CORNET project *GeoComp*

Compensation of geometrical errors of kinematic chains caused by thermal deformations

Authors:

Christian Naumann, Philipp Klimant, Sebastian Lang, Josef Mayr, Evgenii Oborin, Christoph Einspieler, Friedrich Bleicher, Konrad Wegener

Title:

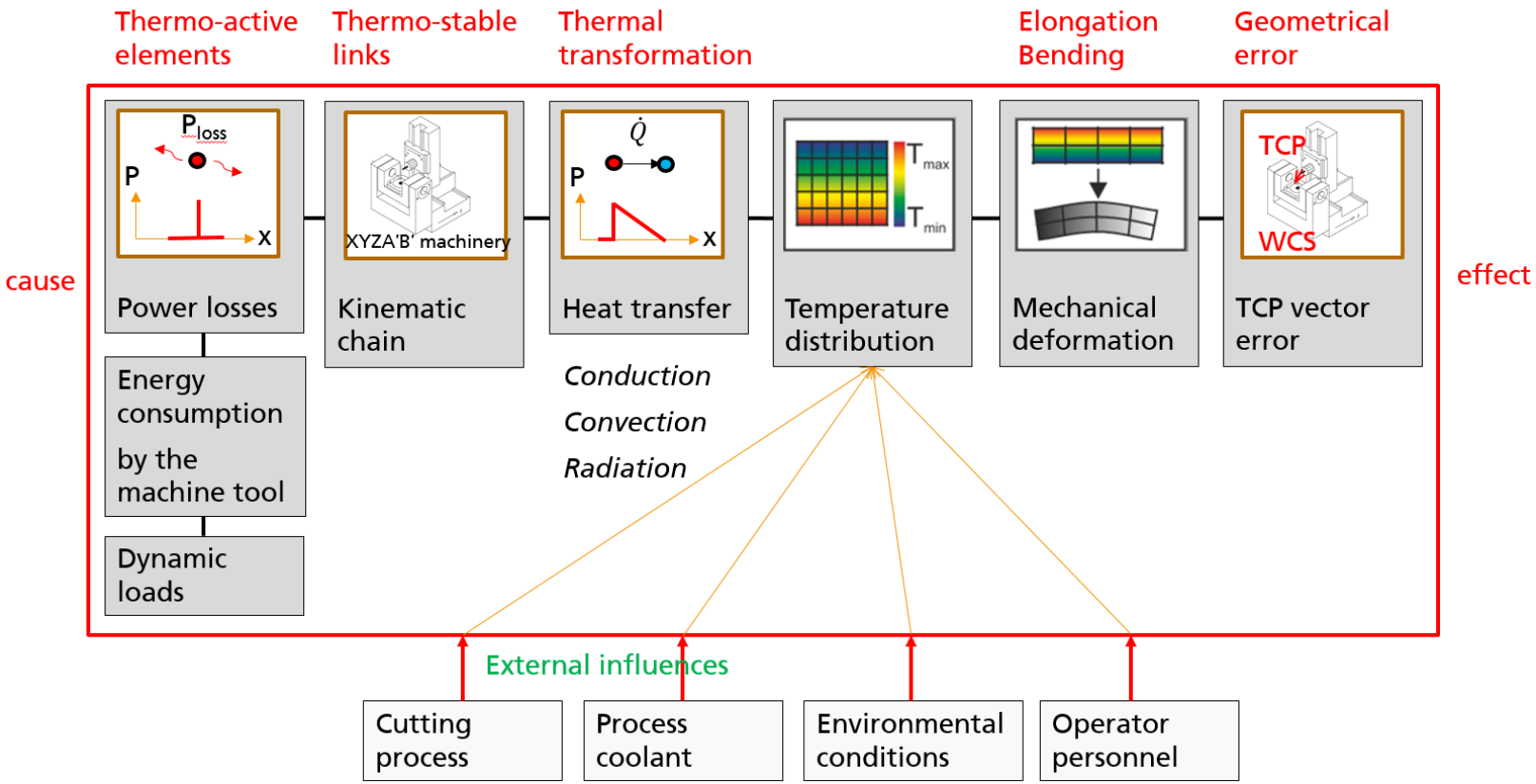
Hybrid thermal error compensation using mixed targeted assembly error models

Special Interest Group: Thermal Issues

Eindhoven, March 14th 2024

Thermal effects in machine tools

Thermo-elastic chain of effects and compensation methods



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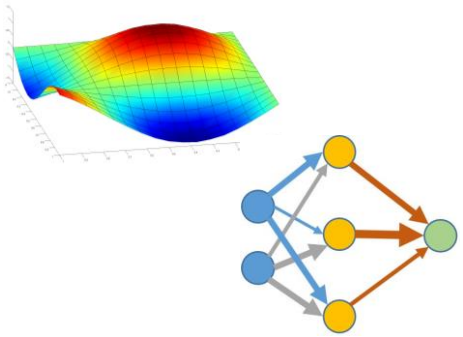
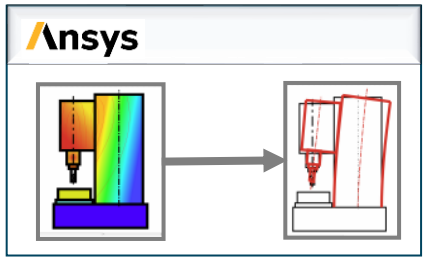


Real-time simulations



cause

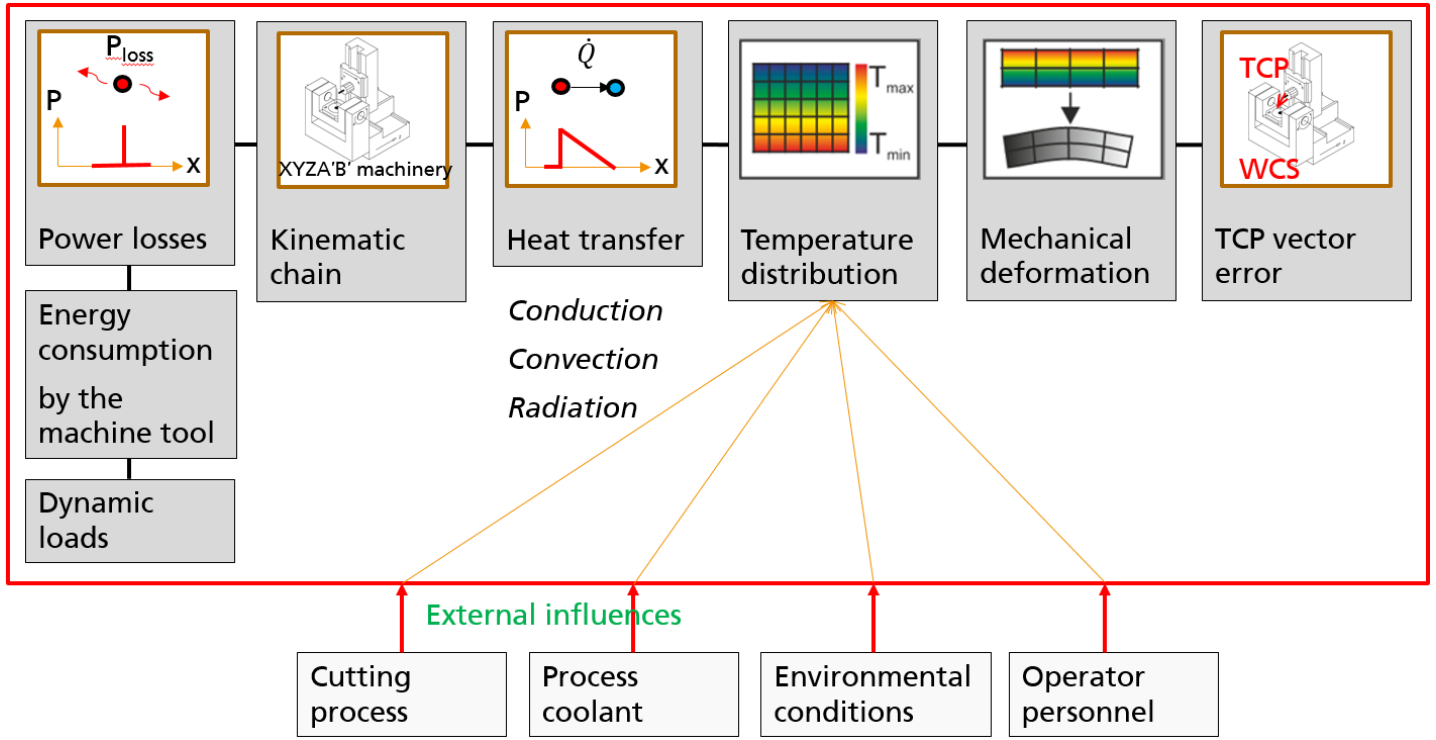
Thermo-active elements

Thermo-stable links

Thermal transformation

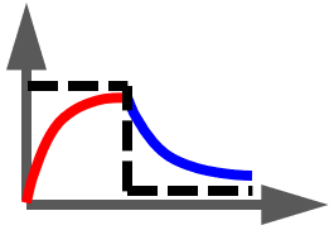
Elongation Bending

Geometrical error

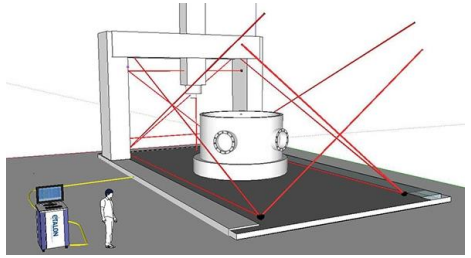


effect

Phenomenological models



Measurement-based models



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Regression models, ANN

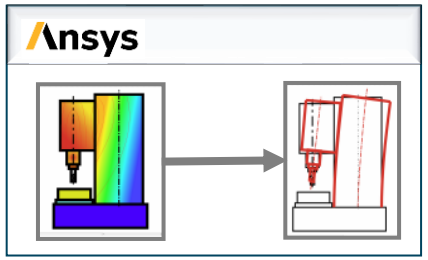
simple implementation

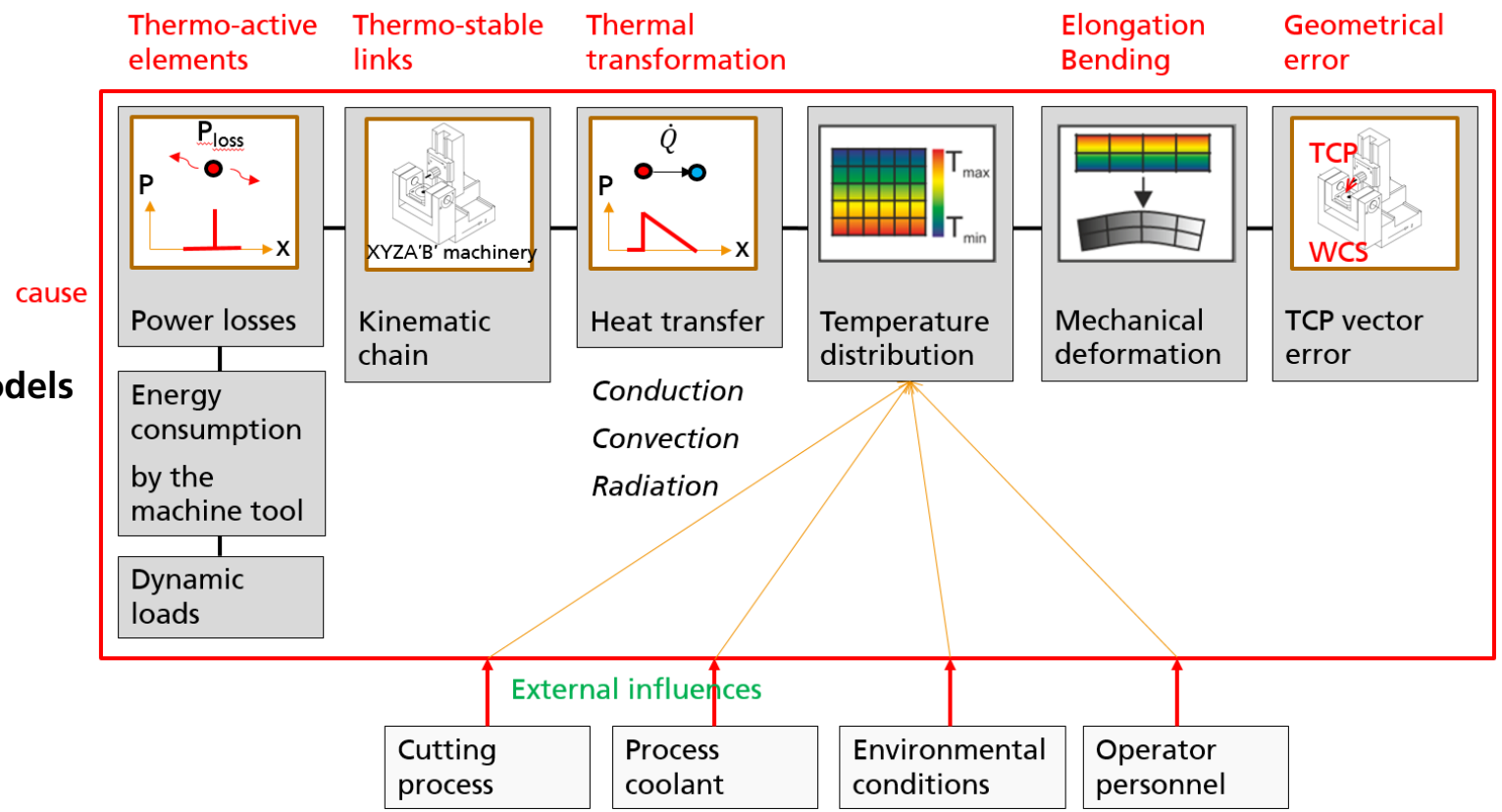
effective for know load cases

data hungry

poor extrapolation

Real-time simulations





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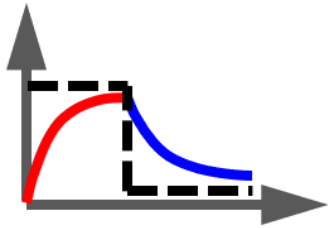

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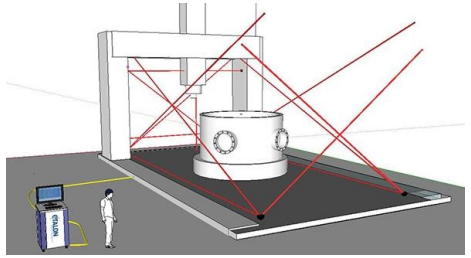

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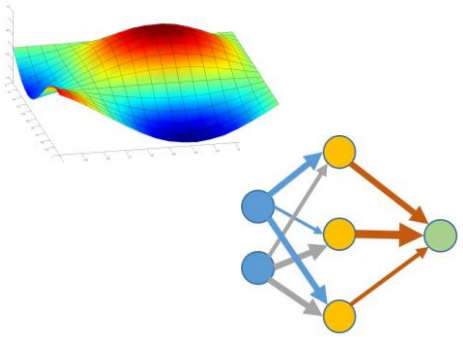

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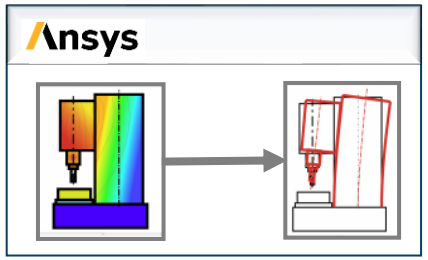

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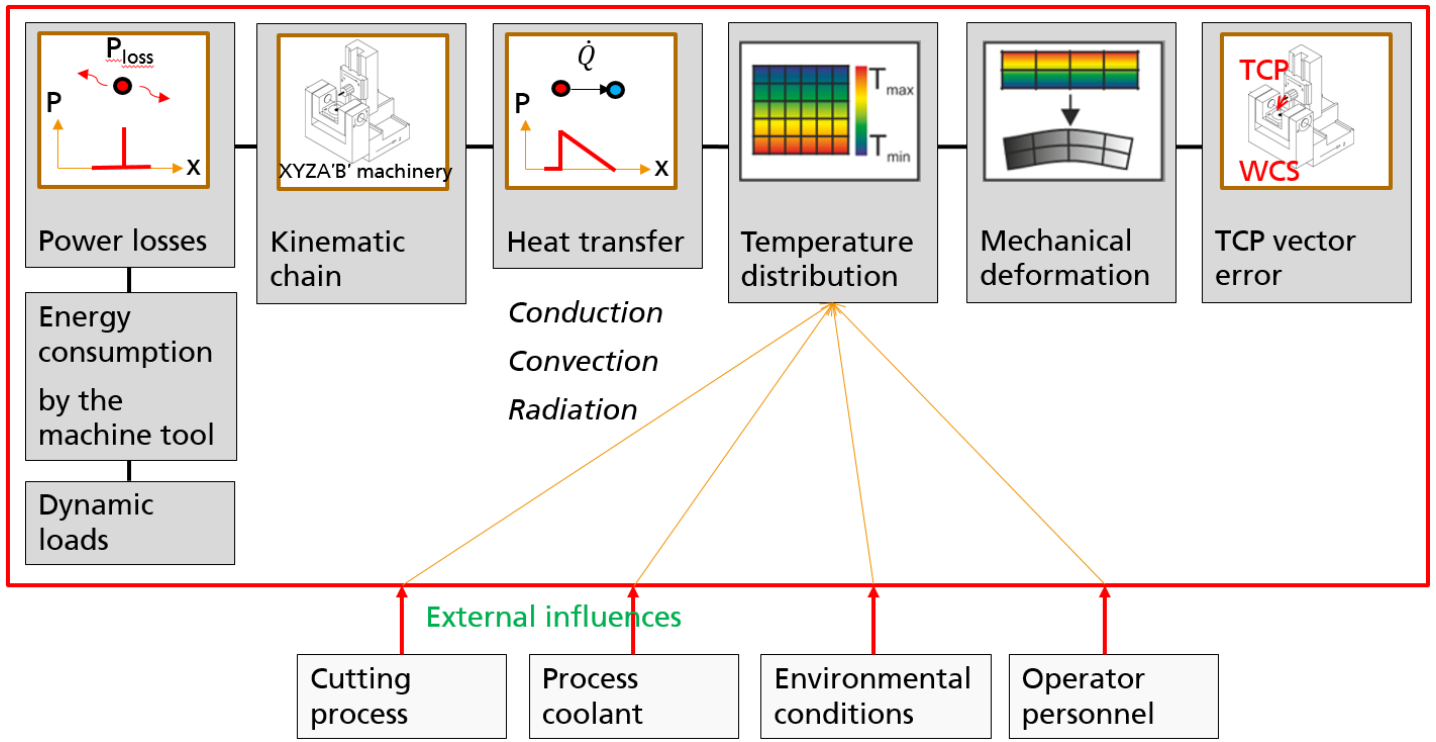
Thermo-active elements | Thermo-stable links | Thermal transformation | Elongation Bending | Geometrical error



effect

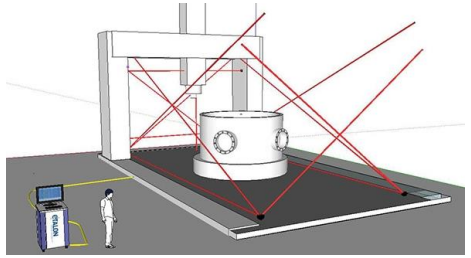
Phenomenological models

simple

good at mapping time-dependent correlations

poor for complex, interacting loads

Measurement-based models



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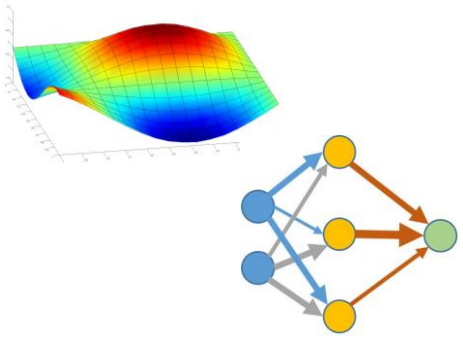
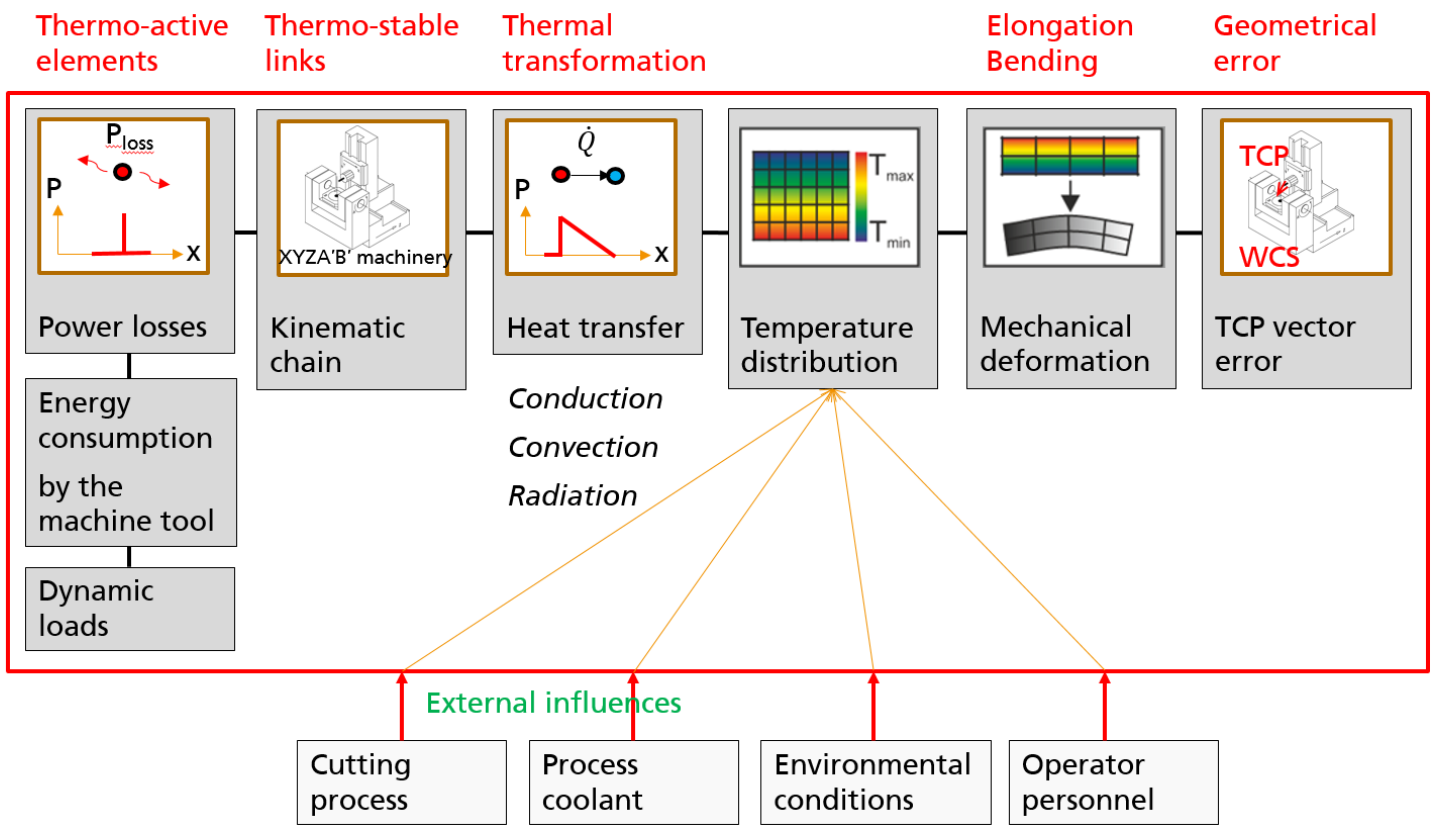


Real-time simulations

good extrapolation

good precision

very time-consuming modelling and parametrization



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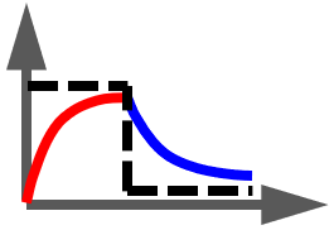

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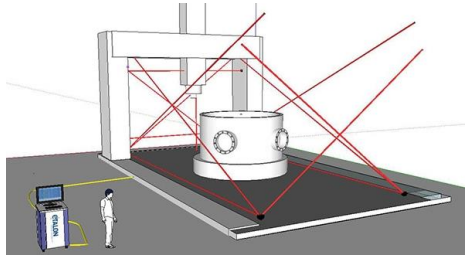

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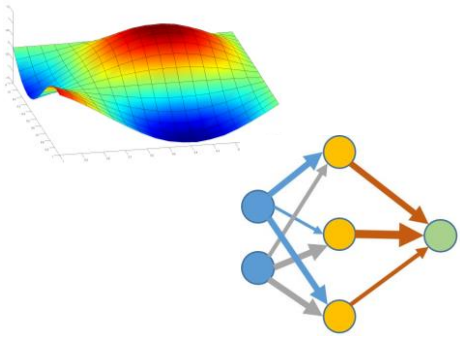

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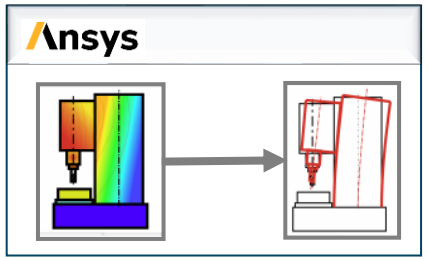

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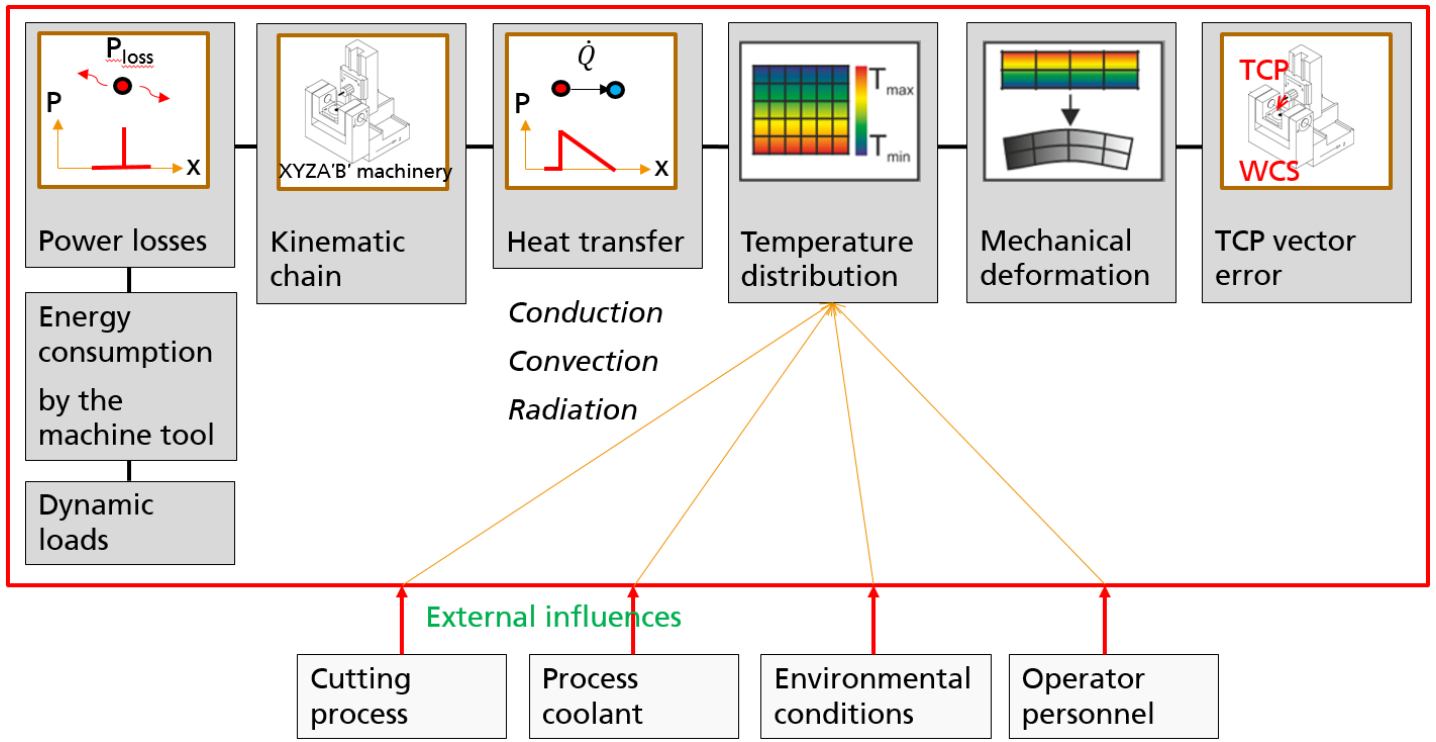

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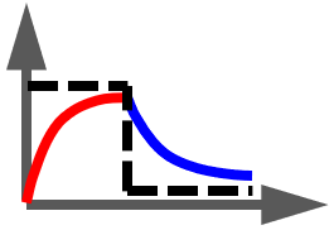

Measurement-based models

simple

reliable even for complex load cases

often loss of productivity

often impractical

Source 1

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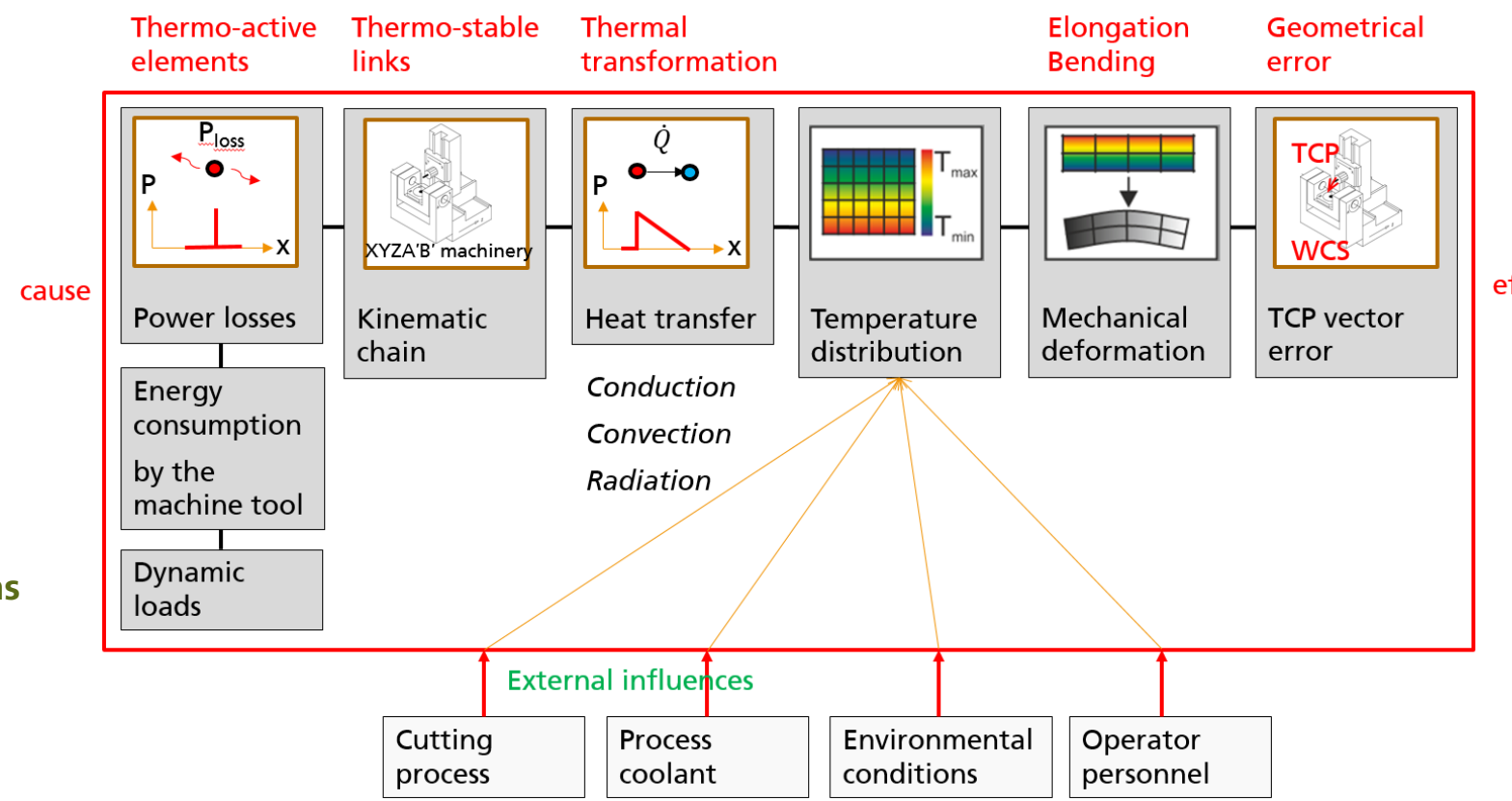
Thermal effects in machine tools

Thermo-elastic chain of effects and compensation methods

Regression models, ANN
simple implementation
effective for known load cases
data hungry
poor extrapolation

Real-time simulations
good extrapolation
good precision
very time-consuming modelling and parametrization



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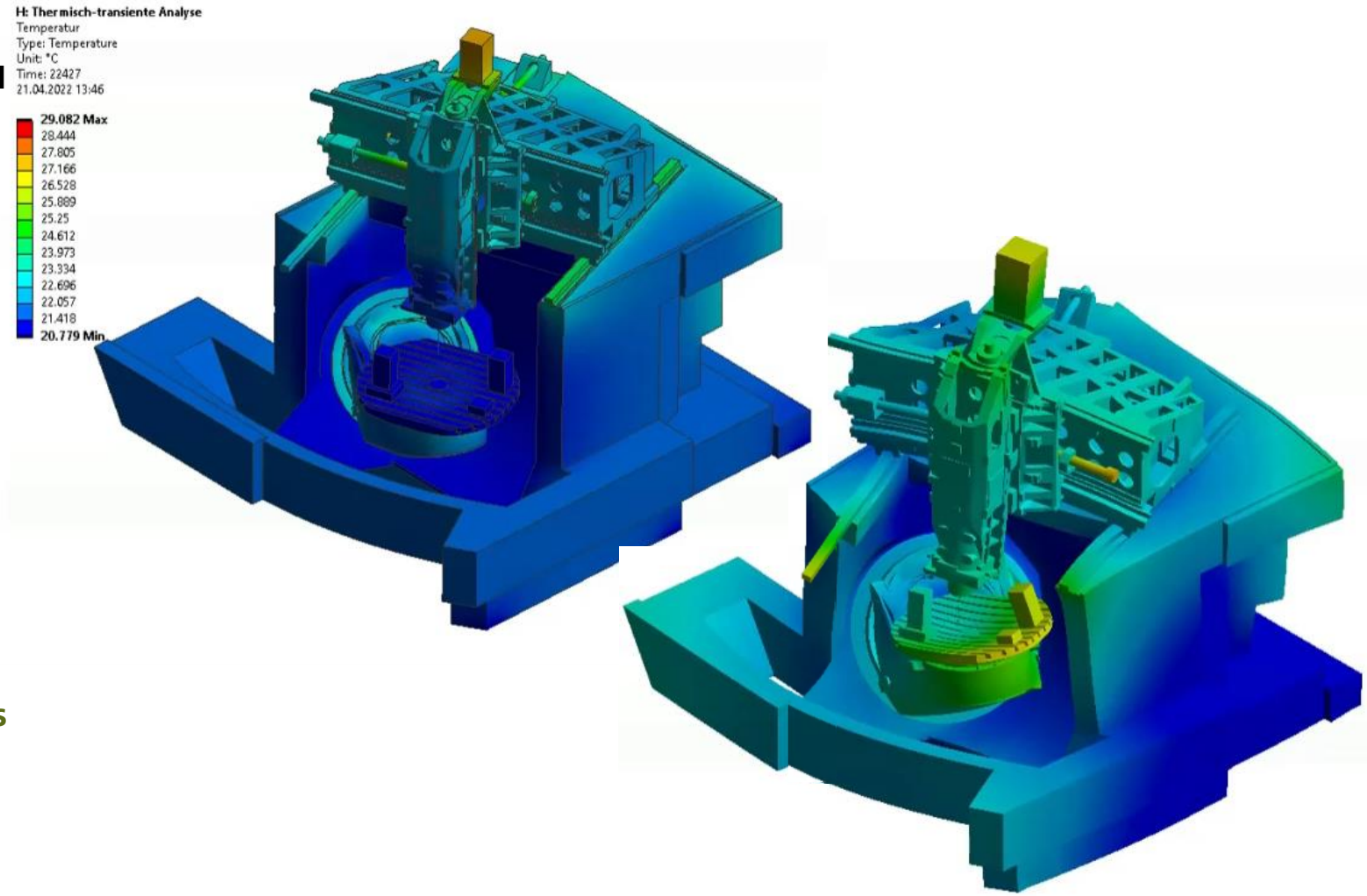

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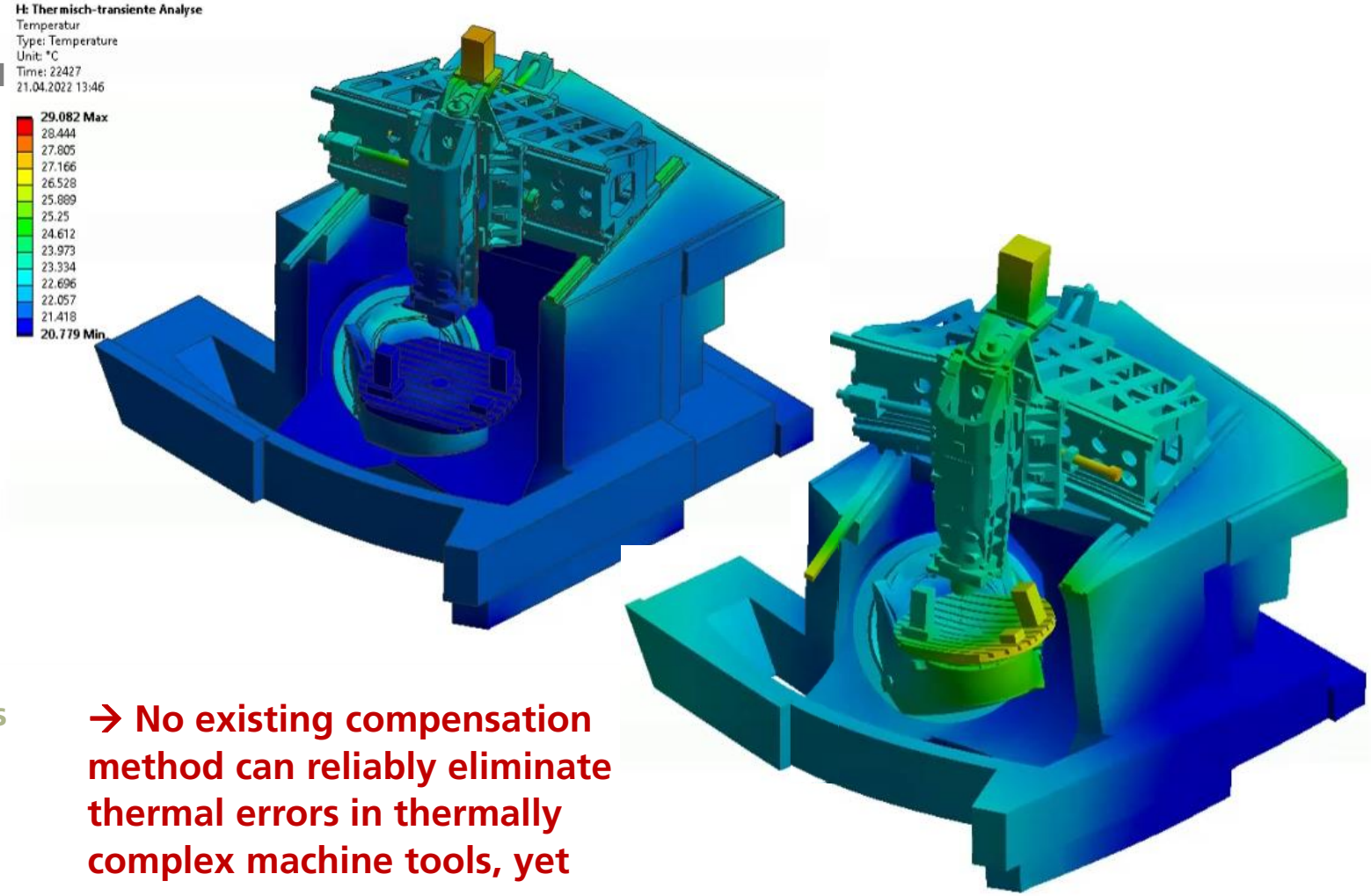

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→ No existing compensation method can reliably eliminate thermal errors in thermally complex machine tools, yet

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Thermal error compensation approach

Mixed targeted assembly error models

Hybrid compensation approach:

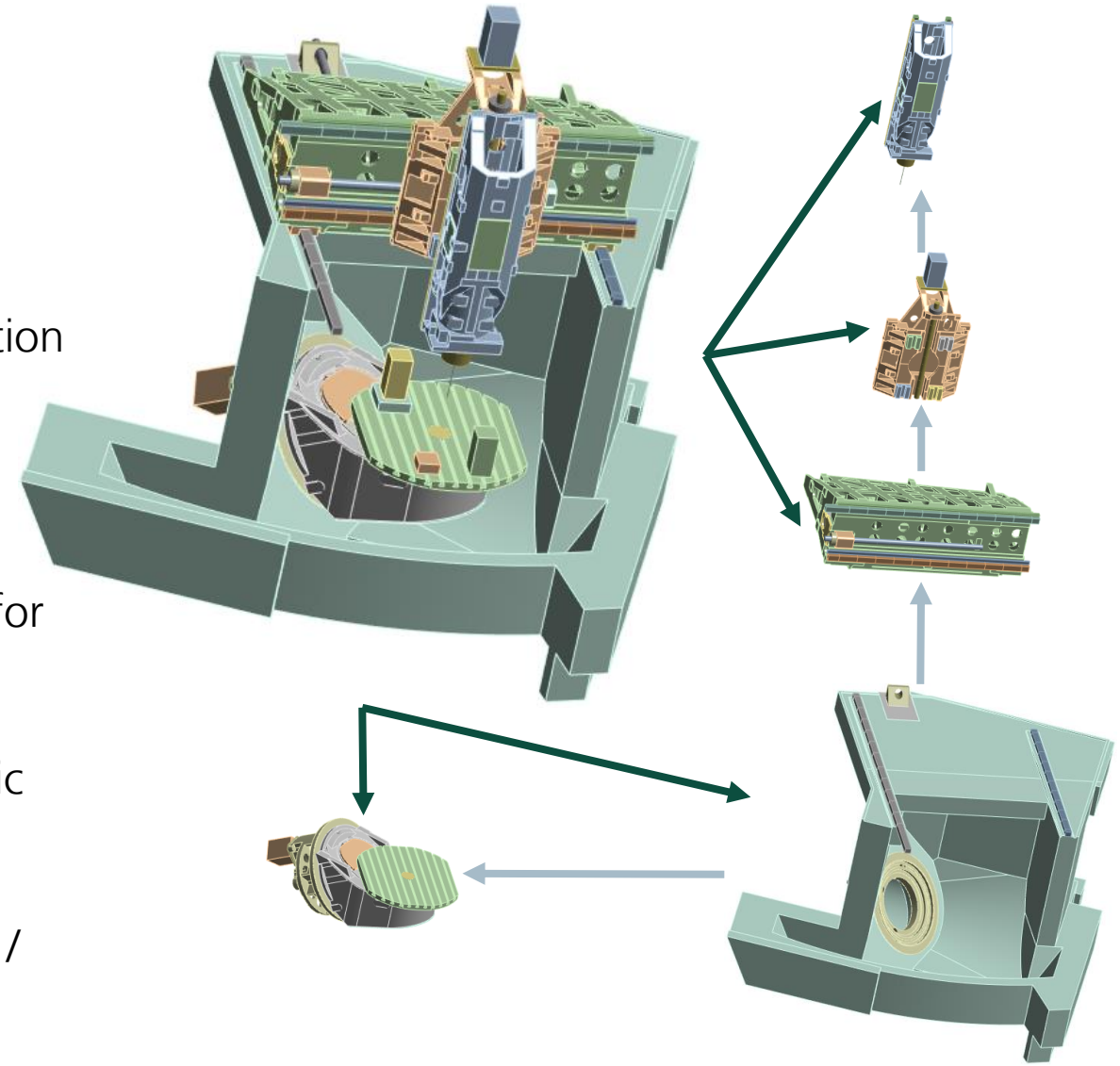
→ Combine the best of the above mentioned compensation models

→ Break down the thermal error to the assembly level

→ Find the most suitable error model or a hybrid model for each assembly

→ Combine the error models using a geometric-kinematic model

→ Optimize the model to account for changing machine / ambient states



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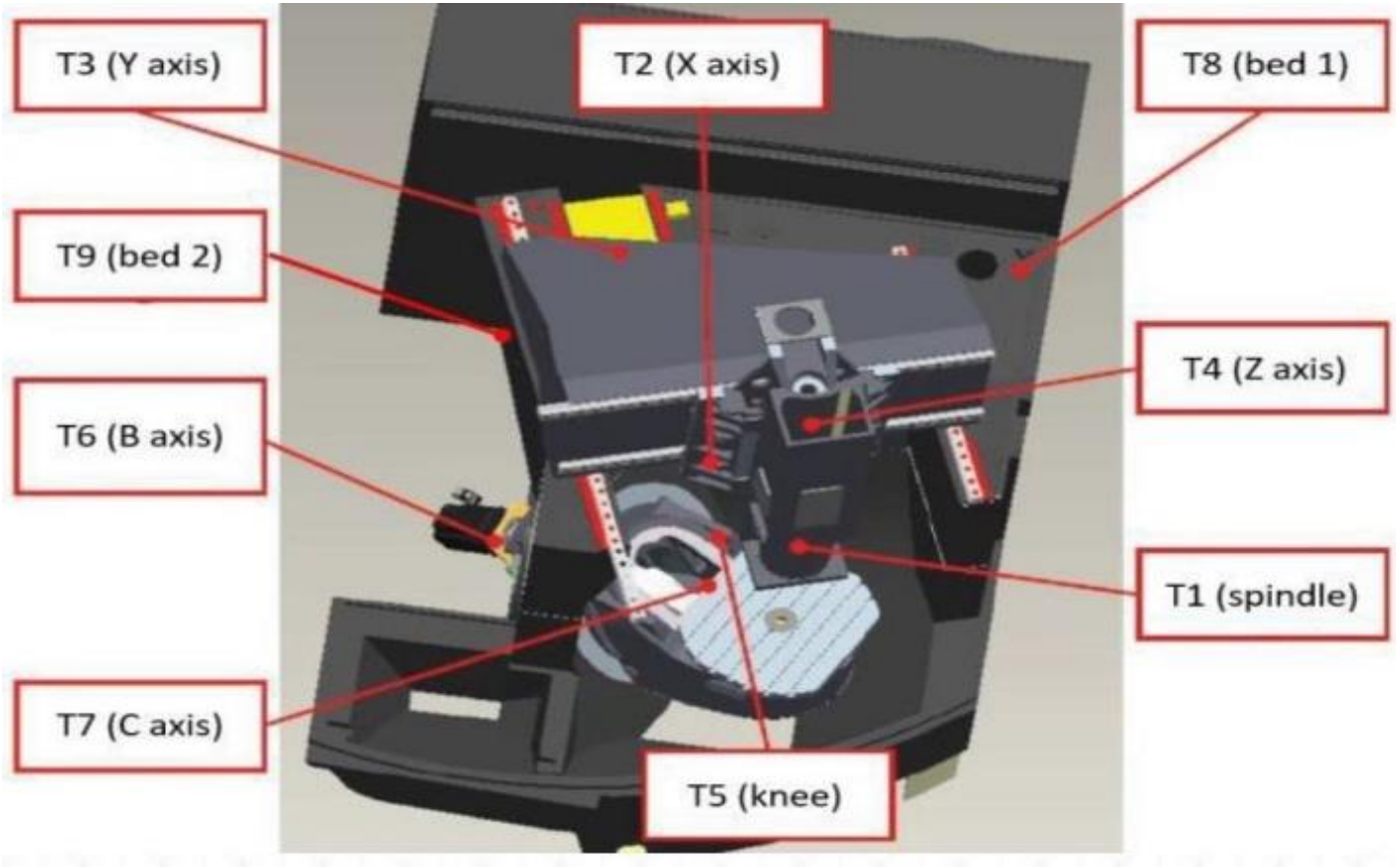
Thermal error compensation approach

Mixed targeted assembly error models

Available model inputs:

- Eight temperature sensors
- Five motor currents
- Five axis positions
- Five axis speeds
- Spindle speed
- (Ambient temperature)
- (Coolant temperature)



Source 3

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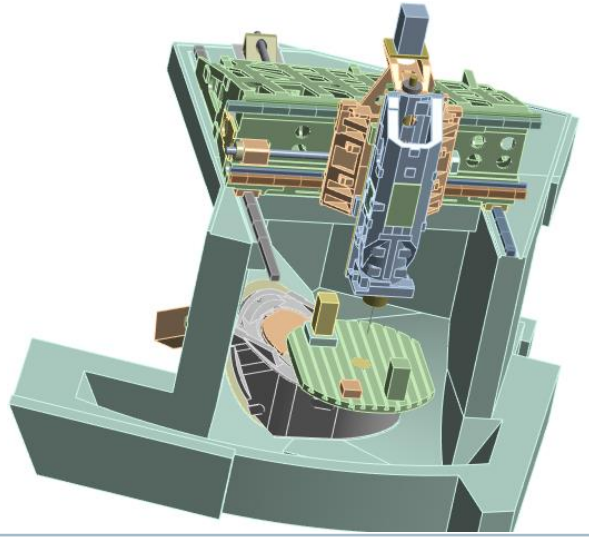
Thermal error compensation approach

Thermo-elastic FEM simulations for model training



Load case		
1 Y-axis movement	A dry heating by cyclic Y-axis motion	G1 Y 75% S 100%
	B heating by cyclic Y-axis motion with cutting fluid	G1 Y 75% S 100%
	C cool-down in standby	-
2 Z-axis movement	A dry heating by cyclic Z-axis motion	G1 Z 75% S 100%
	B heating by cyclic Z-axis motion with cutting fluid	G1 Z 75% S 100%
	C cool-down in standby	-
3 all-axis movement	A dry heating by cyclic sequential motion of all 5 axes	G1 X 75% S 100%
	B heating by cyclic sequential 5-axis motion with cutting fluid	G1 X 75% S 100%
	C cool-down in standby	-

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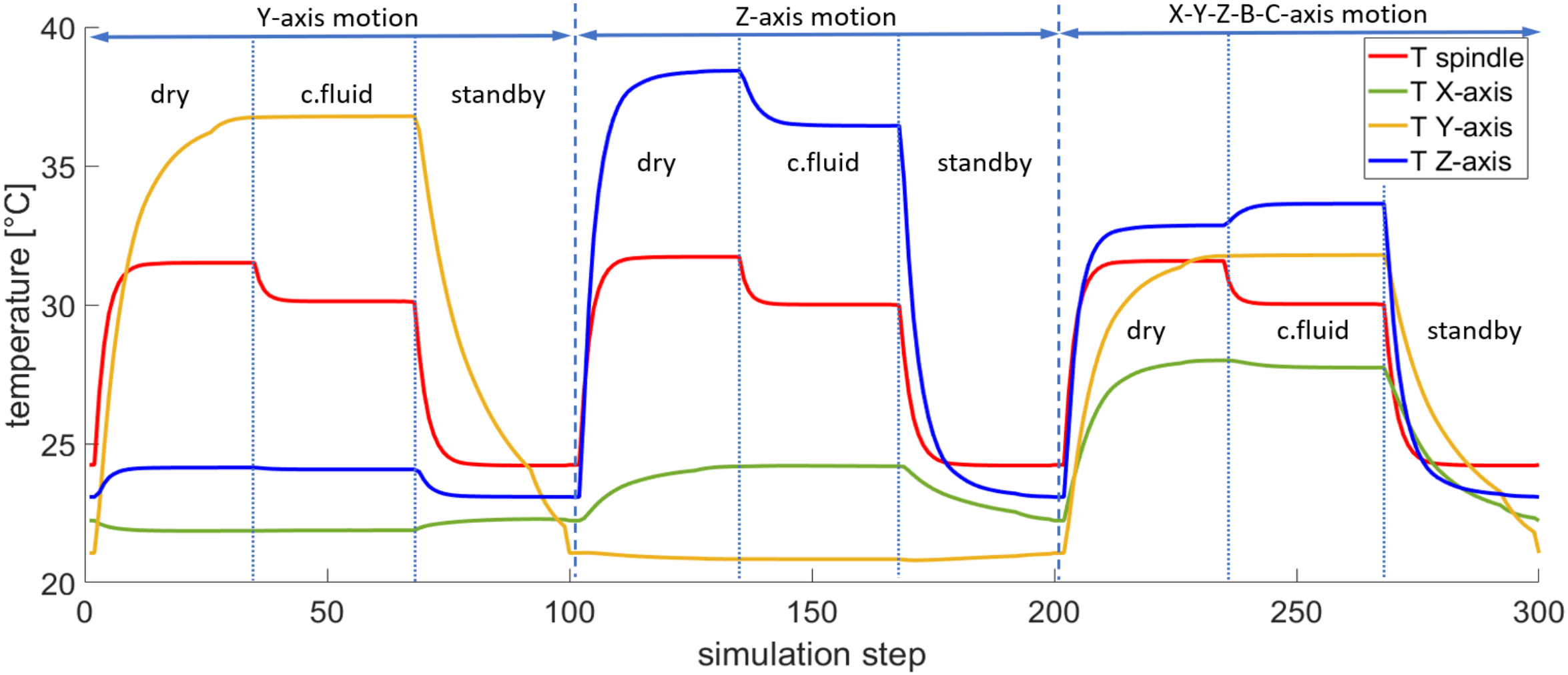
Thermo-elastic FEM simulations for model training



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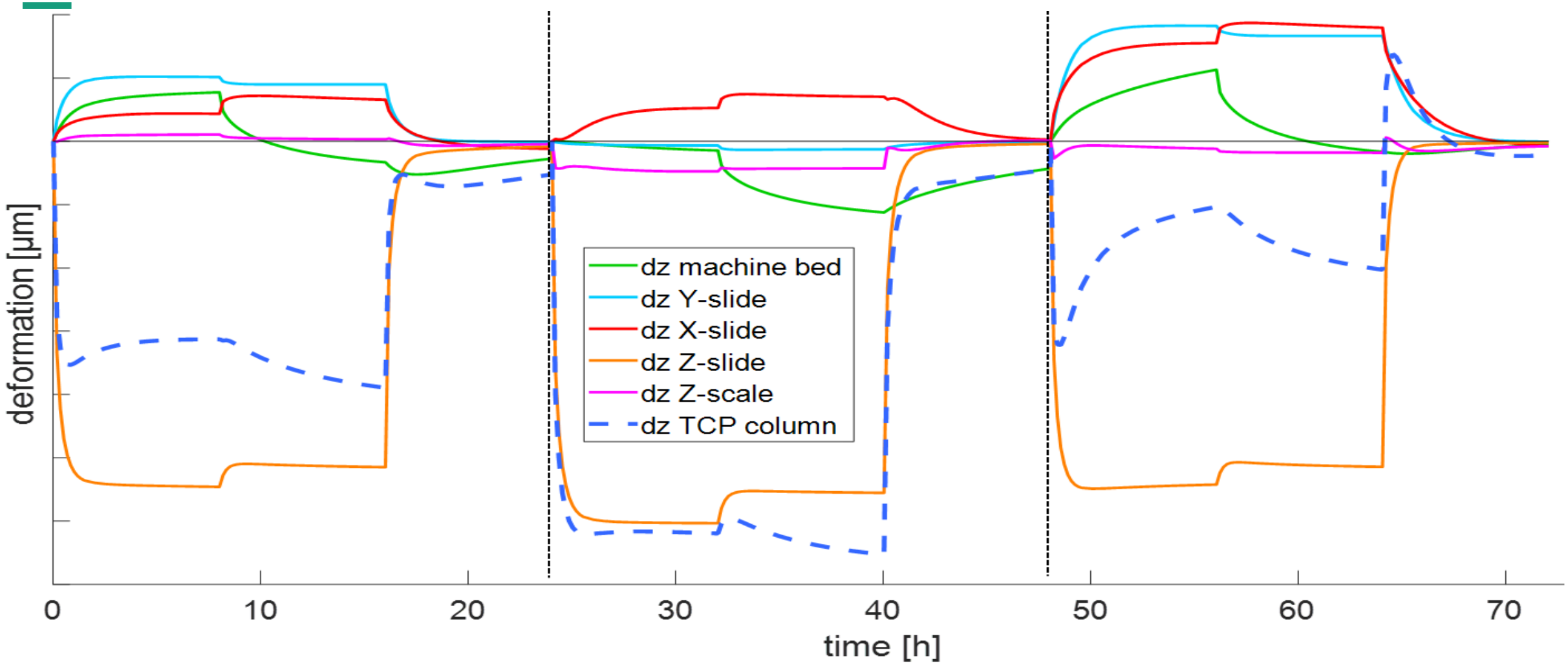

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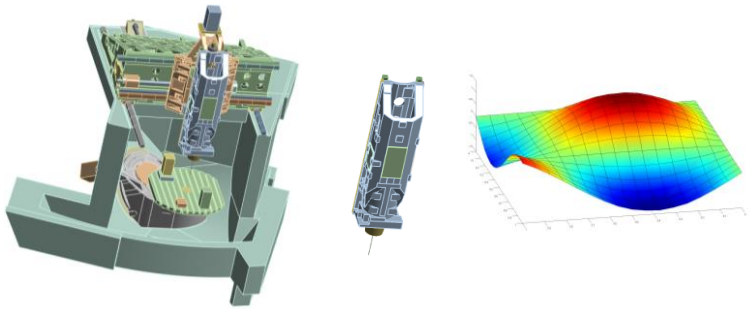
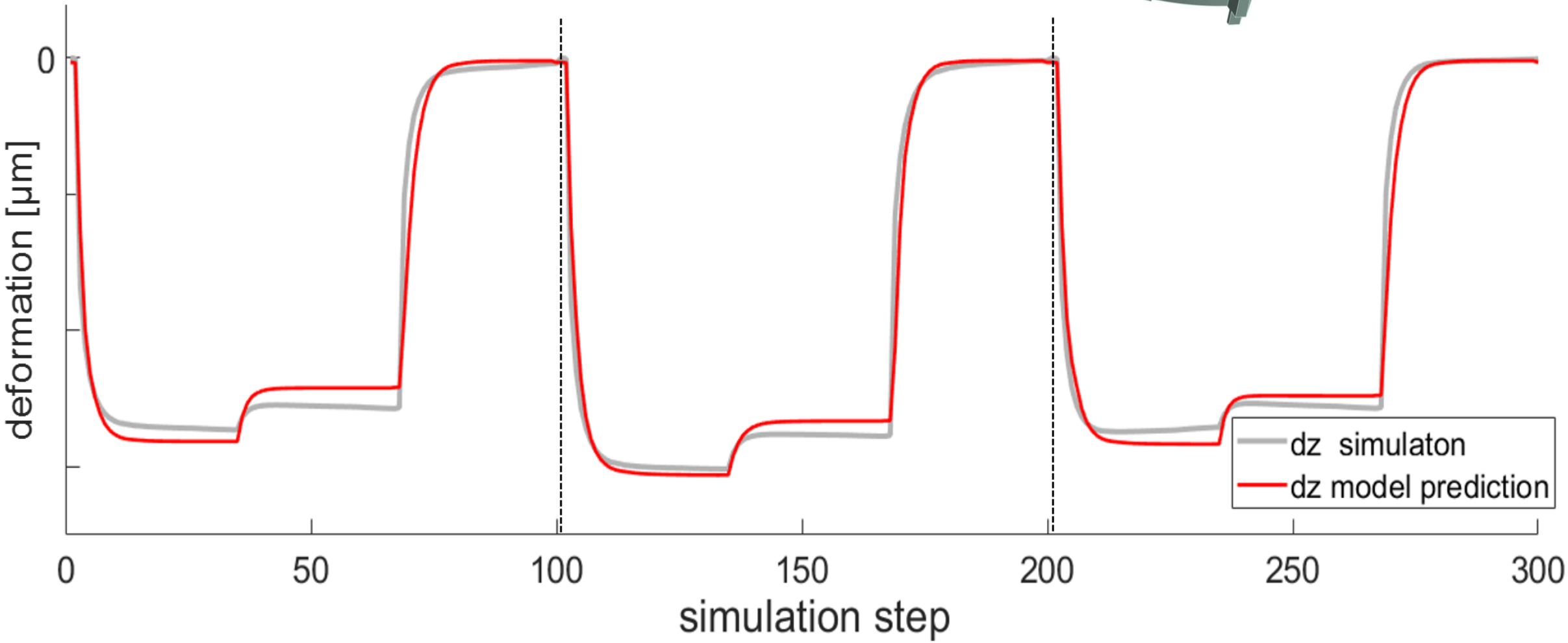
Thermal error compensation approach

Sample assembly thermal error model: dz of z-slide





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Summary and Outlook

Ziele und Teilziele im GeoComp

Summary:

- Current thermal error compensation methods still have limited accuracy and/or high implementation cost
- Combining targeted thermal error models on the assembly level reduces model training effort and simplifies the model requirements
- For the complex example DMU 80 evo, a simple, robust regression model was sufficient to remove most of the thermal error of the column in z-direction

Outlook:

- Finish assembly thermal error models
- Validate on complex simulated load cases
- Validate online using live measurements
- Transfer method to other machine tools (KrauseCo Flex-Modul, Mori Seiki NMV 5000 DCG)

Source 4

Thank you for your attention!

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09126 Chemnitz, Germany
christian.naumann@iwu.fraunhofer.de

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Image References:

1. P. Blaser, F. Pavlicek, K. Mori, J. Mayr, S. Weikert, K. Wegener: Adaptive learning control for thermal error compensation of 5-axis machine tools. In: Journal of Manufacturing Systems, vol. 44(2), 2017, pp. 302-309.
2. Nicole Wörner: Etalon treibt Industrie-4.0-Konzept voran. https://www.elektroniknet.de/messen-testen/neue-technologie-fuer-die-laengenmesstechnik.109748.html, June 6th 2014.
3. C. Naumann, A. Geist, M. Putz: Handling ambient temperature changes in correlative thermal error compensation. In: Proceedings 2nd ICTIMT Prague 2021.
4. https://www.dmgmori.co.jp/en/products/machine/id=1444