distance to grinding wheel: 300µm
grinding wheel: adiabatic



- Elementation of the grinding wheel environment



- multiphase/heat transfer: homogeneous model
- turbulence model: shear stress transport



Fluid flow – CFD simulations – Results coolant flow

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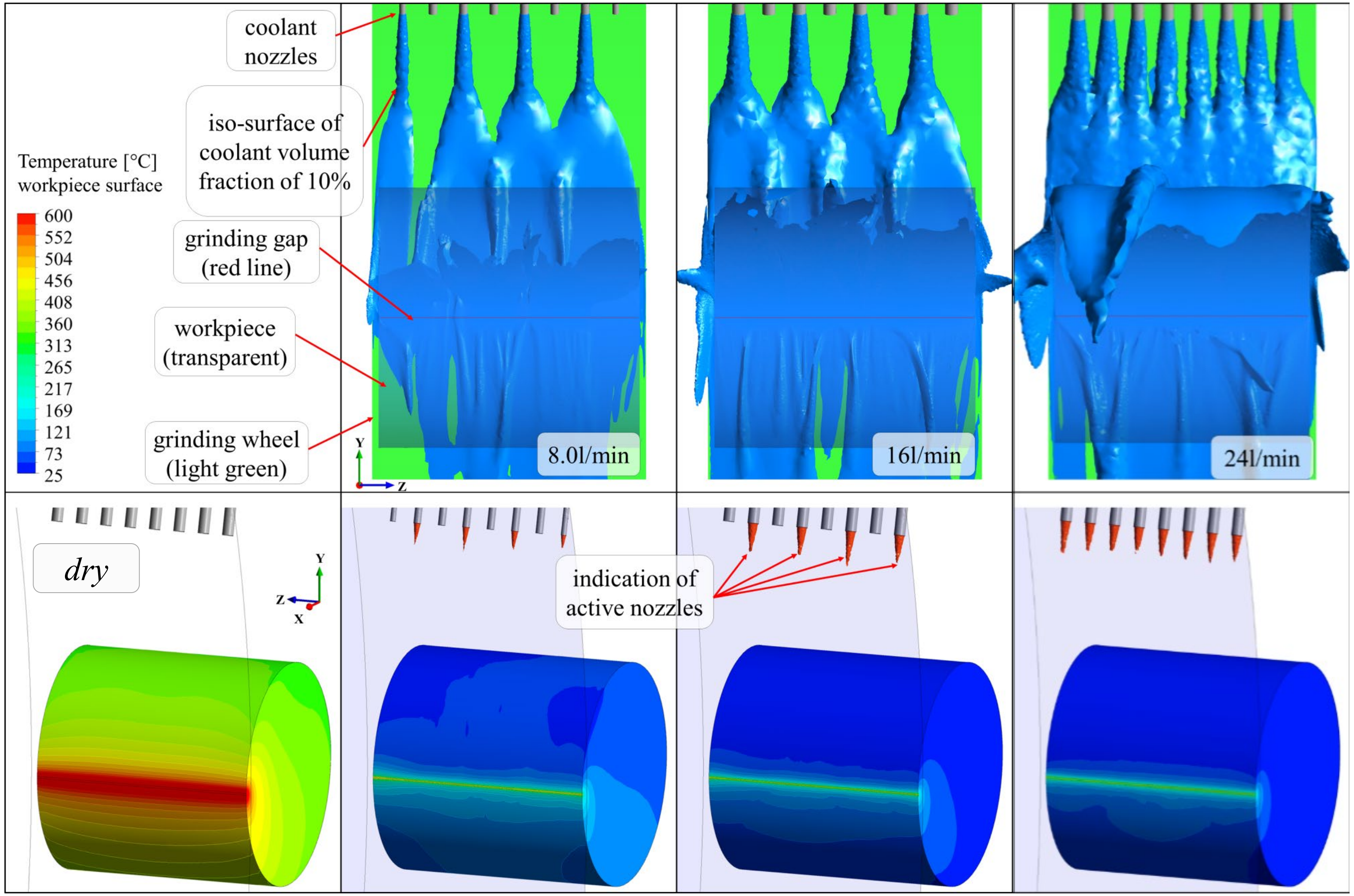
Baumgart 2020

- Steady state simulations
  - Visualize coolant flow propagation above and in grinding gap
  - Share of grinding gap flow
  - Includes impact of air flow
  - Combination of single jets
- Workpiece surface temperature
  - Heat source in grinding gap
    - Conduction: into workpiece
    - Convection: cooling fluid and airflow
  - Temperature distribution on workpiece and in grinding gap
  - Impact of single nozzles

HTC: brilliant assumption



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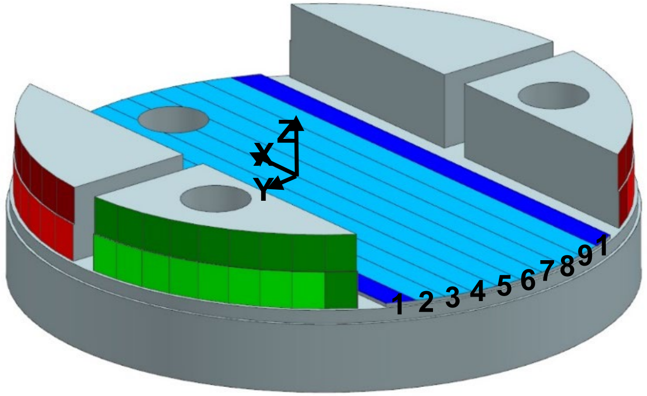
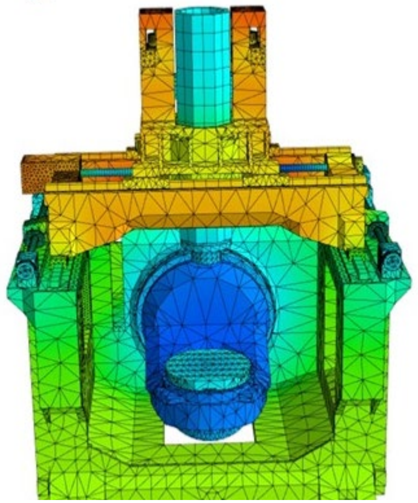
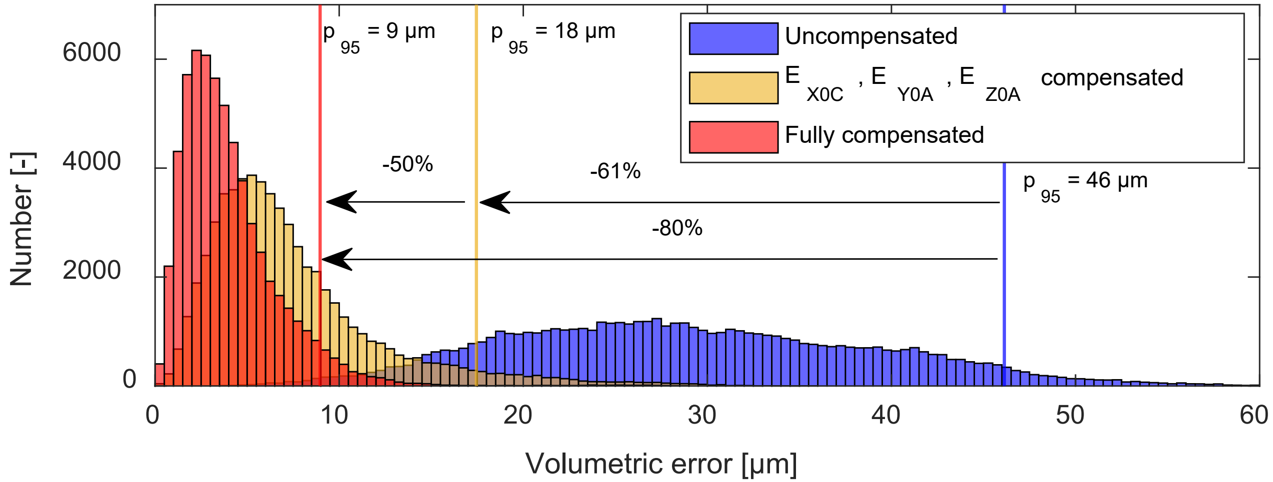
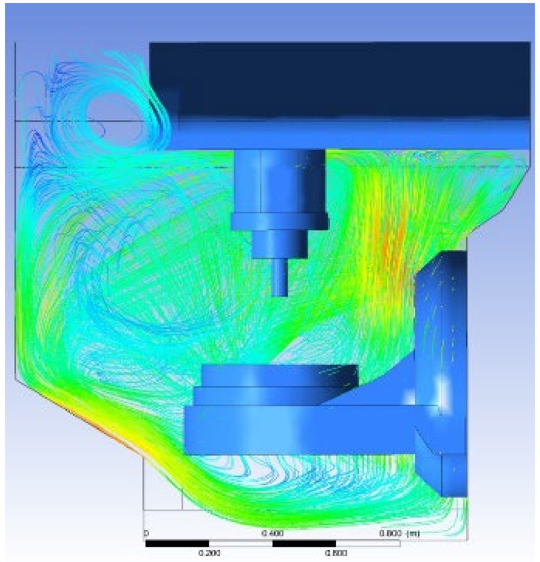




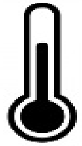




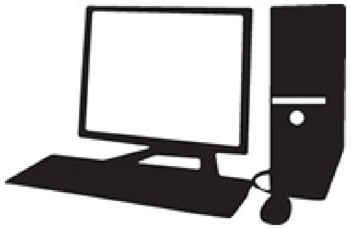
Iterative learning control for thermo-compensation

Power input

Temperature sensors



Temperature Measuring values (every 10 s)

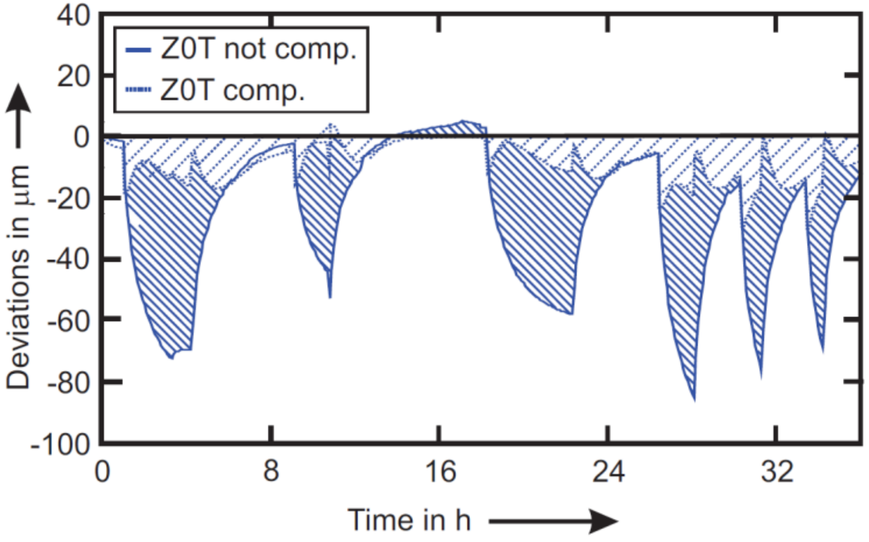


Position values from CNC (every 1 s)

Compensation as X-, Y- und Z-deviation (every 1 s)

ARX-model structure:

$$y[k] + a_1 \cdot y[k-1] + \cdots + a_{n_a} \cdot y[k-n_a]$$
$$= b_0 \cdot u[k] + b_1 \cdot u[k-1] + \cdots + b_{n_b} \cdot u[k-n_b]$$

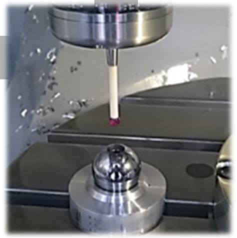


Error estimation (before measuring)

Iterative learning control

Update of parameters

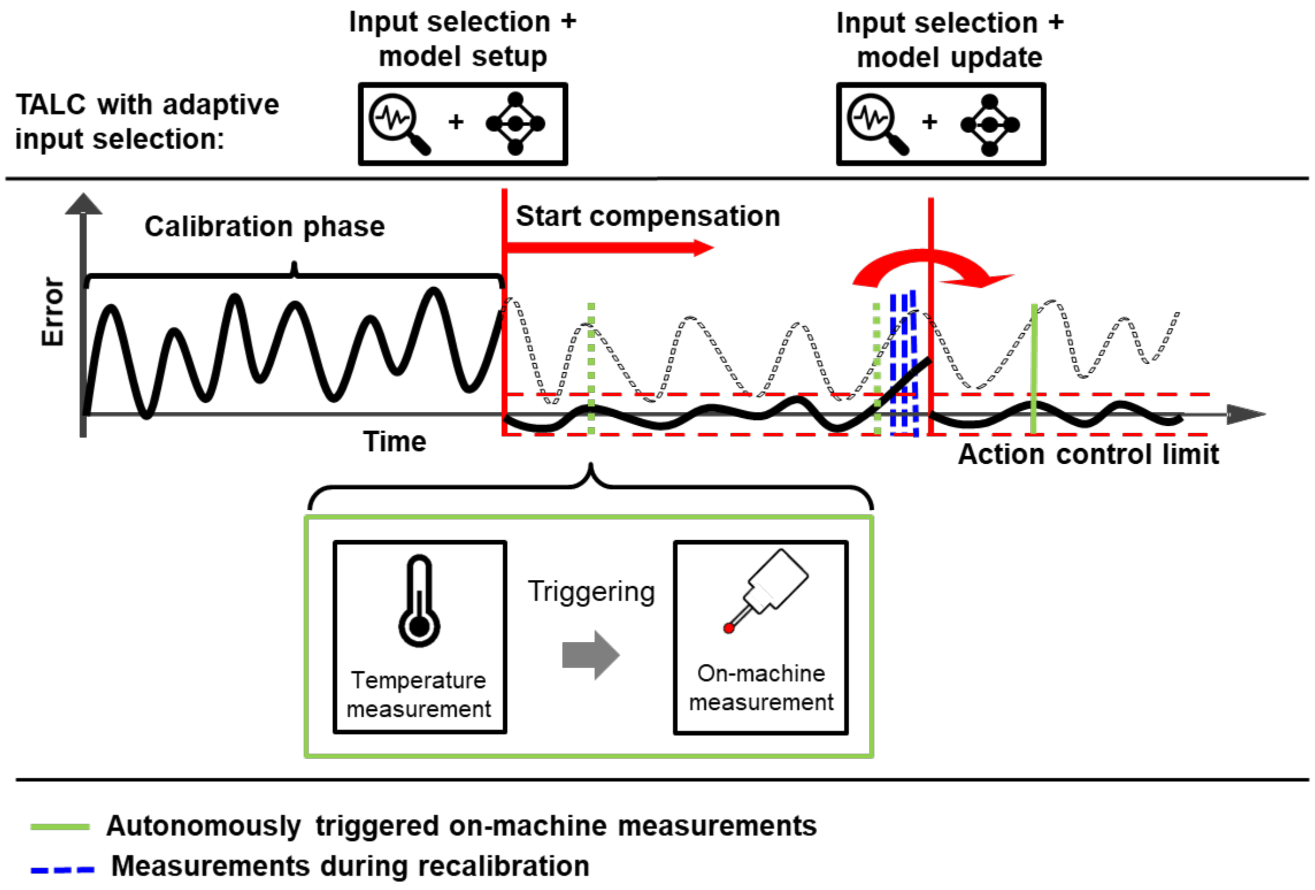
Feedback of residual error from probing



Blaser 2020, Zimmermann 2022

Self-learning thermal error compensation models

- Characteristics
  - Data-driven models with ARX-structure
  - Automatic determination and recalibration of the models
  - Autonomously triggered on-machine measurements
  - Input selection upon model update after clustering of sensors
- Advantages
  - Long-term stability in case of changing boundary conditions
  - “Optimization” of the trade-off between precision and productivity
  - No detailed knowledge about the thermal behavior required



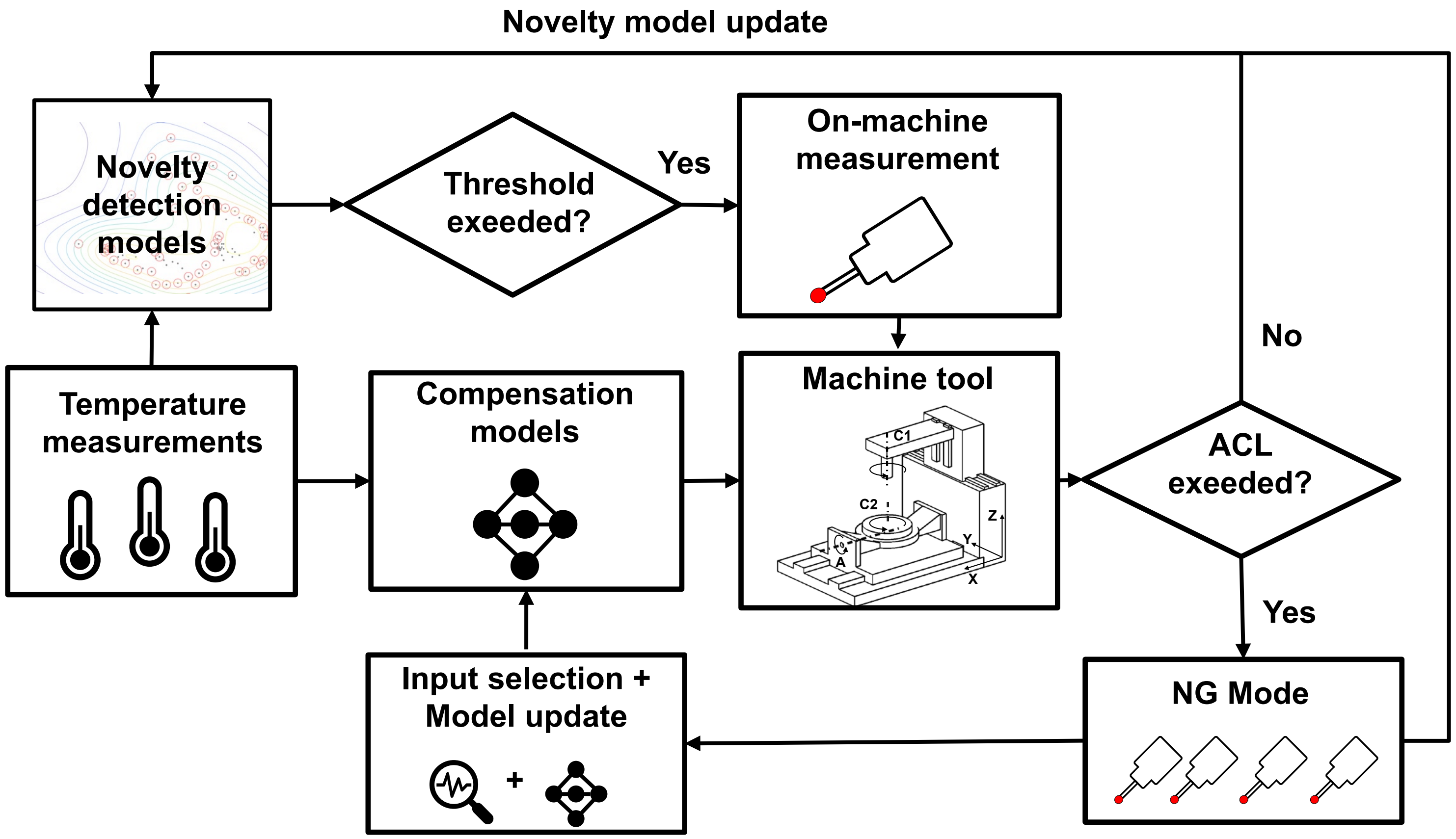
y: Thermal error
u: Temperature

ARX-Modell

$$y[k] = -\sum_{i=1}^{n_a} a_i \cdot y[k-i] + \sum_{n=1}^{N} \sum_{j=0}^{n_b(n)} b_{j(n)} \cdot u_n[k-j]$$

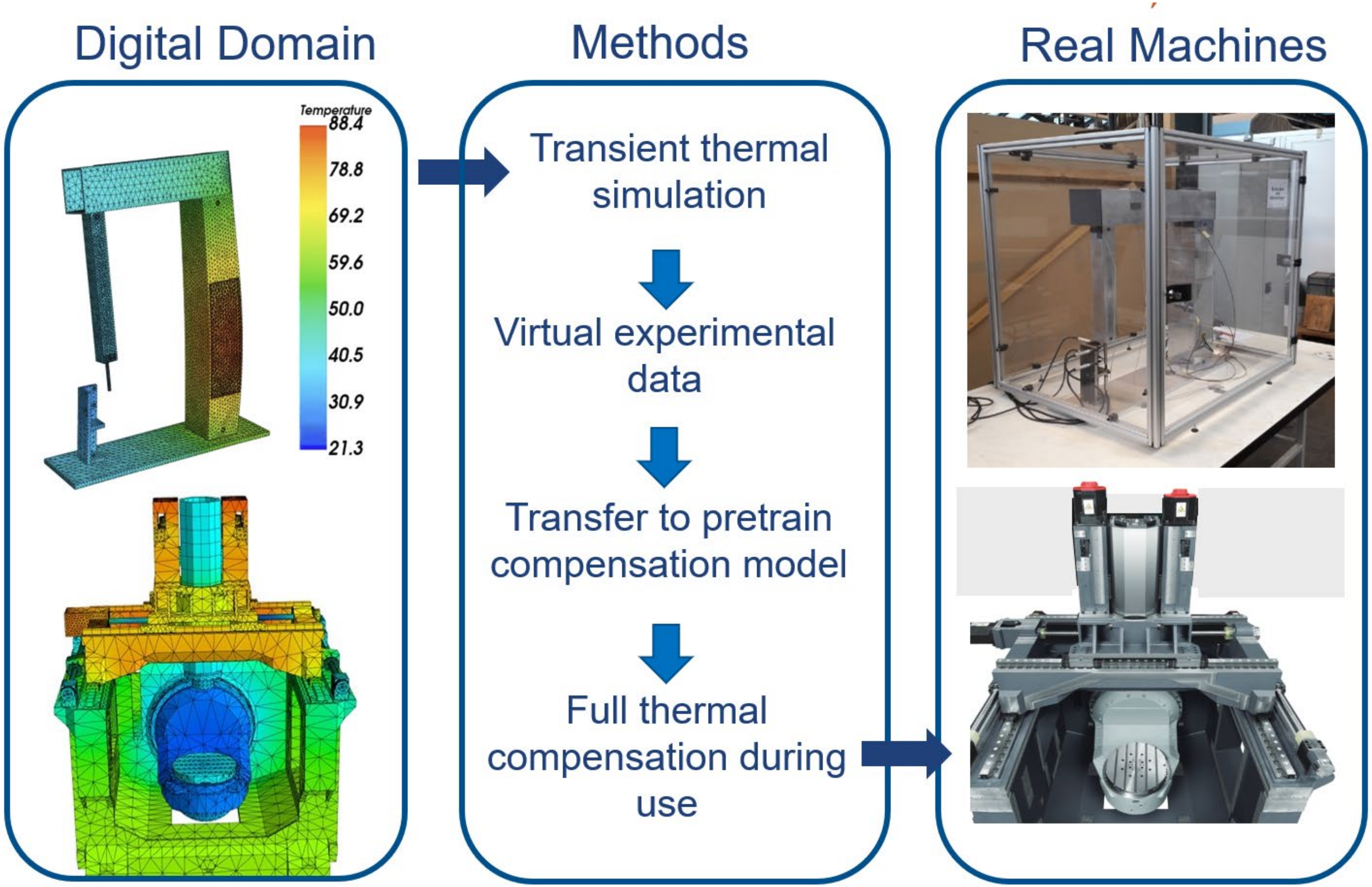
Integration of the autonomous state updates into the TALC

- Novelty detection model for every sensor mounted on the MT
- Identifying conditions differing from the already available training data
- Exceedance of the novelty threshold triggers an on-machine measurement
- Update of the novelty detection models after on-machine measurements



Zimmermann 2022

Physics Informed Training for Thermal Compensation

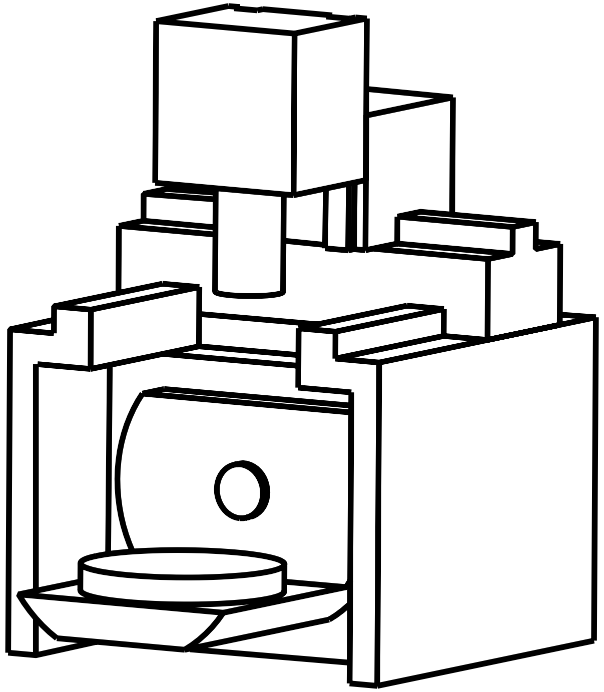


Requirements:
Validated simulation model
Correct physical parameters:
- HTC
- coefficient of thermal expansion
- heat conductivity also across internal boundaries and contacts
- Young’s modulus

5-axis milling machines

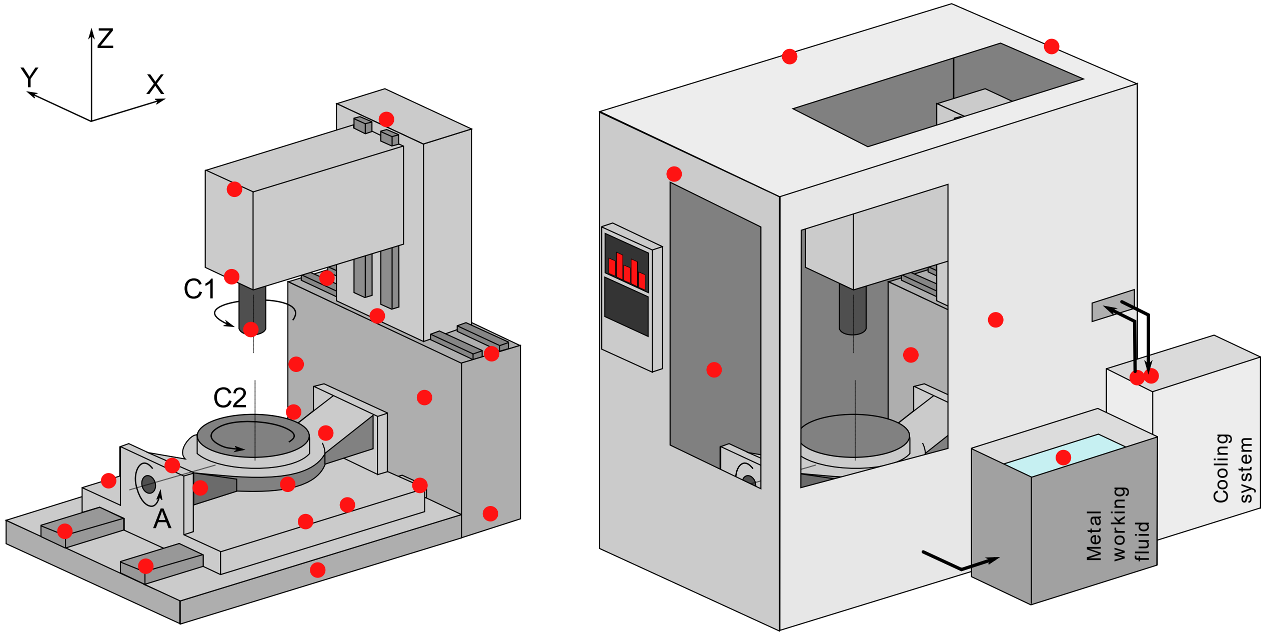
Characteristics

- Superposing of a high number of axis-specific thermal errors at the TCP
- Housing and hollow spaces
- Fluid and chips
- Touch trigger probes for on-machine measurement cycles

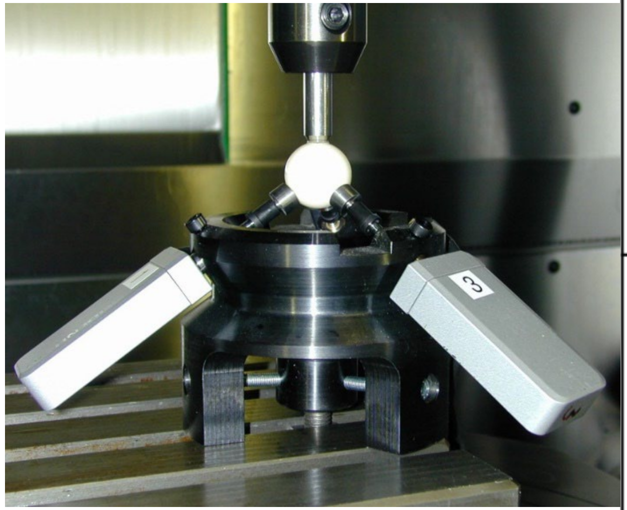


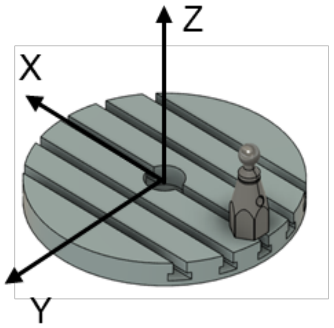
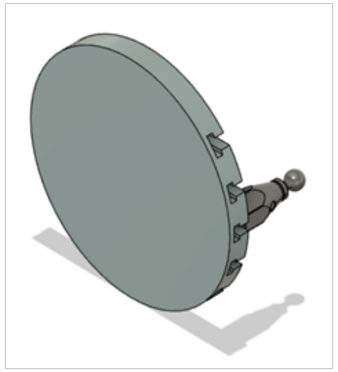
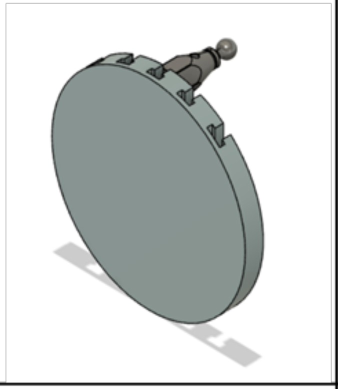
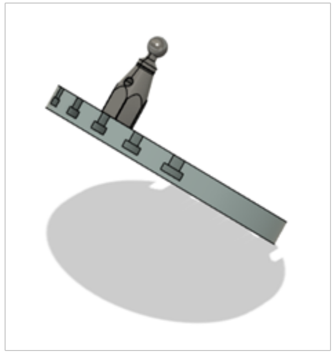
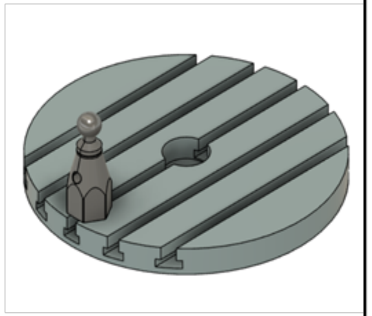
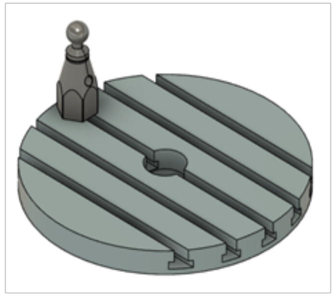
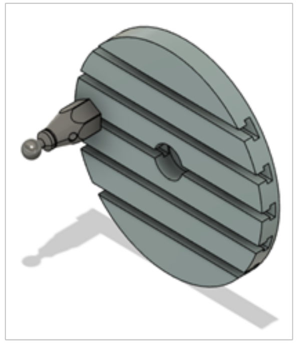
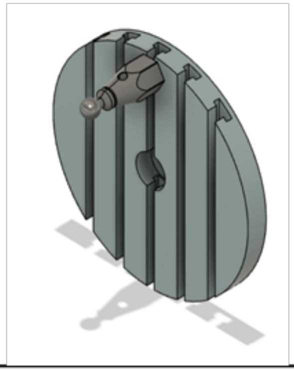
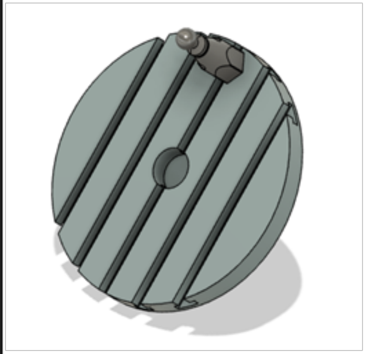
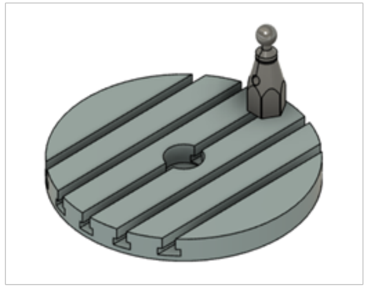
Example model inputs

- Structural temperatures: 26 sensors
- Ambient temperatures: 4 sensors
- Cooling fluid temperatures: 3 sensors
- 15 individual errors identified



In-Process measuring cycle for 5-axis machines



Position 1 $A = 0°, C = 0°$	Position 2 $A = 90°, C = 0°$	Position 3 $A = 90°, C = 90°$	Position 4 $A = 45°, C = 90°$	Position 5 $A = 0°, C = 90°$
				
Position 6 $A = 0°, C = 180°$	Position 7 $A = -90°, C = 180°$	Position 8 $A = -90°, C = 270°$	Position 9 $A = -45°, C = 270°$	Position 10 $A = 0°, C = 270°$
				

Swiss type lathes

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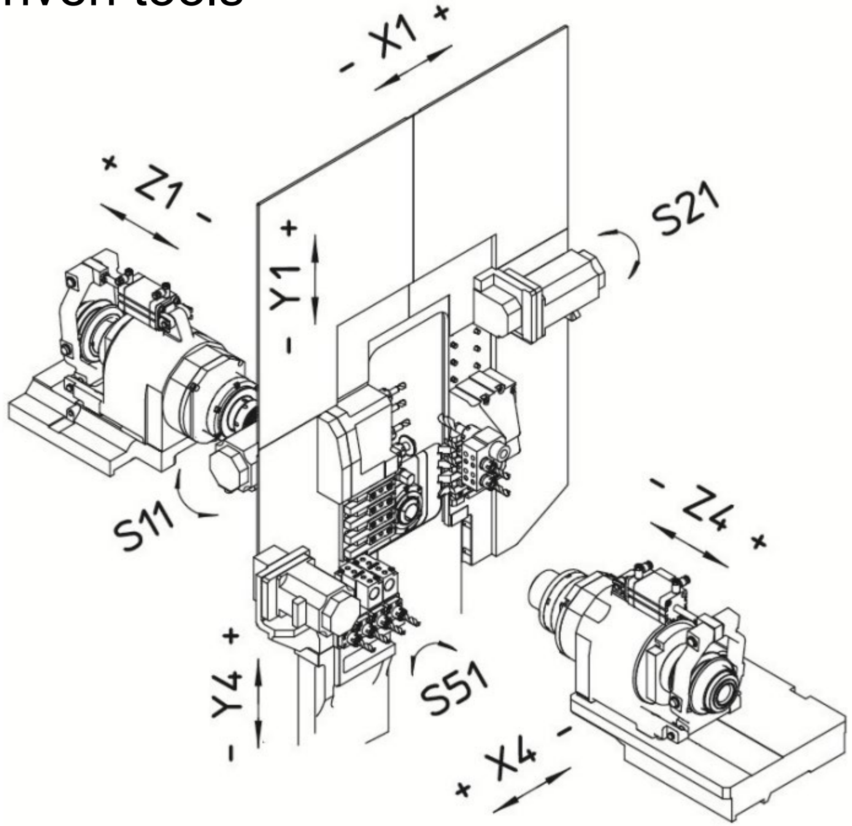
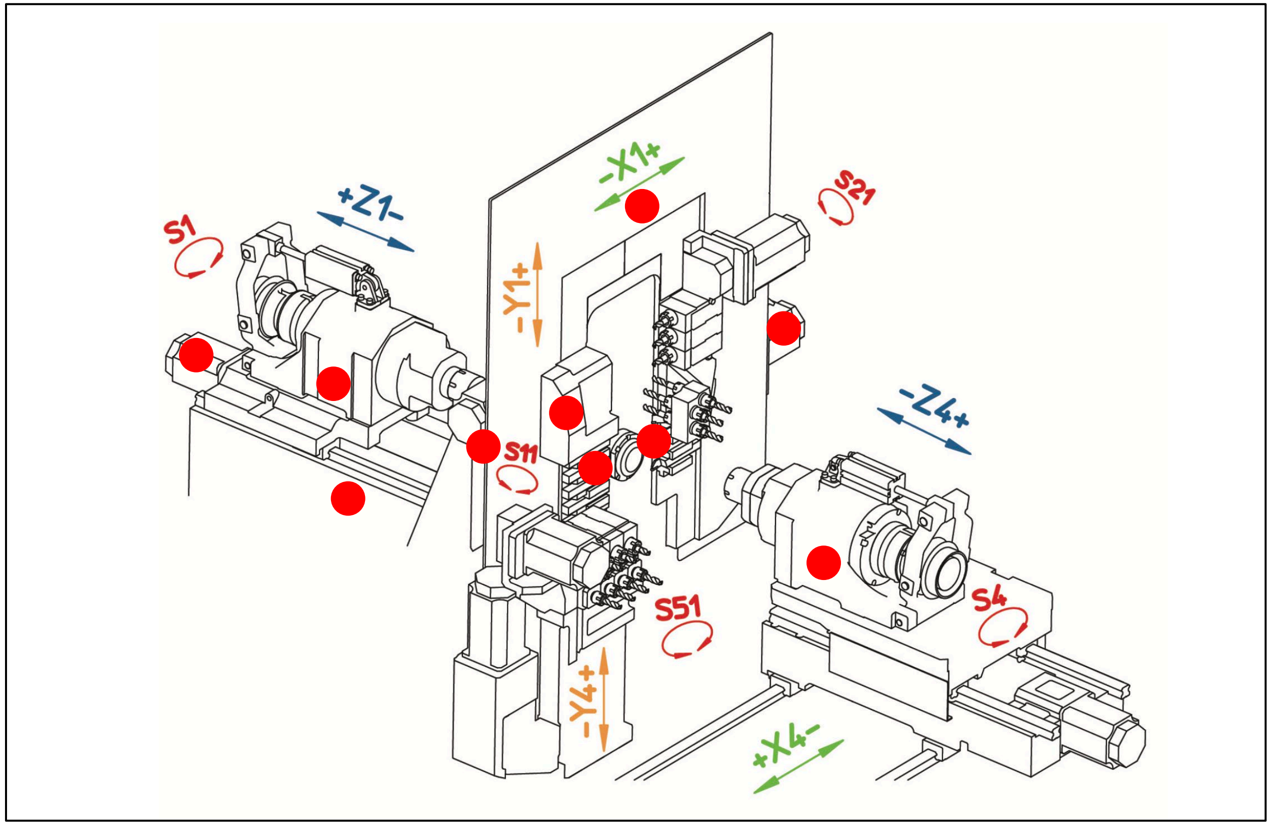
Characteristics

- Several TCPs
- Often no touch trigger probe available
- Sensitive to door opening effects
- Driven tools

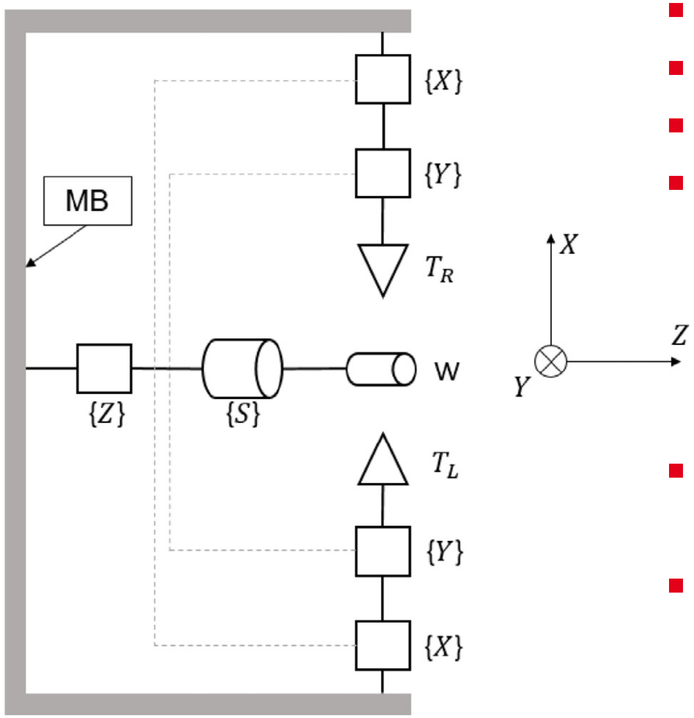


Model inputs

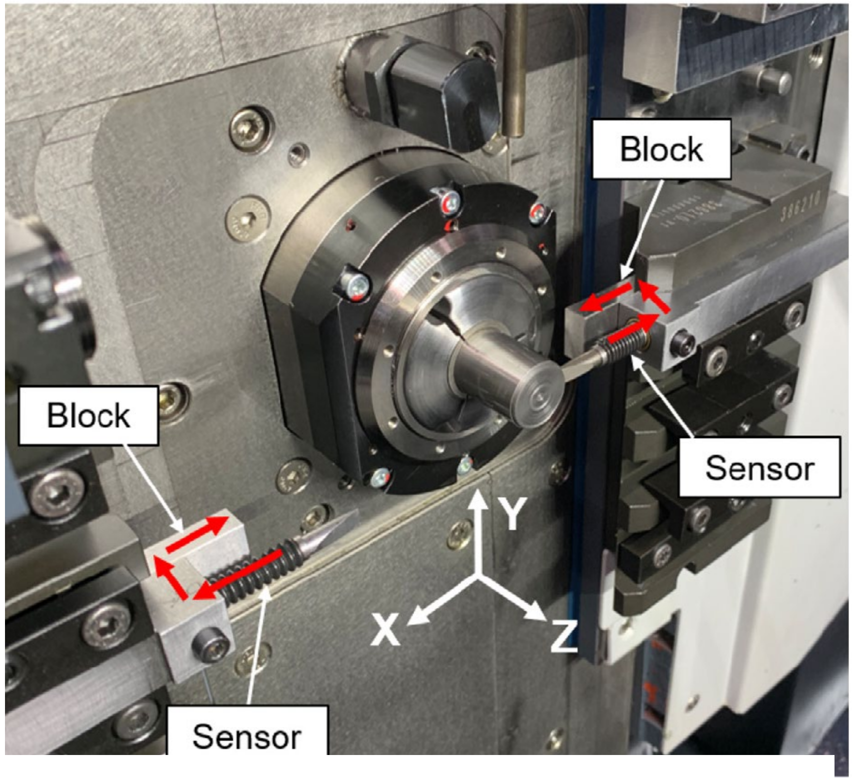
- Structural temperatures: 33 sensors
- Ambient temperatures: 3 sensors
- Cooling fluid temperatures: 2 sensors



Swiss-type lathe measuring concept

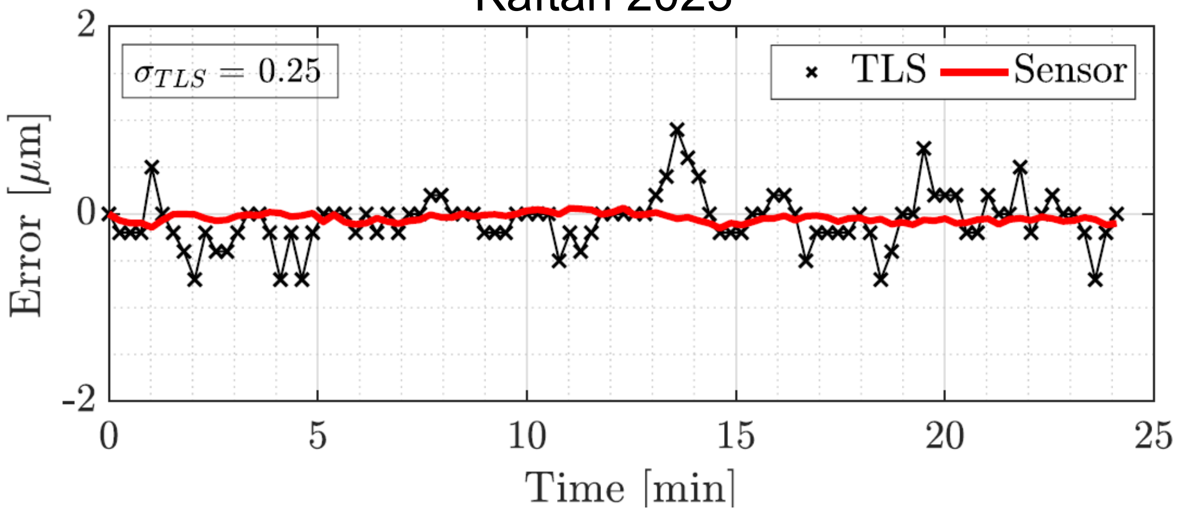


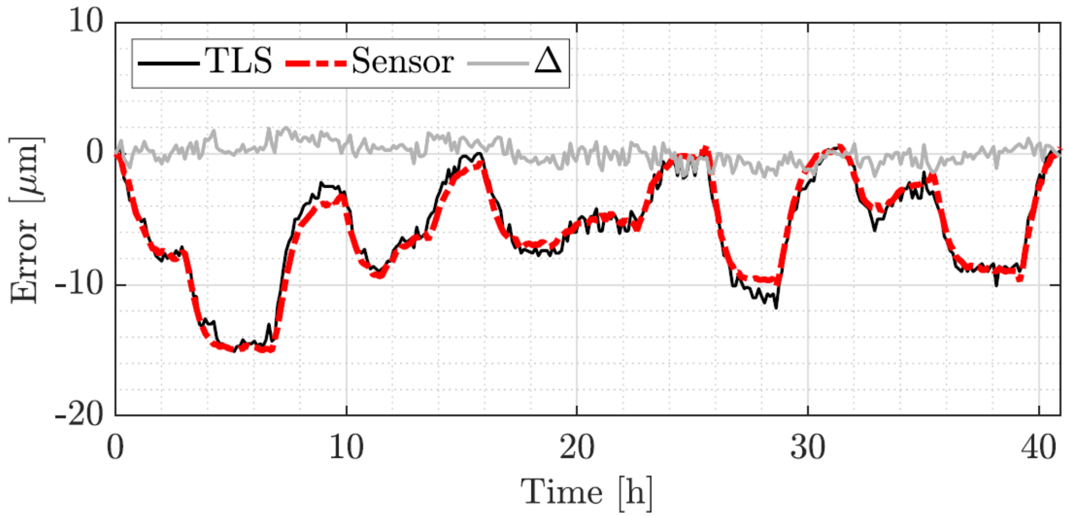
- Probing of calibrated measuring cylinder
- Utilisation of Torque limit skip function
- ➔ Force 42.5 N
- ➔ Repeatability of ± 1µm



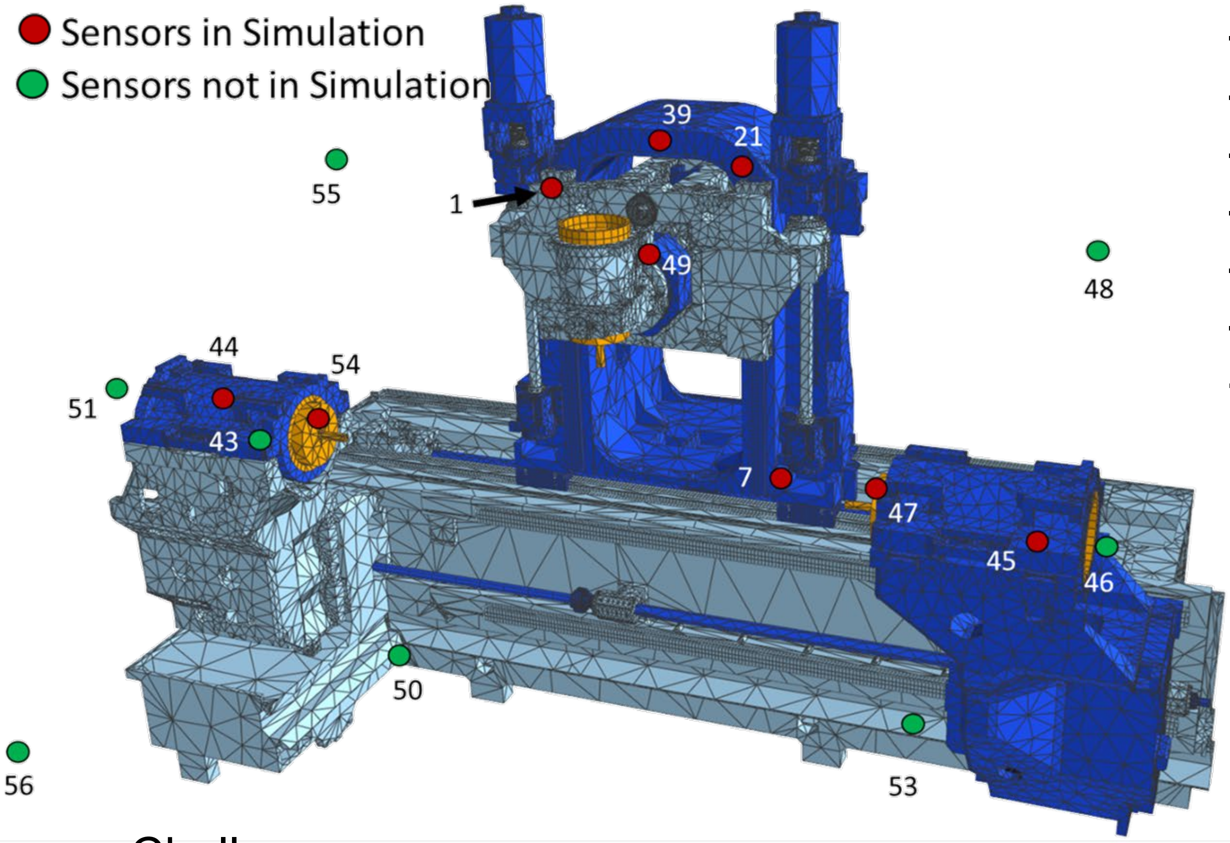
- Take into account driven tools with their concentrated heat input
- Transfer of behavior from tool to tool by FEM of the tool holder

Kaftan 2023

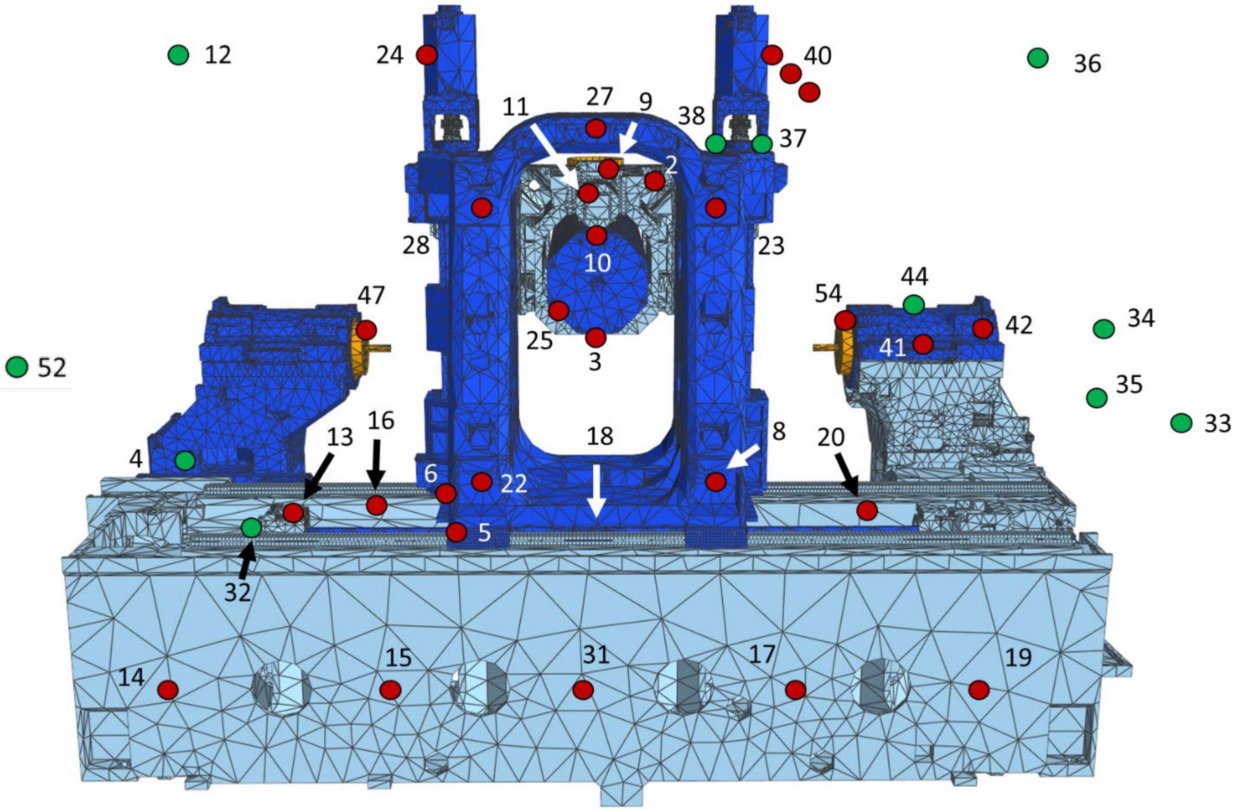




Turning-milling machines

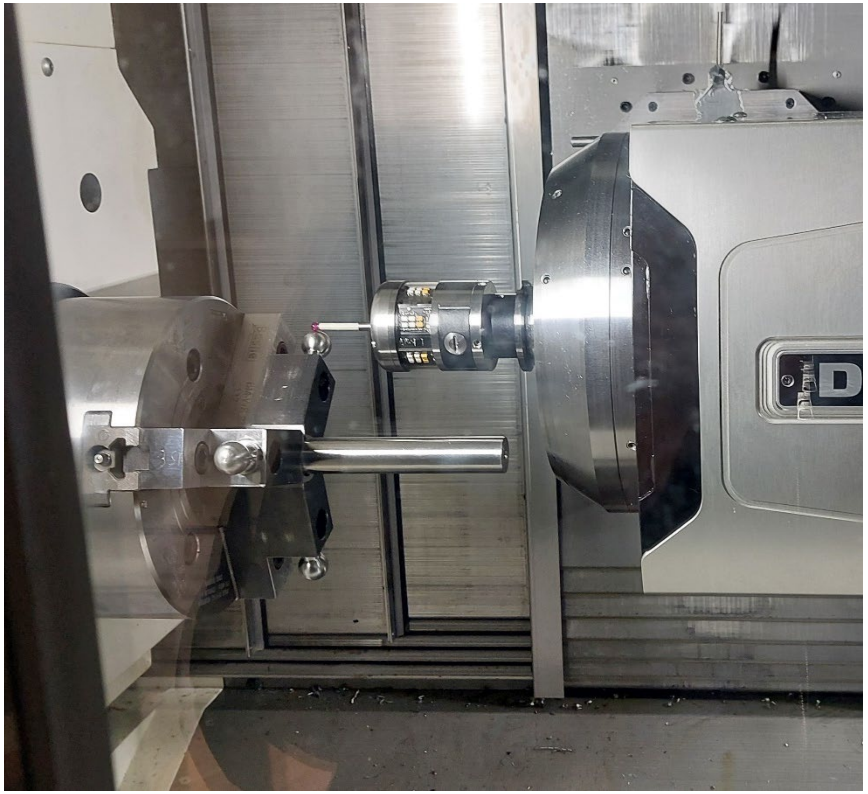


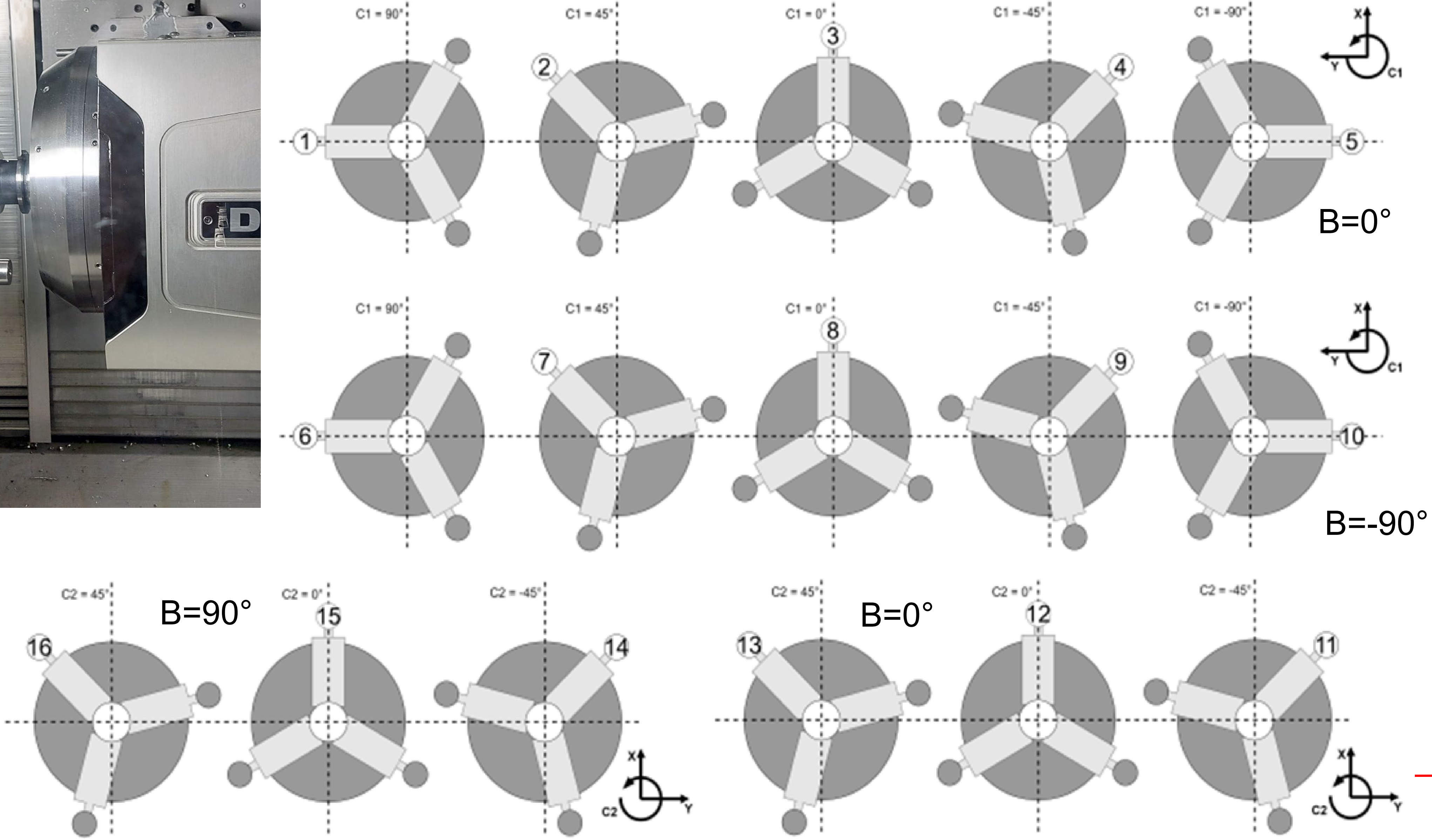
Sensor placement:
- Close to position measuring heads,
- Close to frictional heat sources,
- Workpiece spindles (in milling machines the table),
- Tool spindle head,
- Environment of the machine,
- Working area and places within the housing,
- All main structural elements,
- Coolant temperatures at different places in the coolant lines.



Challenges:
- 2 WCPs
- 7 axes
- Separation of axis errors
- No standard available
- Load cycles turning & milling

Geometrical probing of Turning Milling Machines





Future:
Inbuilt artifacts
for probing

Geometrical probing of Turning Milling Machines

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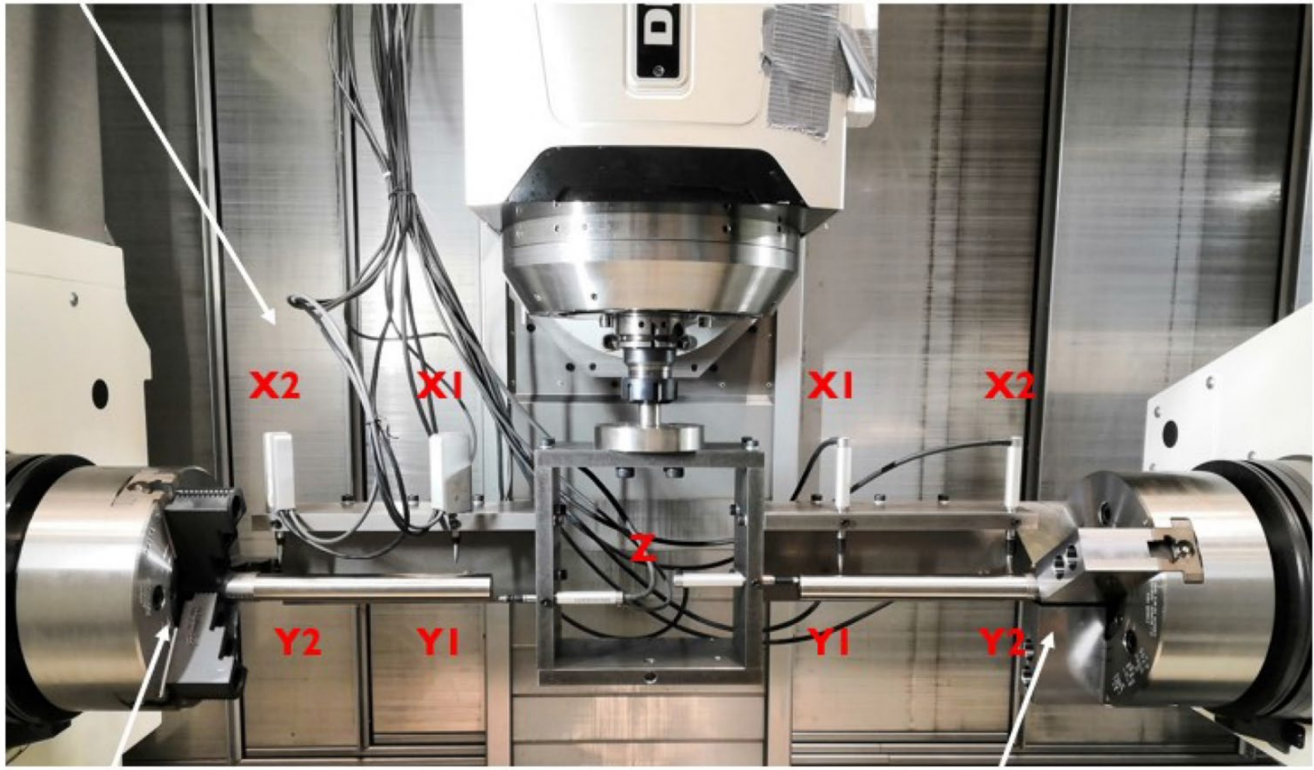
Only groups of location errors can be distinguished
19 representative location errors for compensation

Workpiece spindle 1	Workpiece spindle 2	Milling spindle
E_{X0w1}	E_{X0w2}	E_{B0X}
E_{X0C1}	E_{X0C2}	E_{A0Y}
E_{Y0C1}	E_{Y0C2}	E_{C0Y}
E_{A0C1}	E_{A0C2}	E_{Z0B}
E_{B0C1}	E_{B0C2}	E_{A0B}
		E_{COB}
		E_{X0t}
		E_{Y0t} ➔ Bad condition
		E_{Z0t}

Alternative for initial calibration: double spindle analysis



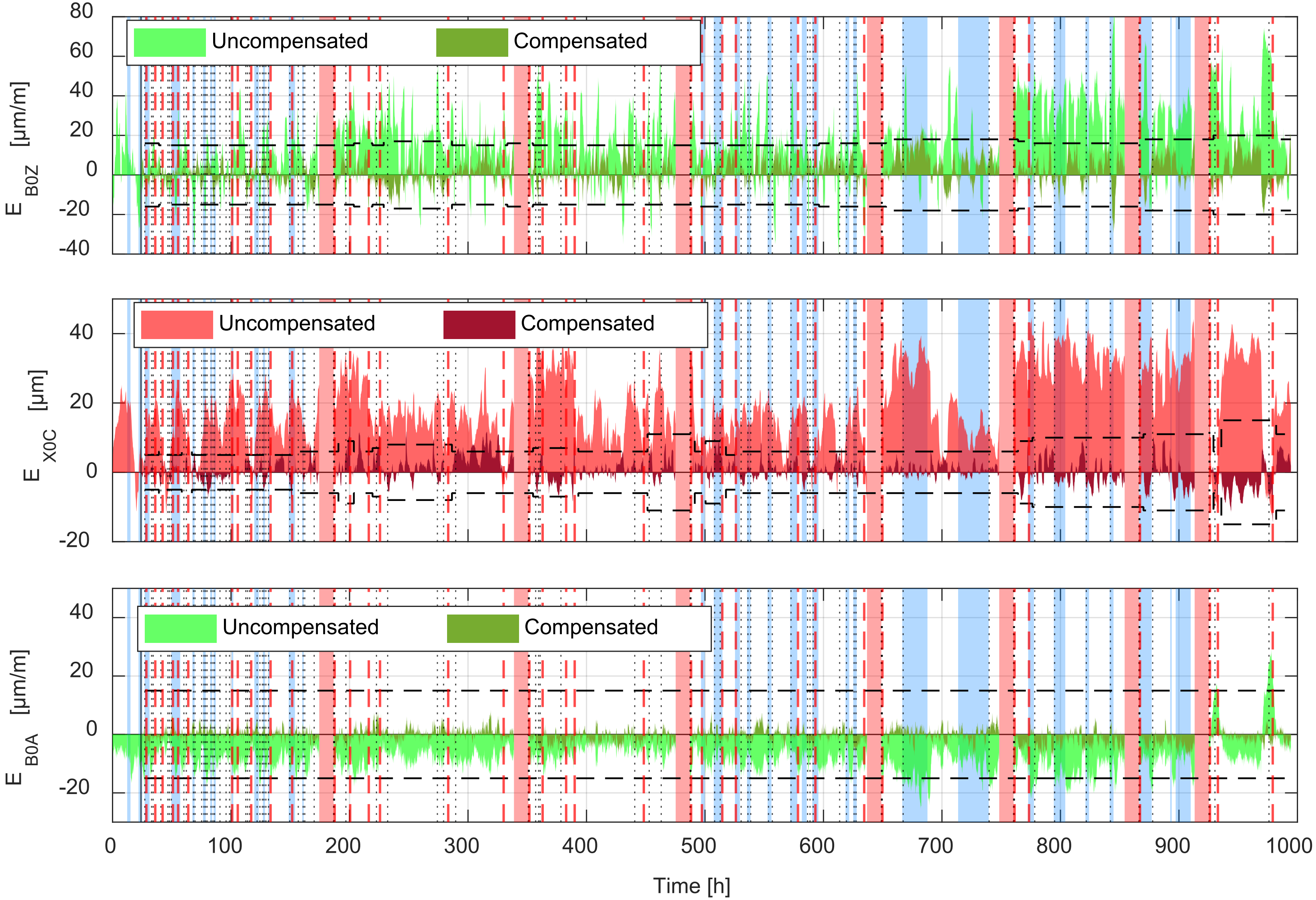
Rotating spindle (main)

Rotating spindle (counter)

Results of a thermally compensated 5-axis machine tool

3 out of 15 identified errors shown

Zimmermann 2022



Initial model training:
24 h

State update interval:
adaptive

Action Control Limit:
± adaptive

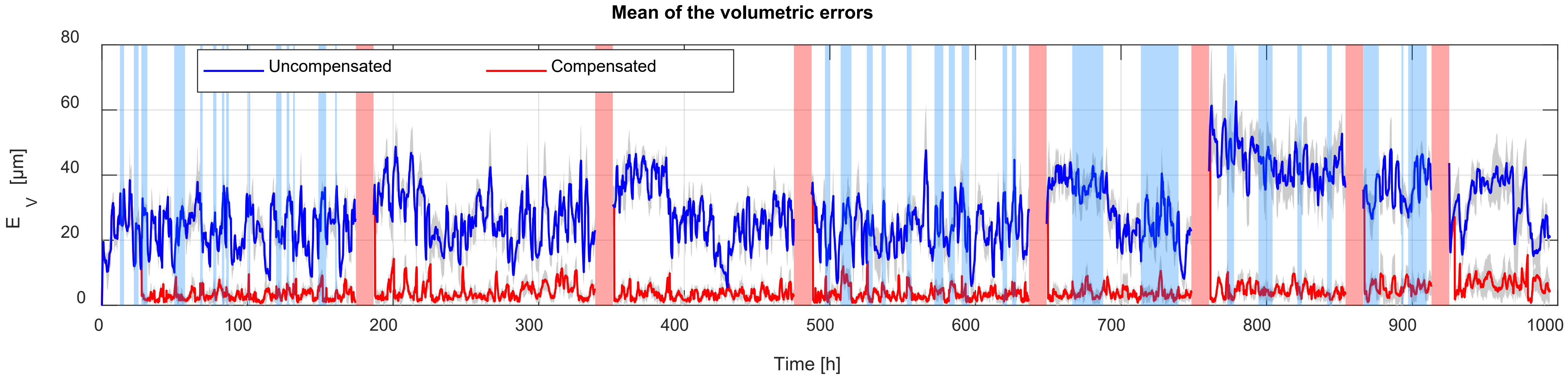
Number of model updates:
36

Measurements per model update:
16

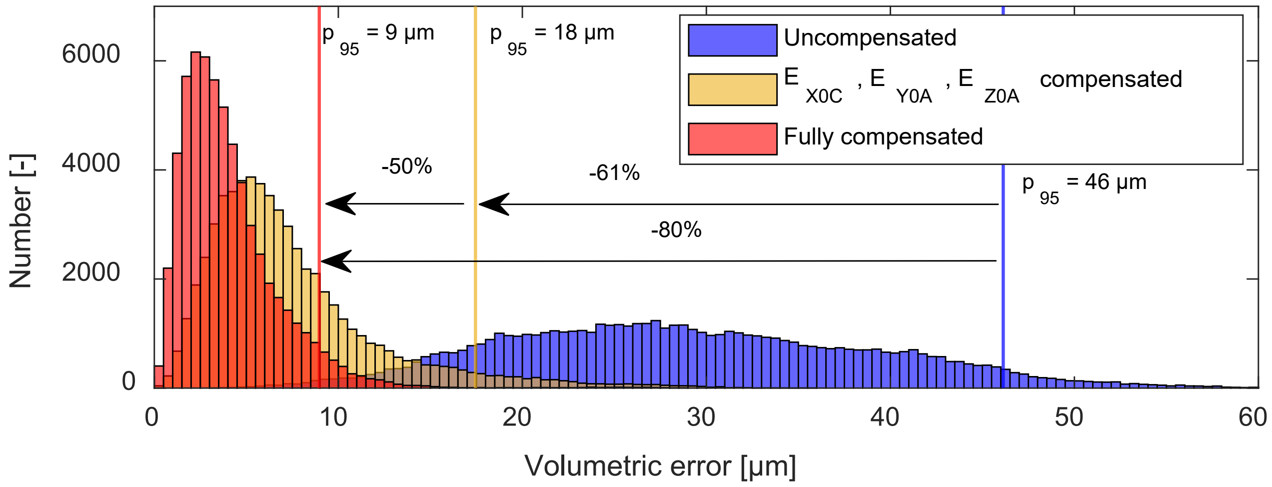
RMSE reduction:
E_{B0Z}: 70%
E_{X0C}: 84%
E_{B0C}: 72%

Volumetric RMSE:
30.7 µm ➔ 4.8 µm

Volumetric thermal errors of a 5-axis machine tool



Statistical distribution of the volumetric errors at all measurement positions for the whole time series

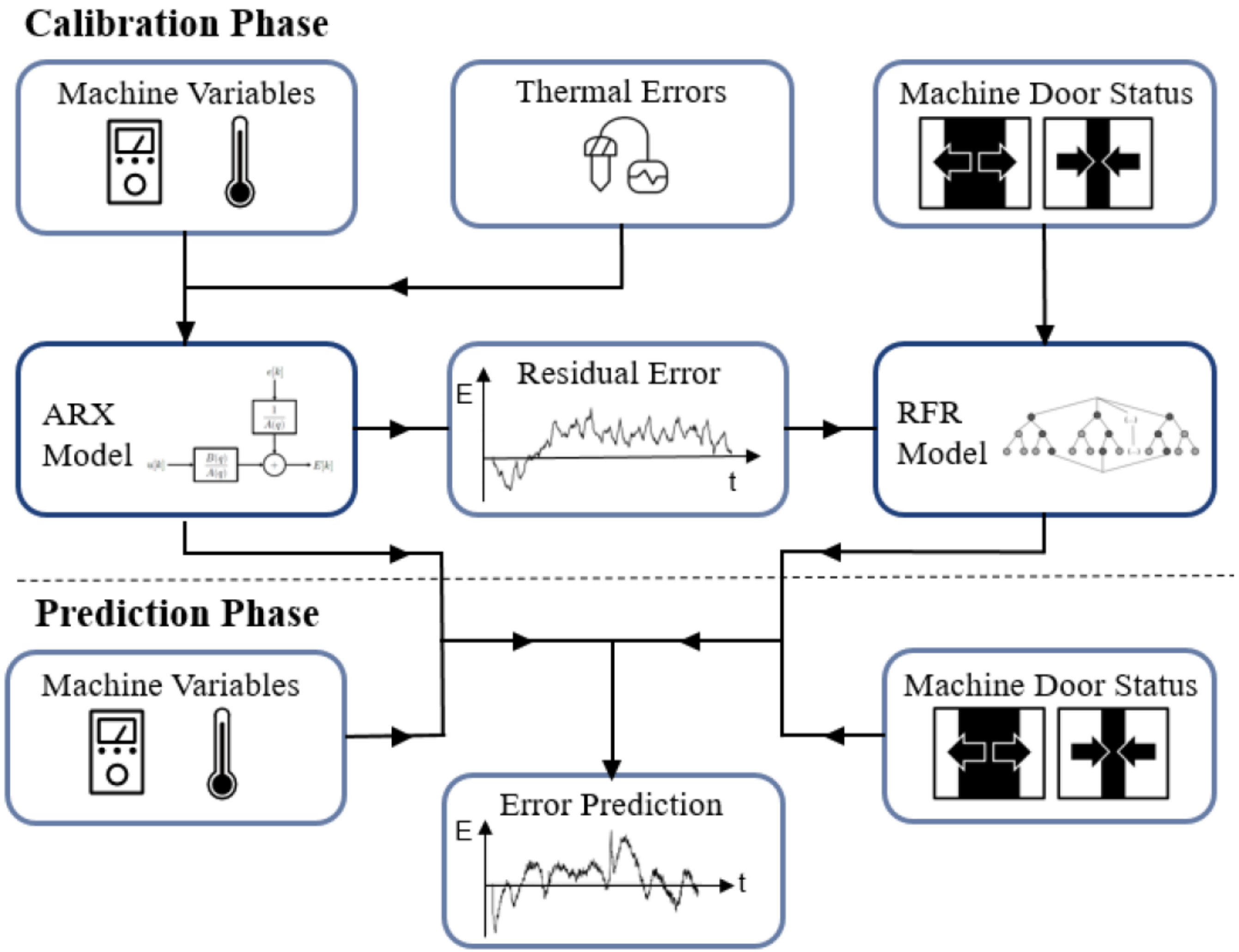


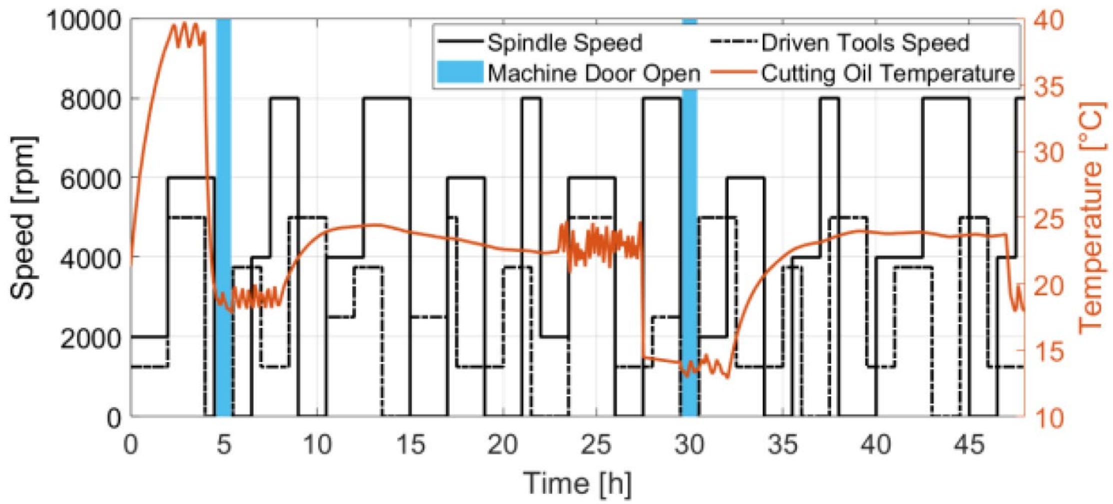
Volumetric RMSE:

30.7 µm ➔ 4.8 µm
reduction 87%

Thermal errors of a Swiss type lathe

- Sudden working space condition changes by opening and closing of doors.





RFR: Random forest regression

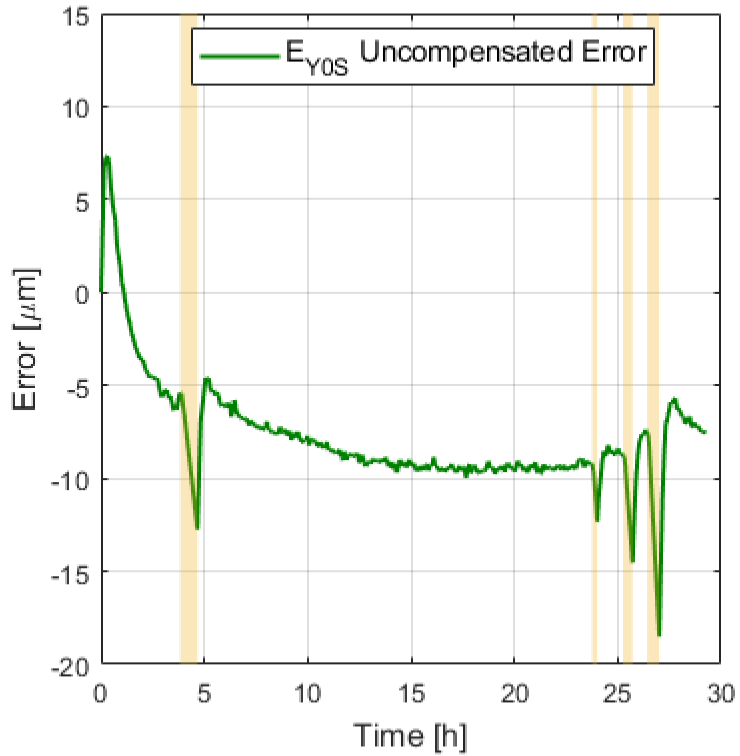
Kaftan 2023:

Thermal errors of a Swiss type lathe

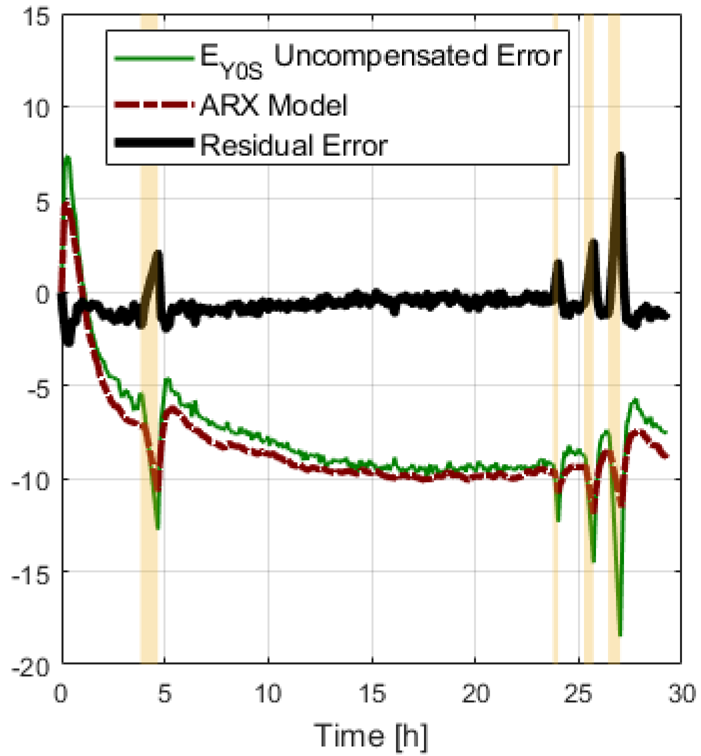
- Thermal compensation of sudden working space condition changes by opening and closing of doors in swiss-type lathe machining.

Machine Door Open

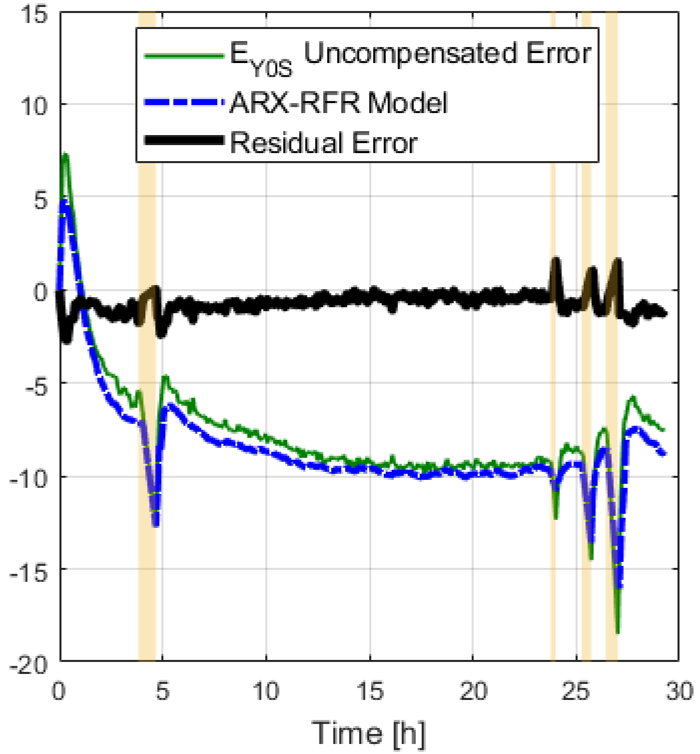
Uncompensated	ARX-Model	ARX-RFR Model



P2P Error reduction: 0%



P2P Error reduction: 28%



P2P Error reduction: 77%

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- **Thermal behavior in cutting operation**
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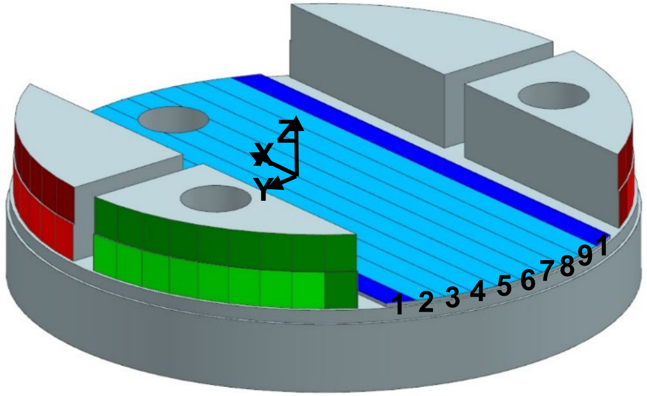

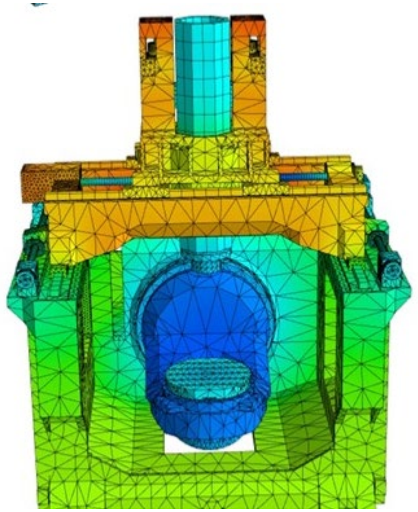

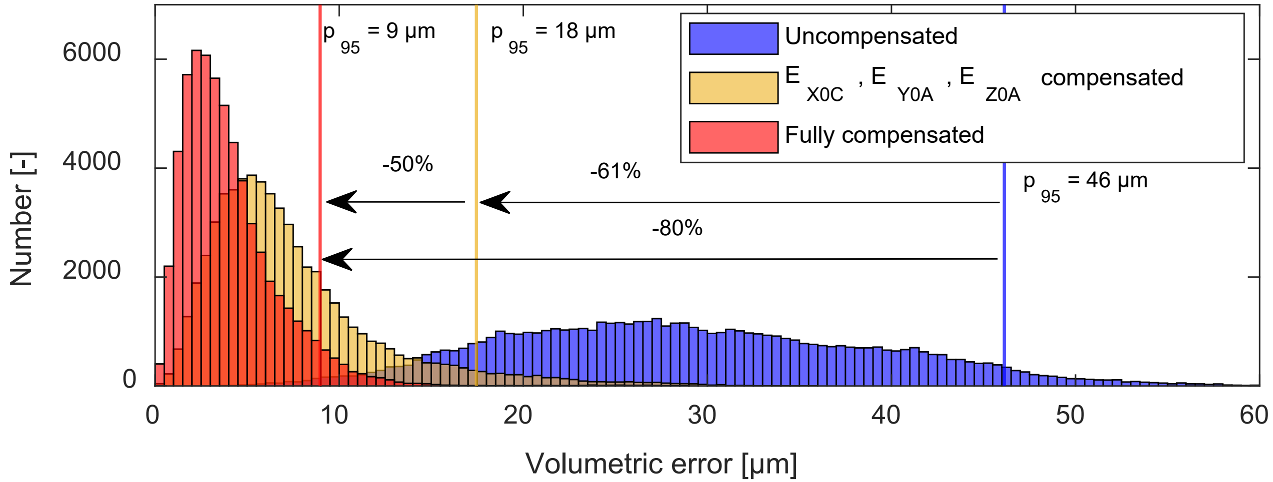

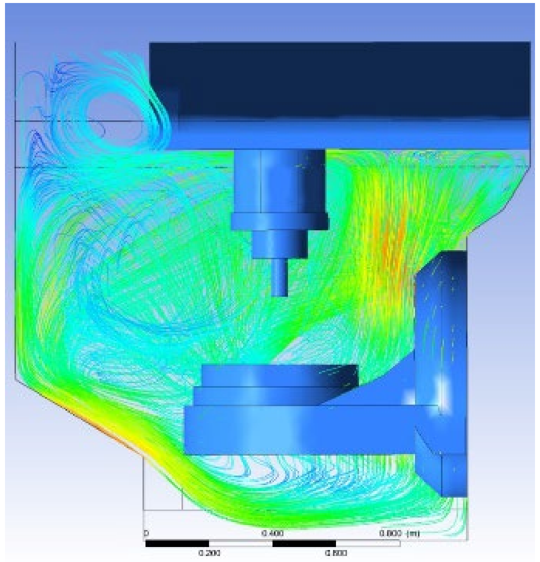

Evaluation of thermal compensated machine tools under machining conditions

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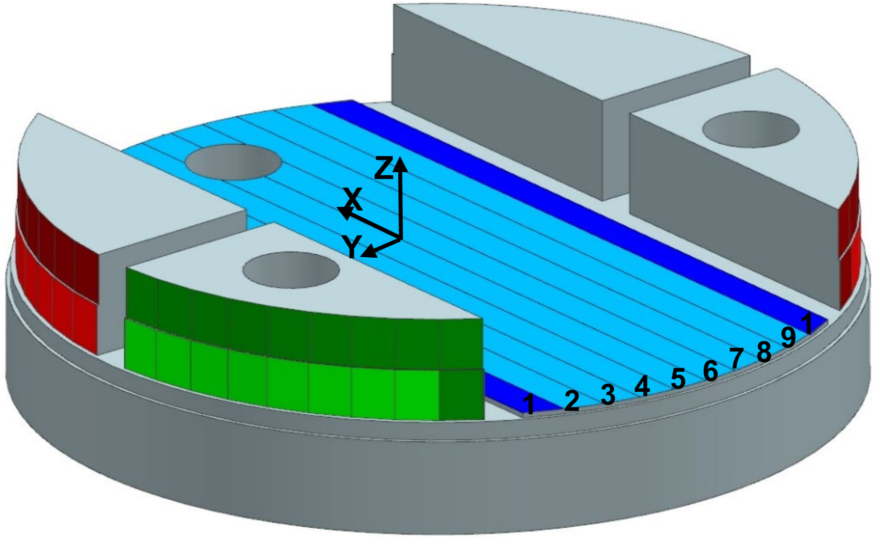
Thermal test piece



- Evaluation of the axis-specific thermal errors – identification of single errors

Impeller

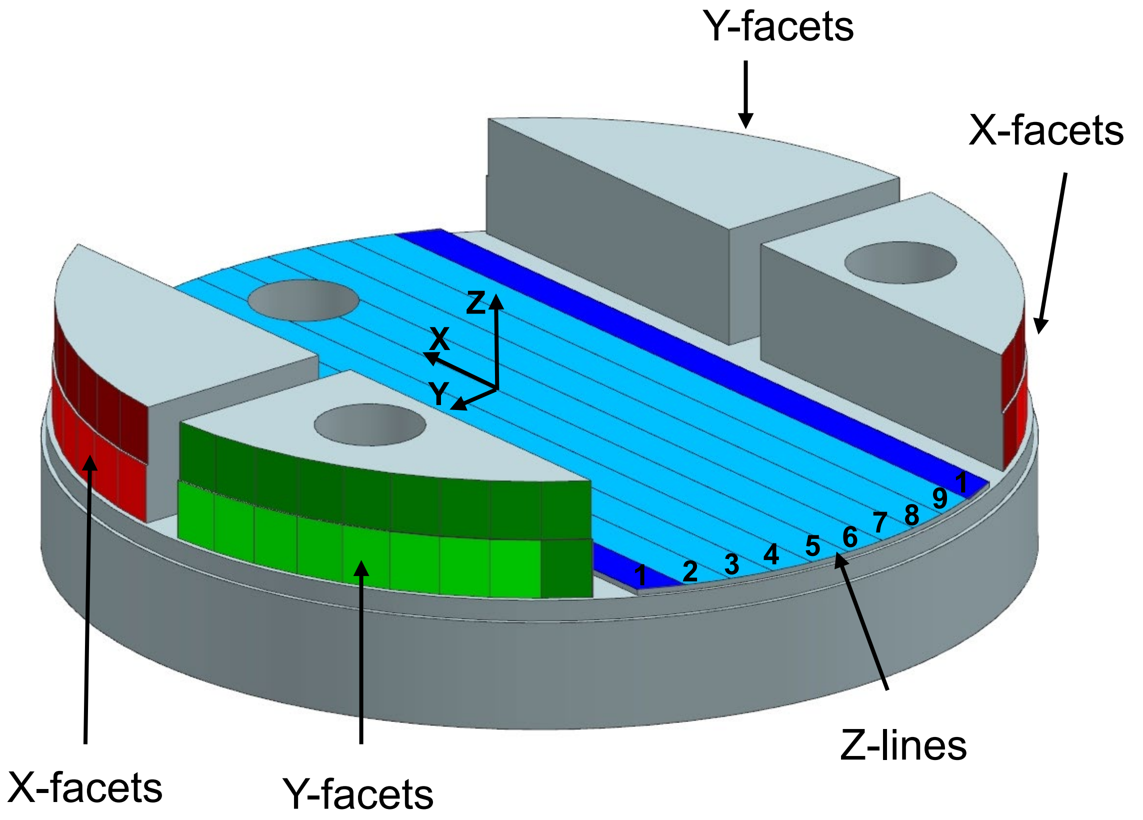
- Evaluation of the volumetric thermal errors – interpolating manufacturing case

➔ Dry and wet maching of Aluminium
➔ Thermal behaviour of the workpiece is not yet included
➔ Analysis of the thermal error compensation at additional working space positions

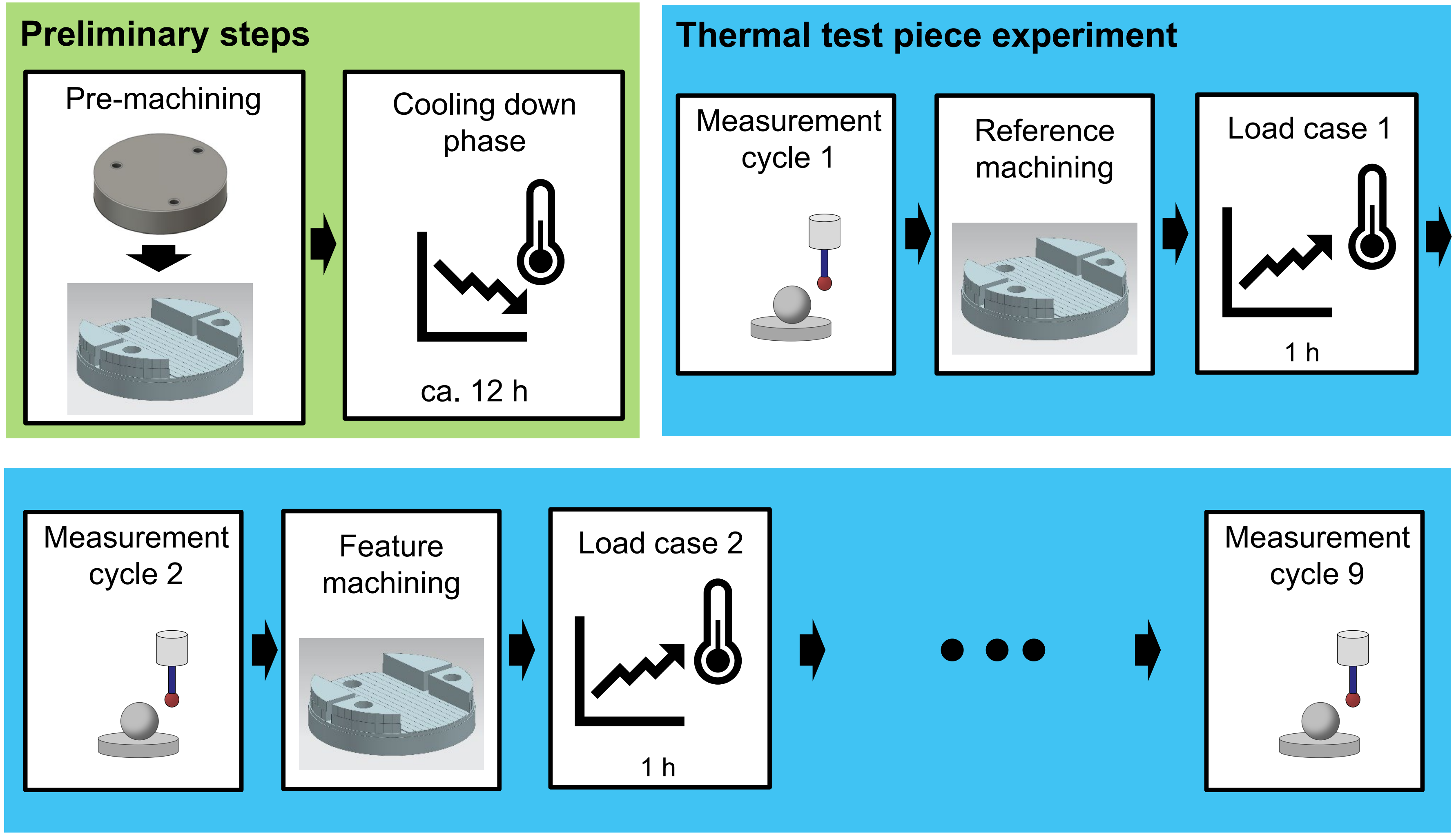
Analysed thermal test piece (TTP)

- Developed at IWF (ETH Zürich), and defined in ISO 10791-10:2022
- Considered thermal errors of a rotary axis for nine time steps
  - X-direction: E_X
  - Y-direction: E_Y
  - Z-direction: E_Z
  - Radial direction: E_{TTP}
- Characteristics:
  - Diameter: 160 mm
  - Material: aluminium

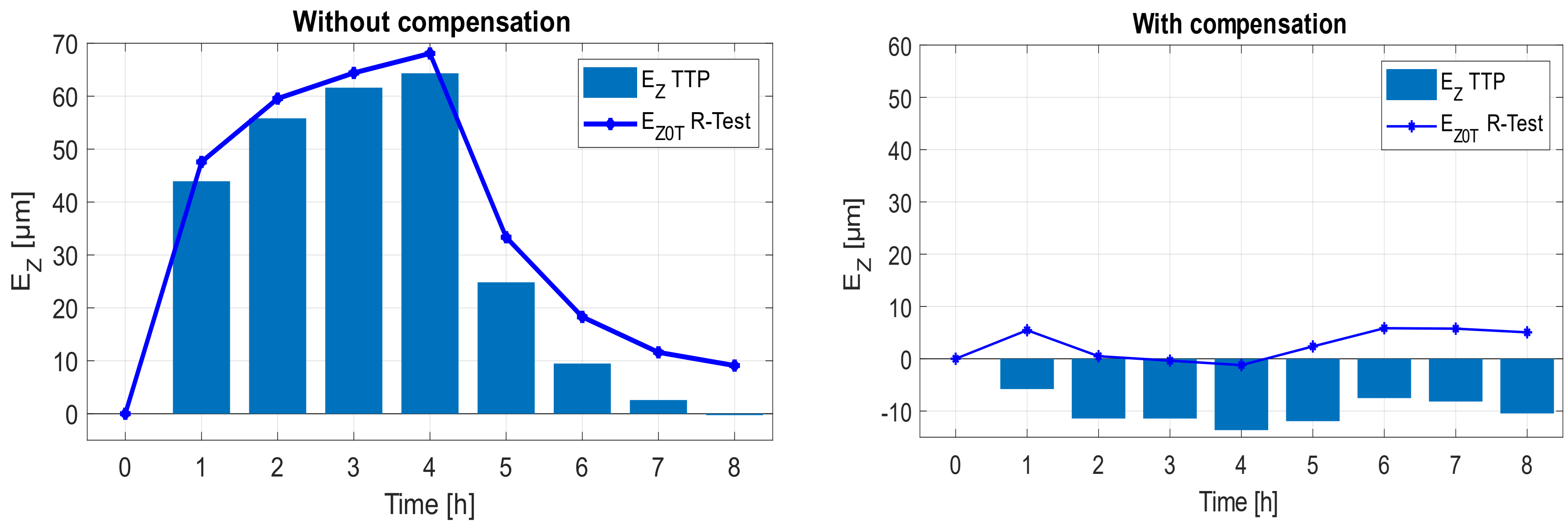
Wiessner 2017



Procedure of thermal test piece experiments



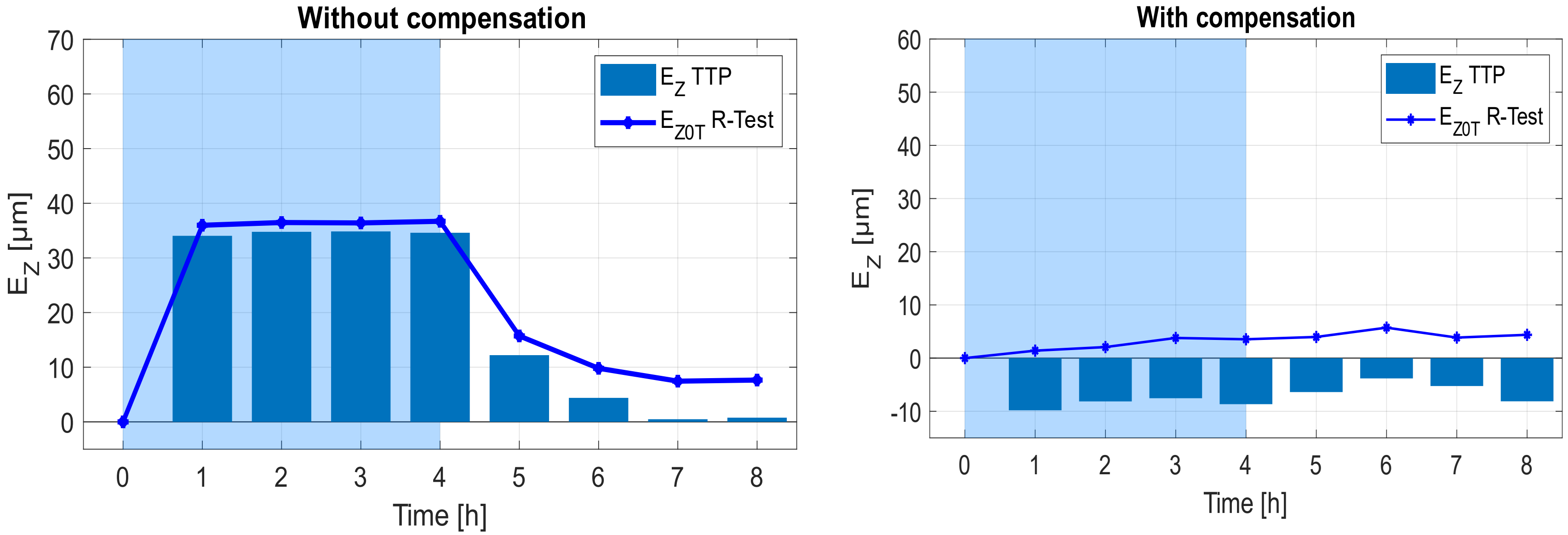
Compensation results for the TTP error in Z-direction



Error reduction

Peak-to-peak error
79%

Root-mean-square error
75%



Error reduction

Peak-to-peak error
72%

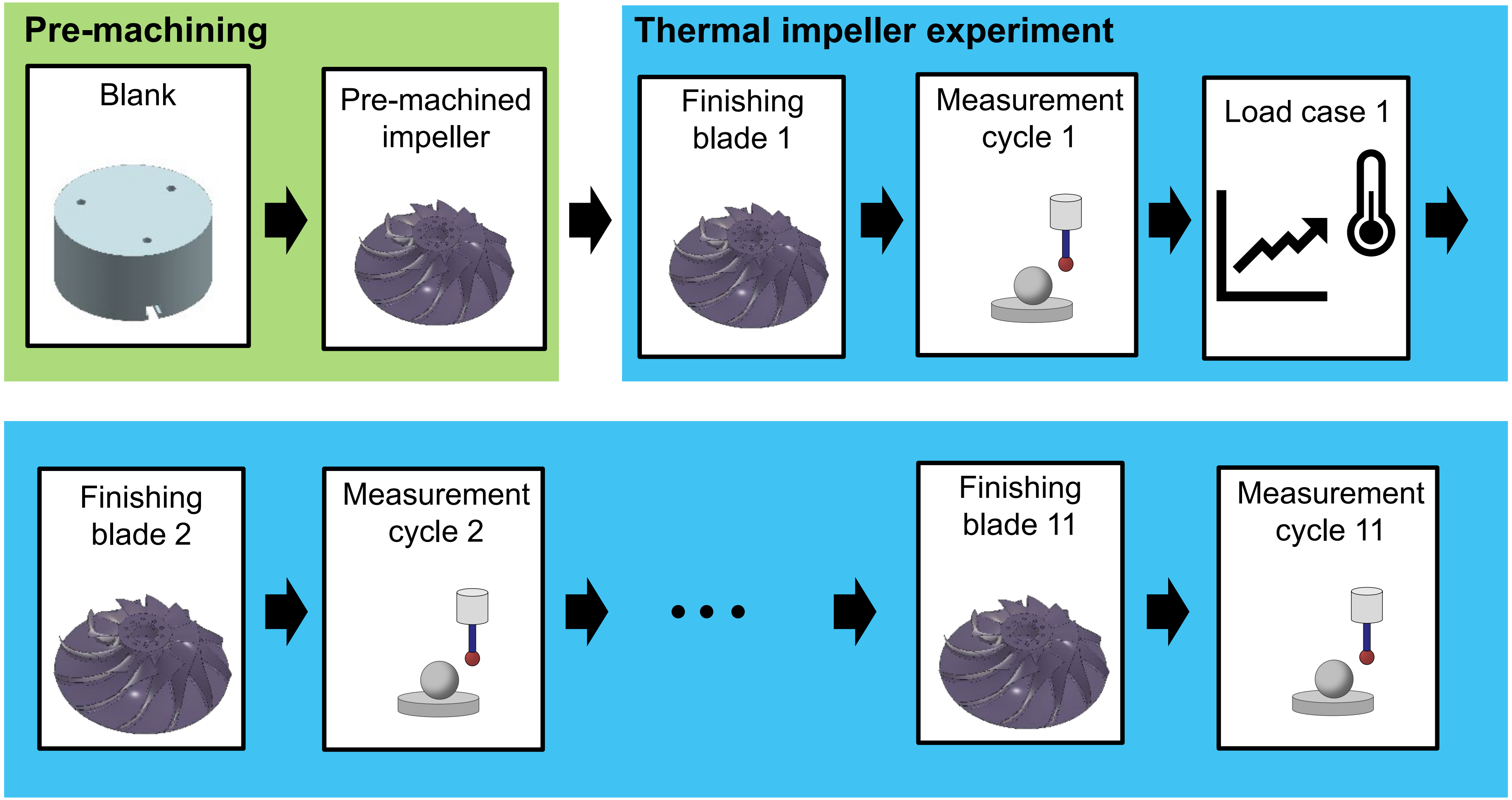
Root-mean-square error
70%

Evaluation of the self-learning thermal error compensation during simultaneous 5-axis milling

- Using impellers to evaluate thermally compensated 5-axis machine tools
  - Offering repeating features
  - Free-form surfaces for 5 axis interpolation
  - Enabling relative analysis of thermal errors
  - Already used to evaluate geometrical compensation strategies

- Characteristics of the used impeller
  - Number of blades: 11
  - Blade thickness: 1 mm
  - Finishing of all blades with the same NC-code
  - Material removal during finishing: 100 µm

Procedure of thermal impeller experiments



Comparison between the uncompensated and the compensated impeller

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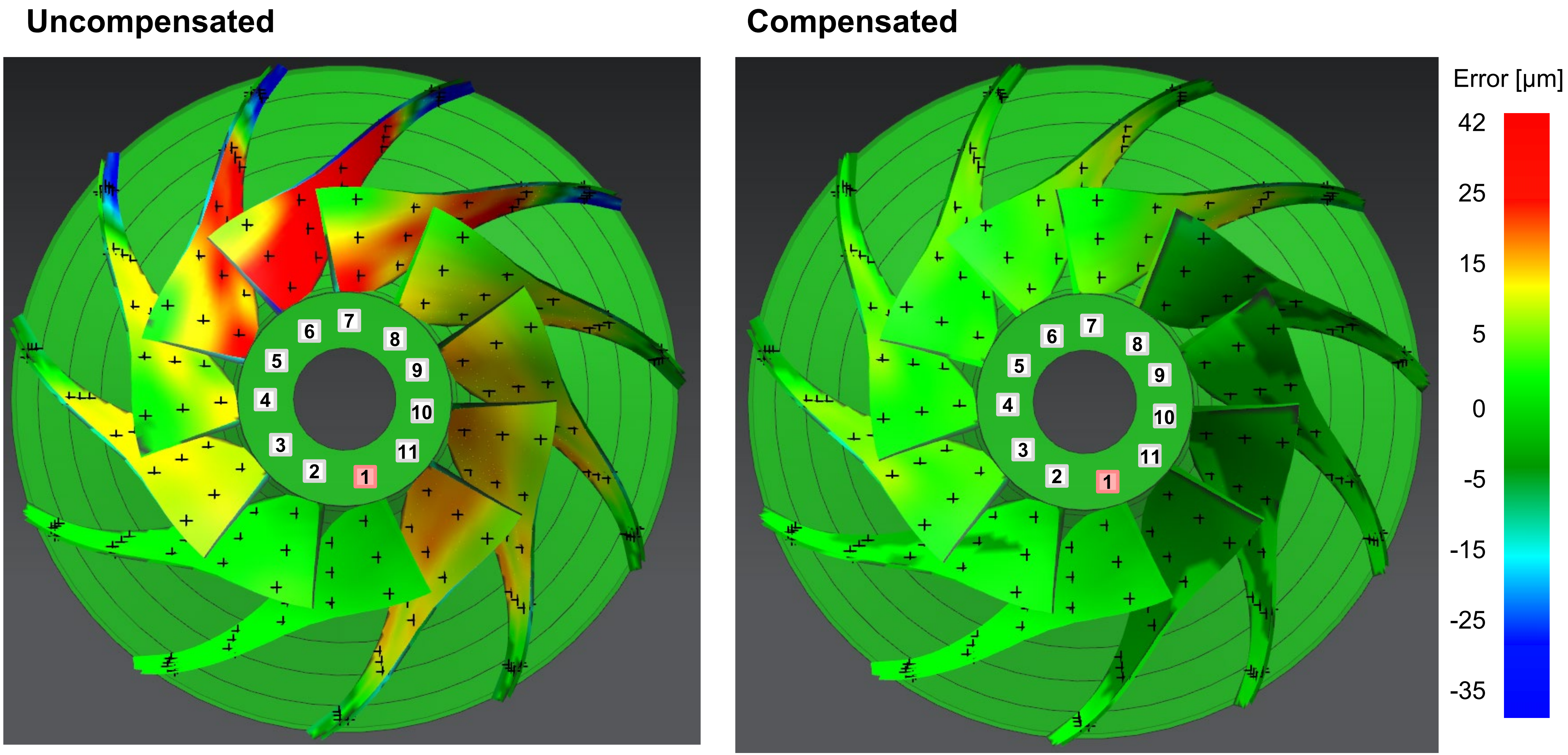

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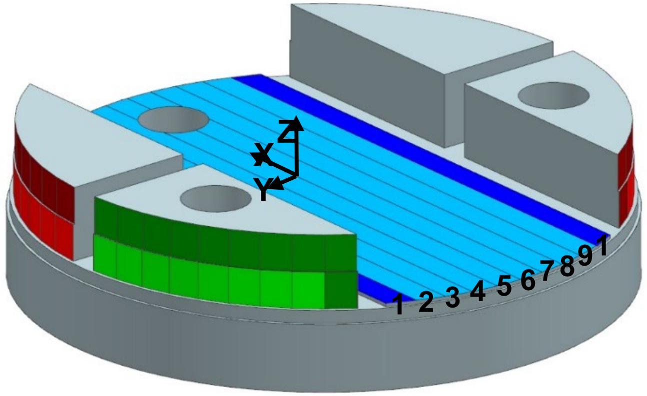
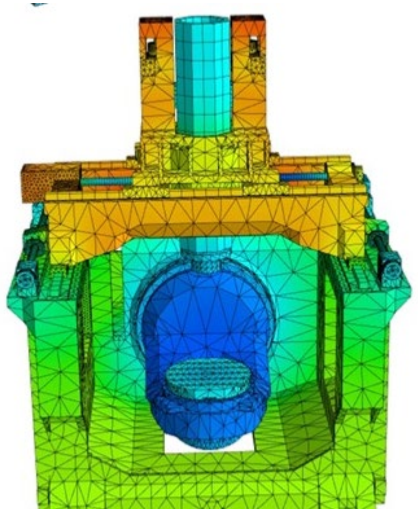
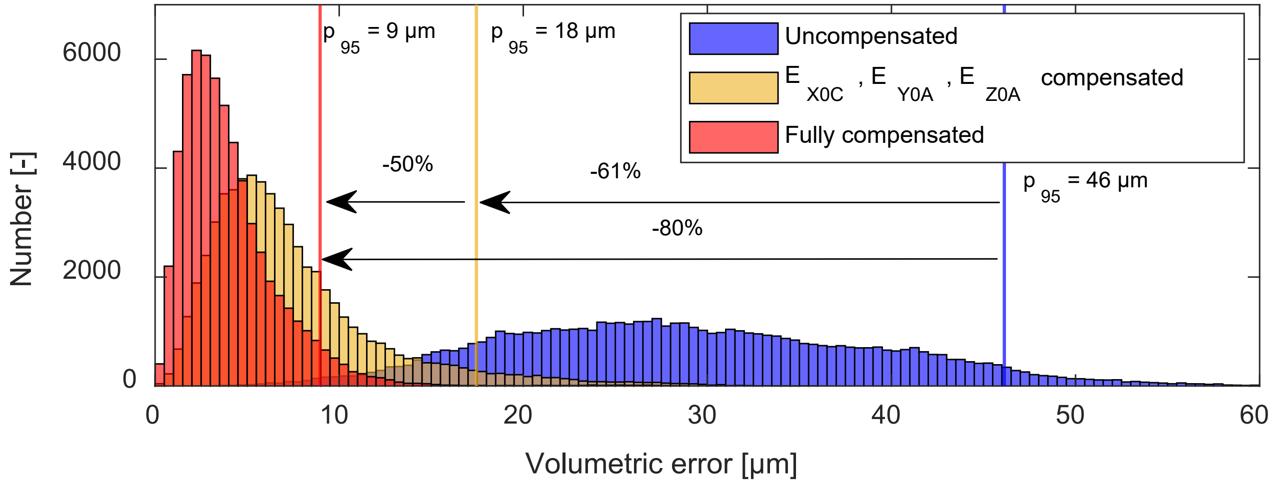
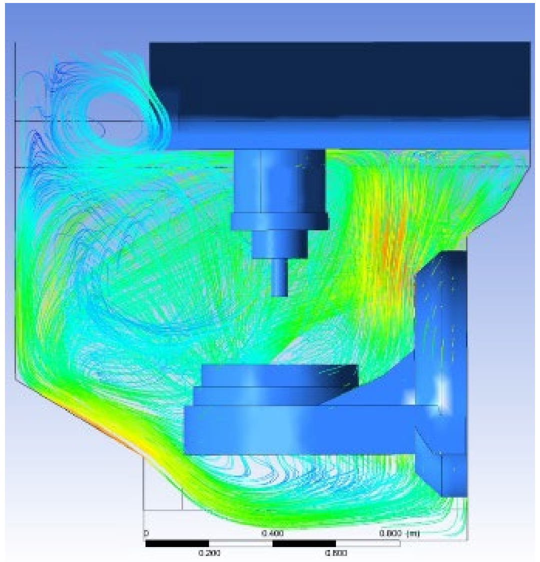


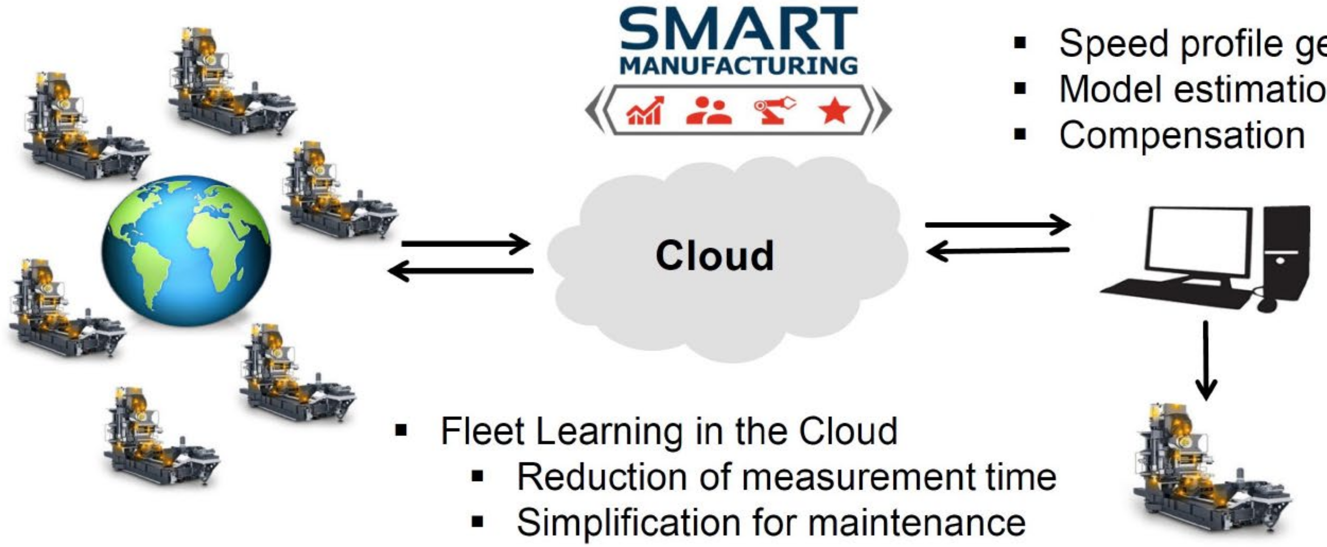






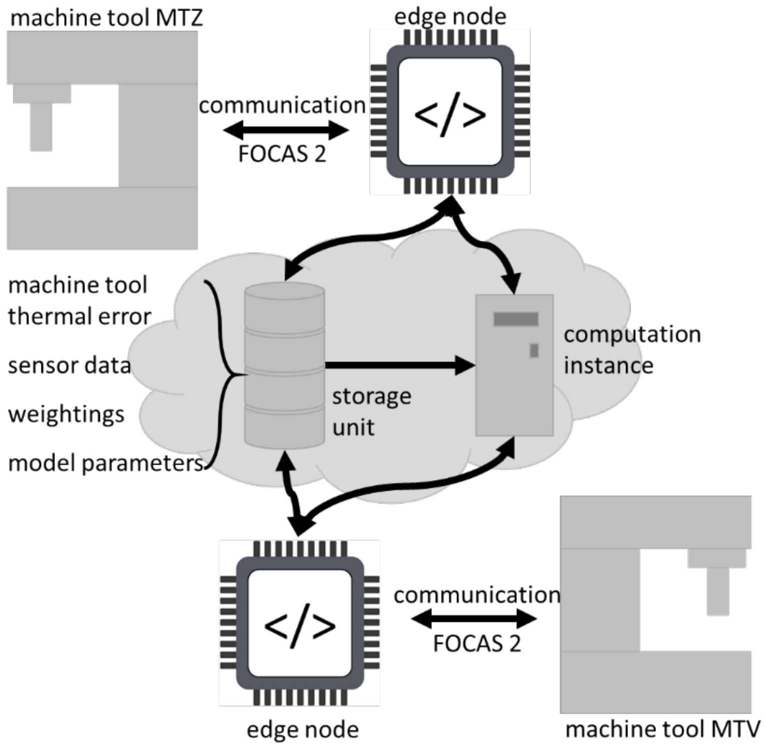
Connectivity for thermal compensation

- Can trained models be exchanged between machines:
  - same type
  - same type series but different size
  - same class



- Speed profile generation
- Model estimation
- Compensation

- Fleet Learning in the Cloud
  - Reduction of measurement time
  - Simplification for maintenance



Mayr 2022

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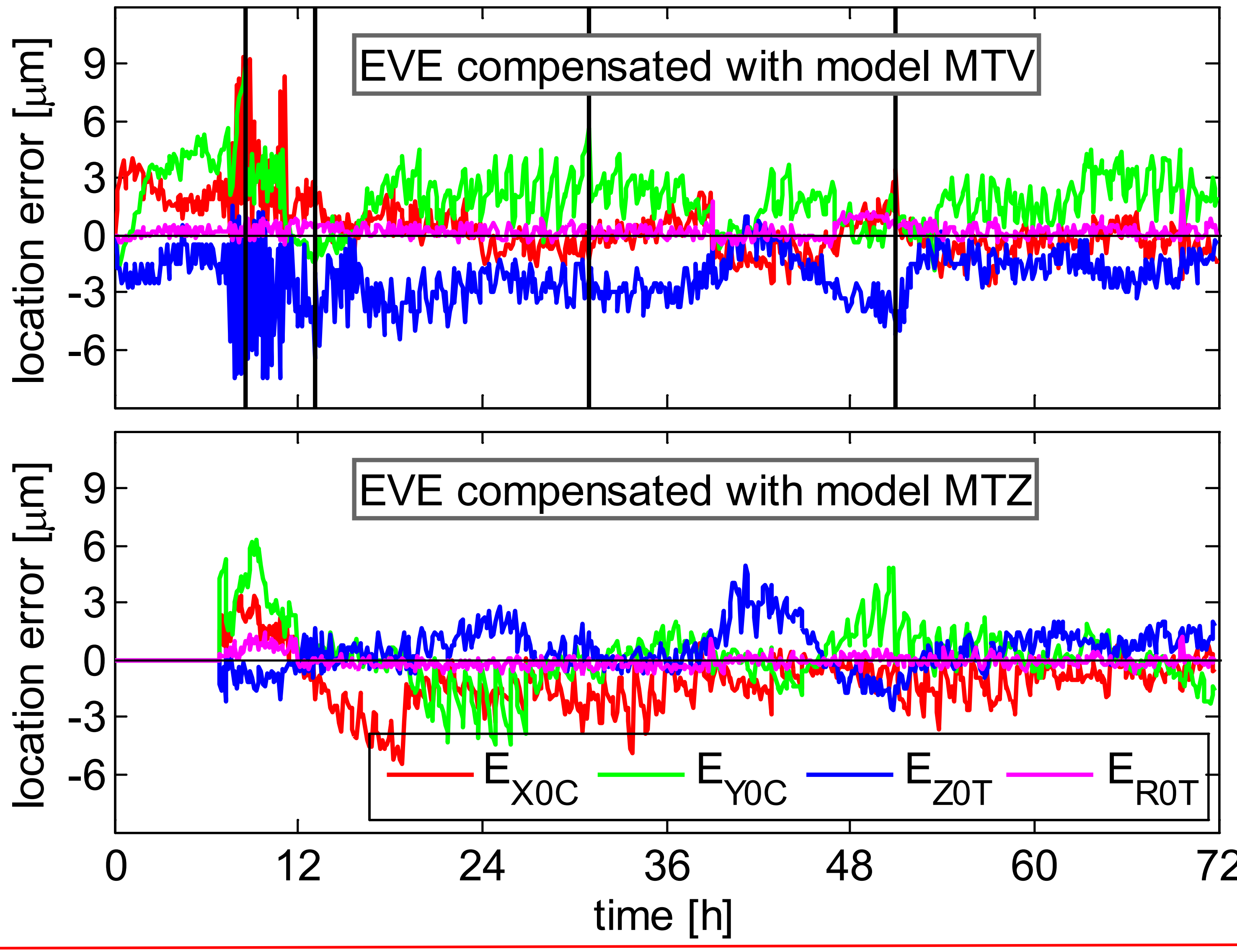
- Same type
- Difference in equipment
- Different age and wear state
- Different environmental conditions

  - ➔ Teaching effort significantly smaller
  - ➔ Better learning results with worse environment



Stoop, Sulz,… 2022

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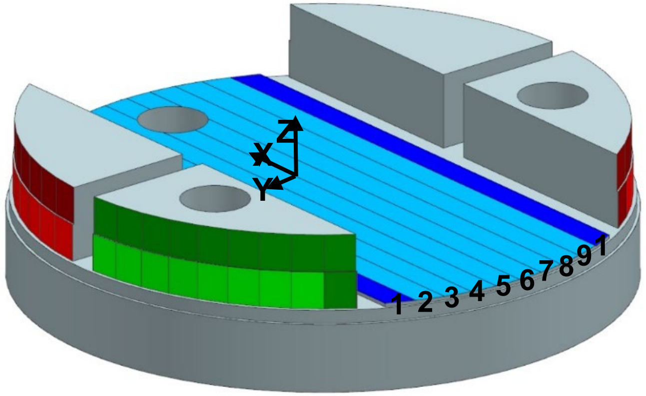

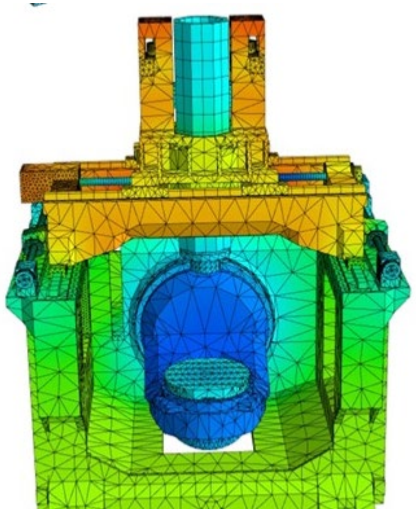

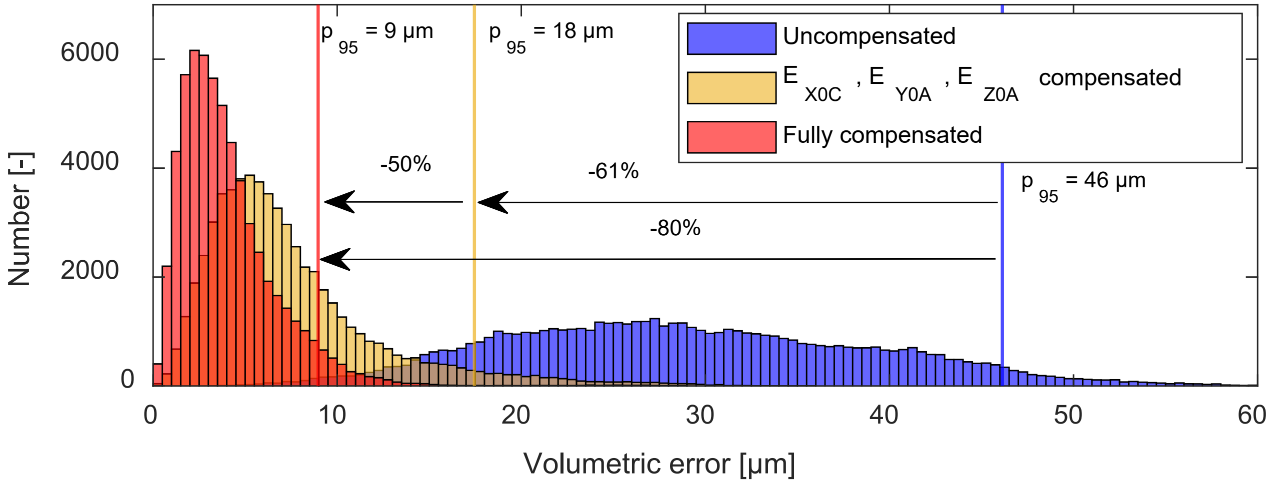

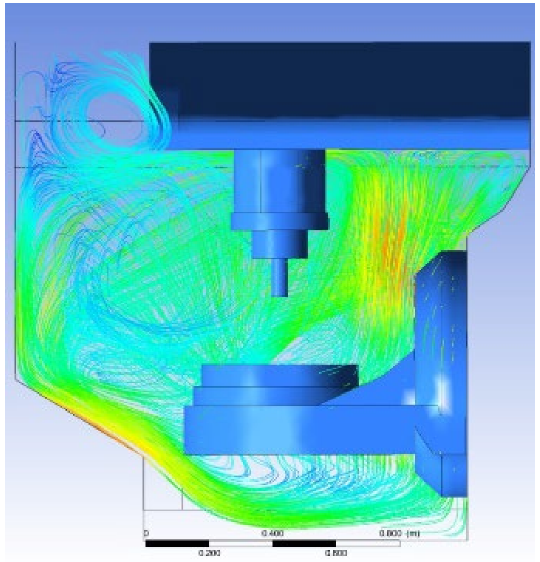

Conclusion

- Compensation approaches:
  - Field equations
  - Model order reduced field equations
  - Phenomenological self learning models
- Cooling simulation in all aspects still lacks suitable heat transfer coefficients
- Long term stable thermal compensation possible with ARX models and input selection
- Different approaches for different types of machine tools necessary
- Thermal test pieces demonstrate the thermal movements of machine tools
- Full thermal compensation of five axis machine tools works even with five axis interpolation
- Federated learning among machine tools possible and able to bridge at least differently equipped machines
- Open challenges:
  - Accuracy in FEM simulations (physical parameters)
  - Fluid and air influence (convection, flow, heat transfer, evaporation, exhaust, covers)
  - Thermal memory and time delay
  - Mechanical interfaces
  - Thermal behavior of workpiece

The support of MTTRF, San Francisco is greatly acknowledged

ICTIMT 2025 in June, 17-19 in Zurich

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ETH zürich

IWF
Institut für Werkzeugmaschinen und Fertigung
Institute of Machine Tools and Manufacturing


Thank you for your kind attention
Machine Tool is cool!