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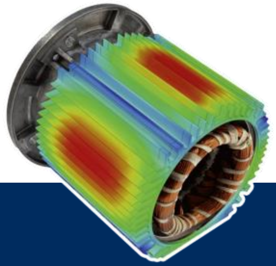
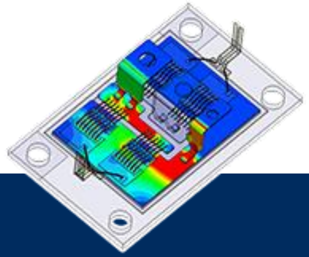
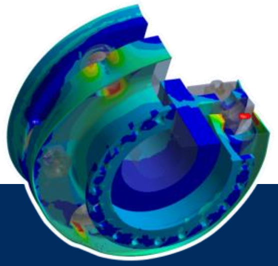
Simulation ist mehr als Software®

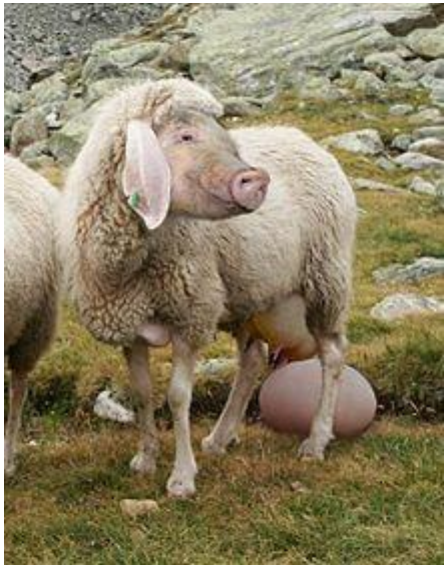
Automatized optimization of a machine tool cascade controller based on system simulation

Motivation

- machine tools:
  - highly complex electrified system (mechanics, electrical machines, sensors, control, influences from the environment,…)
  - interaction of several components across physical domains with controller

- tasks for the manufacturer
  - high cutting speed (HPC) → dynamics ↑ → mass ↓
  - surface quality → stiffness ↑ → mass ↑
  - robust processes/ high life times
  - reduce costs

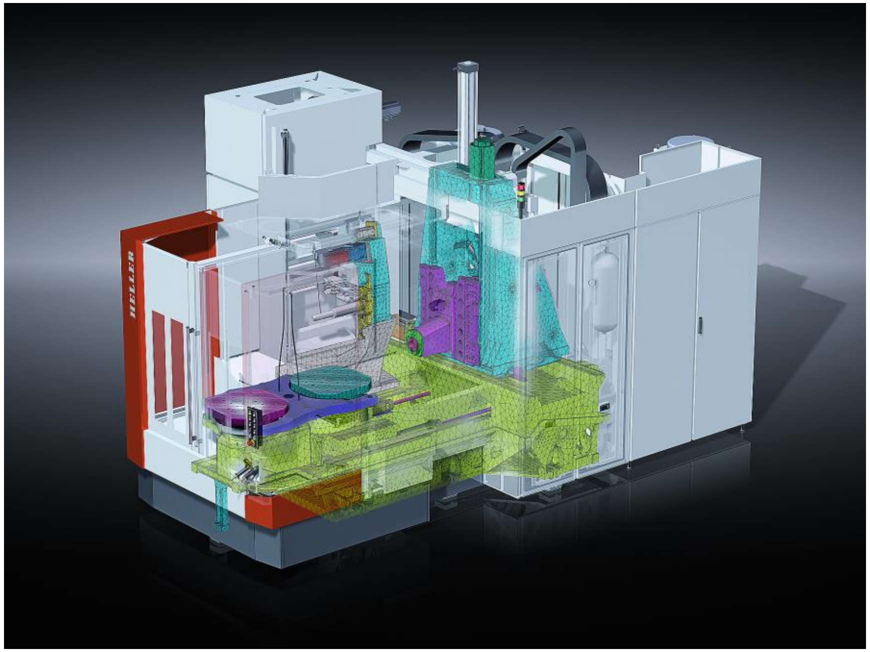
  → competing goals



Source: Wikipedia

How to reach these targets?

- try-and-error
  - expensive (physical prototypes)
  - time consuming
- optimization based on numerical models
- Challenge: model the whole systems behavior → system simulation



Source: Gebr. Heller Maschinenfabrik GmbH

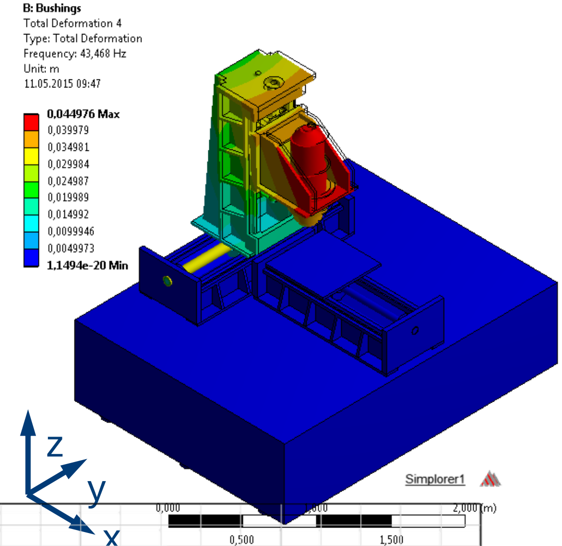
Some general thoughts on system simulation and abstraction

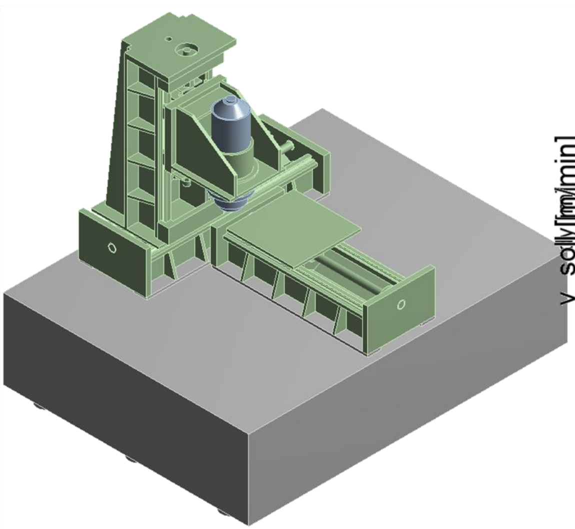
choice of the correct level of abstraction:

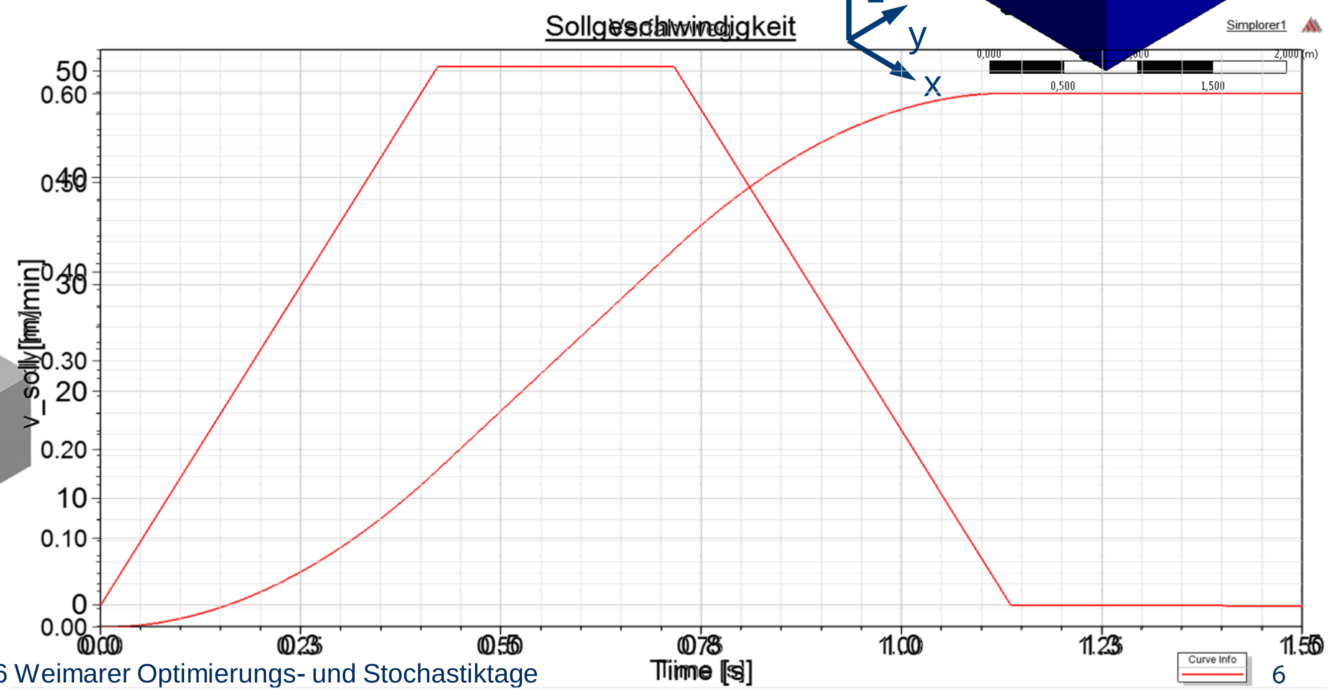
- What should be simulated?
- Which time constants for which effects?
- Are the time constants in the same range?
- Which effect has to be taken into account, what can be neglected?

Scenario: rapid traverse from tool changer to workpiece

- fast traverse of the machine tool column from tool changer to WP → tool is not cutting
- travel distance 60cm in ~ 1.1s, v_{max} ~ 50m/min
- Oscillation peak to peak at TCP after 1.5s < 2µm



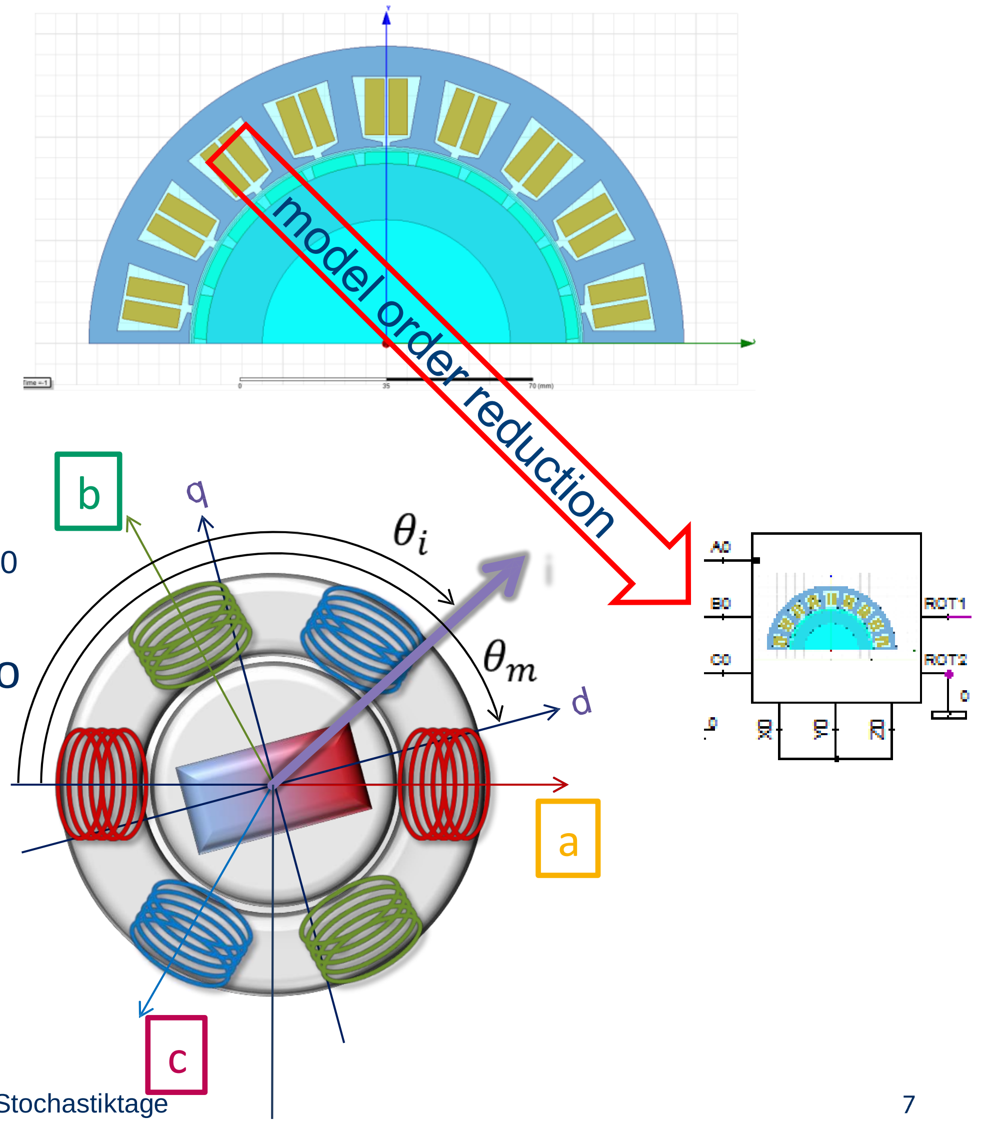




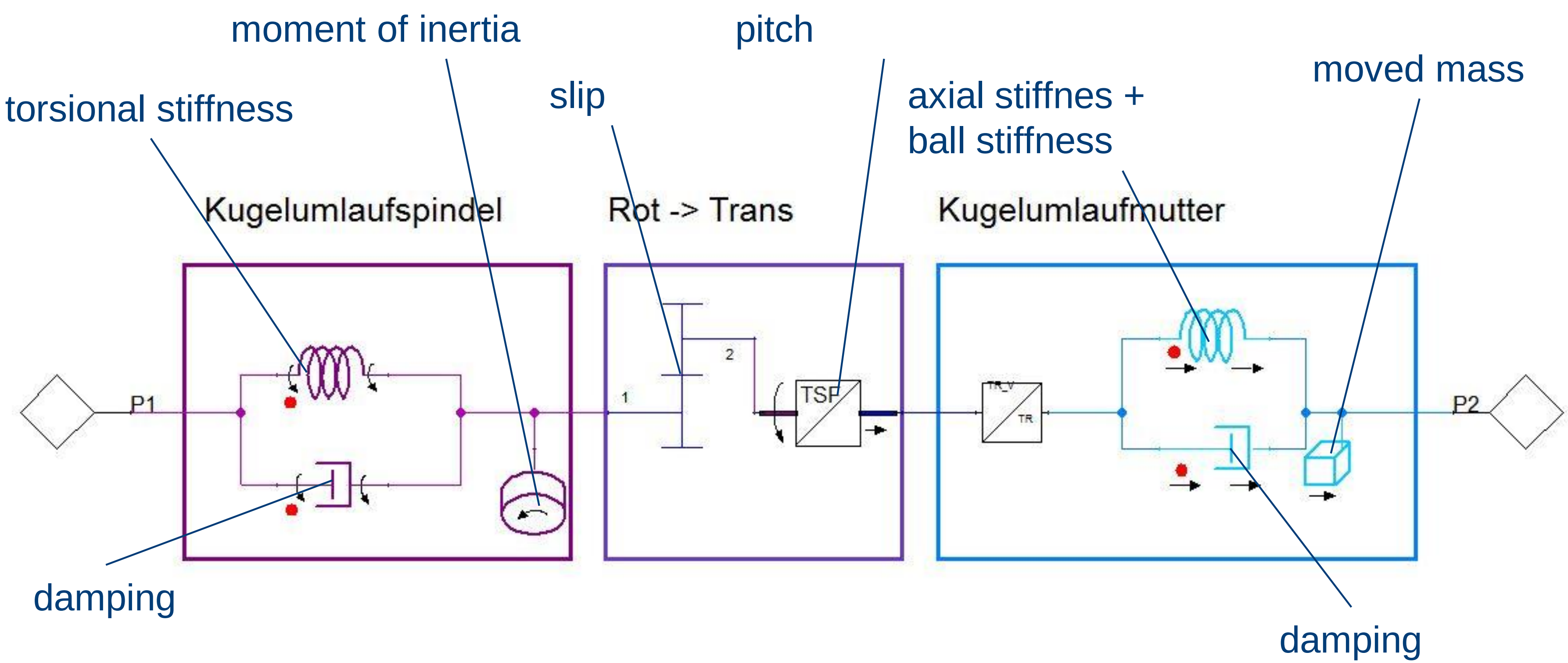
components: axis drive

- PMSM
- 11 pole pairs

- model order reduction: ECE-model (equiv. circuit extraction)
- variation of currents I_d, I_q and rotational angle θ_m
- lookup-table: flux linkage Ψ_d, Ψ_q, Ψ_0 + torque
- takes into account: saturation due to material nonlinearities
- does not take into account: eddy current effects

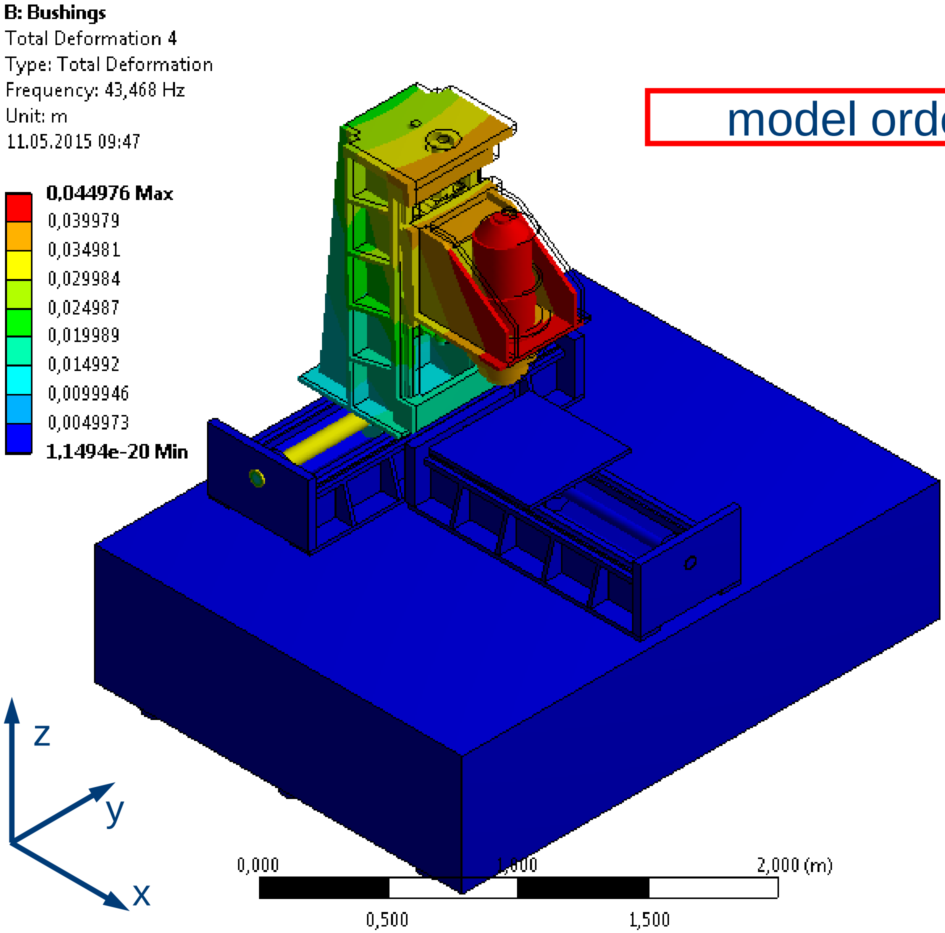


components: ball screw drive

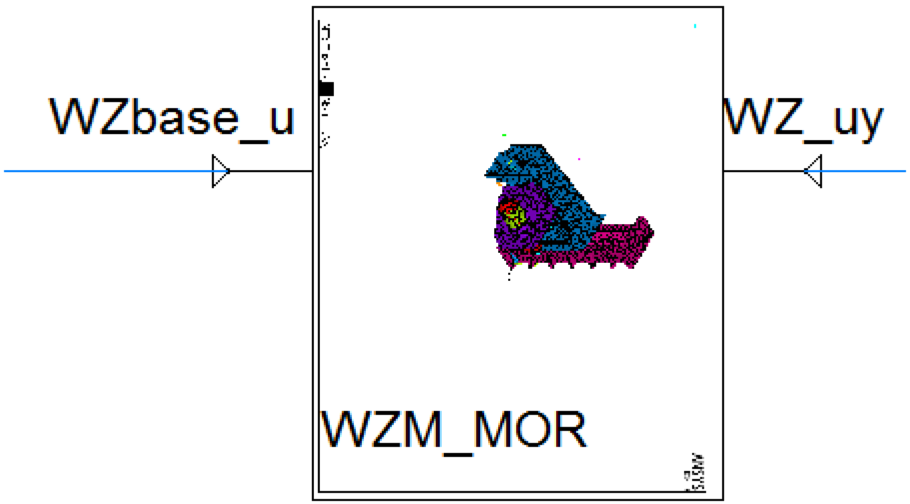


- nonlinear stiffness: function of position
- nonlinear behavior (clearance, etc.): nonlinear contacts

components: moved machine tool column



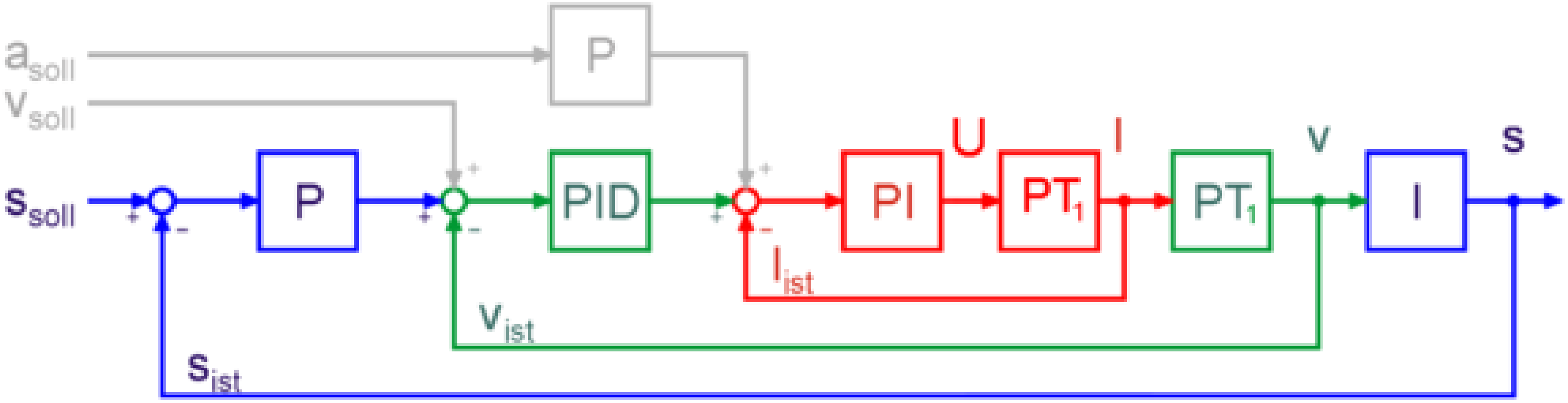
model order reduction



basic concept: cascade control

- control of processes with time constants of different orders of magnitude
- basic control concepts (P, PI, PID)
- stepwise activation

- can be extended to more advanced control algorithms



Source: www.Wikipedia.de

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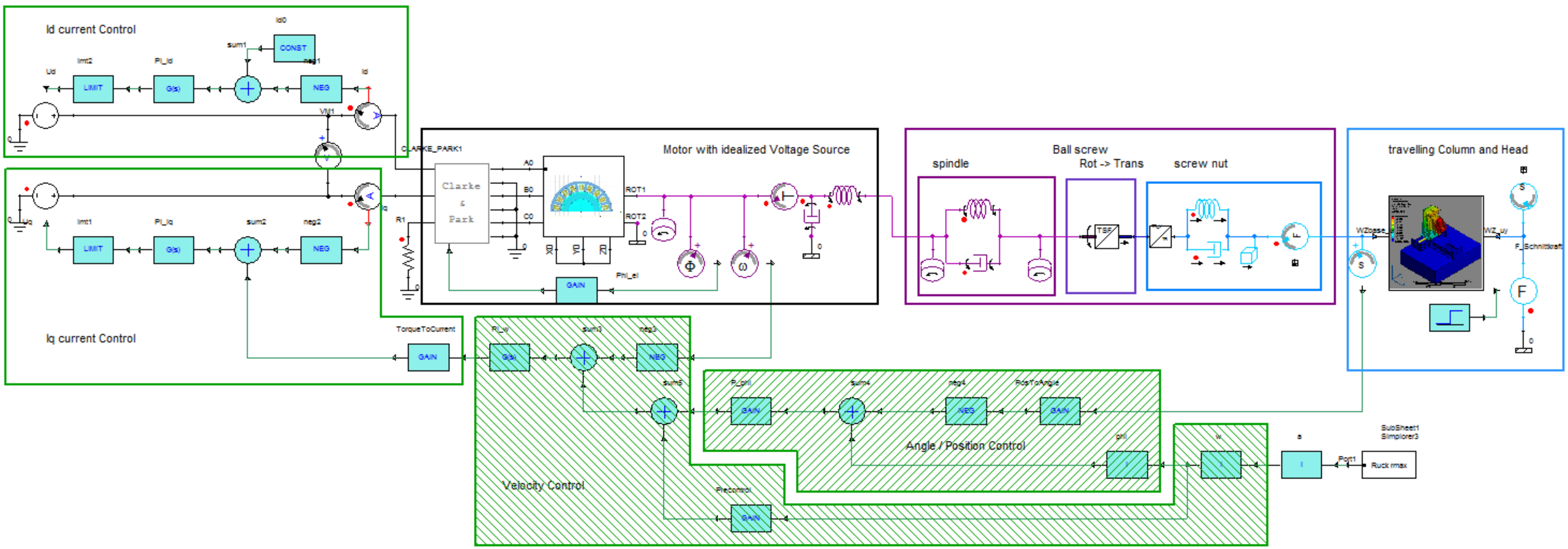
system model of machine tool in SIMPLORER



application example: control optimization

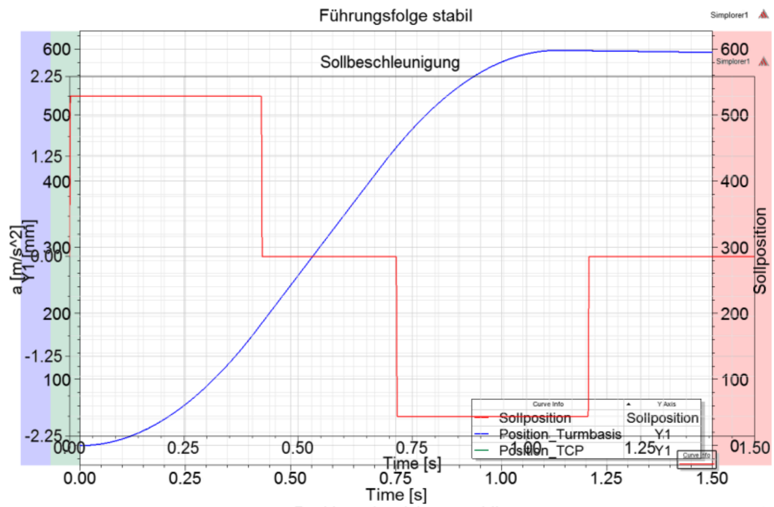
- state of the art:
  - in frequency domain
  - sequential closing / optimization of the cascades
- advantages:
  - Easily feasible
  - well-proven
- disadvantages:
  - no consideration of nonlinearities
  - manual tuning neccessary

- alternative:
  - in time domain
  - based on systems simulation
  - parallel optimization of cascades
- advantages:
  - consideration of nonlinearities
  - automated optimization of control parameters
  - starting values from rules of thumb

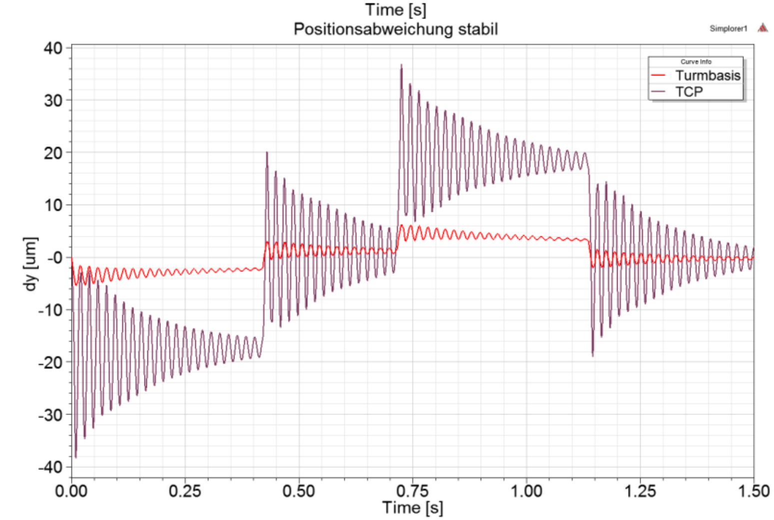
Educated guess: find control parameters

- Based on analytical approaches and some manual tuning for stabilization

→ position of TCP and column base follow the set-point in desired manner



- Persistent control deviation for accelerated movement
- Oscillation with peak-to-peak amplitude at TCP ~4.5 µm after 1.5 s
- Goal: Amplitude p2p < 2 µm

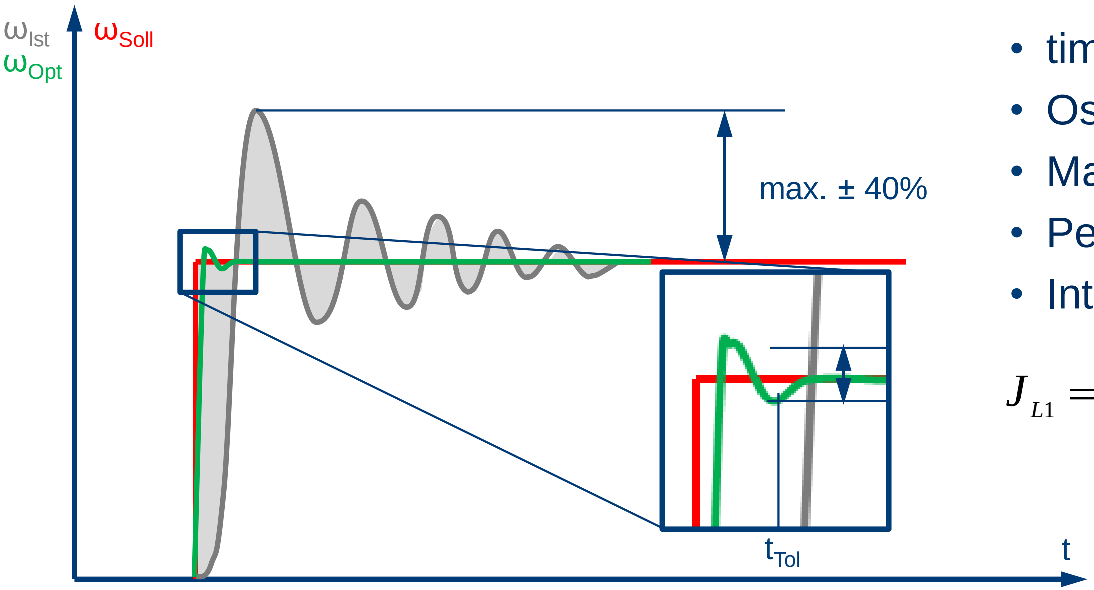


Optimization in time domain

- Basic requirements:
- Control must behave stable
- Control value should follow setpoint value the fastest possible way
- Maximum overshoot ~40%

- Optimization goals:
  - Minimal control deviation
  - Fast settlement to final value
  - Few oscillation at end of observed time

→ transfer to characteristic values:



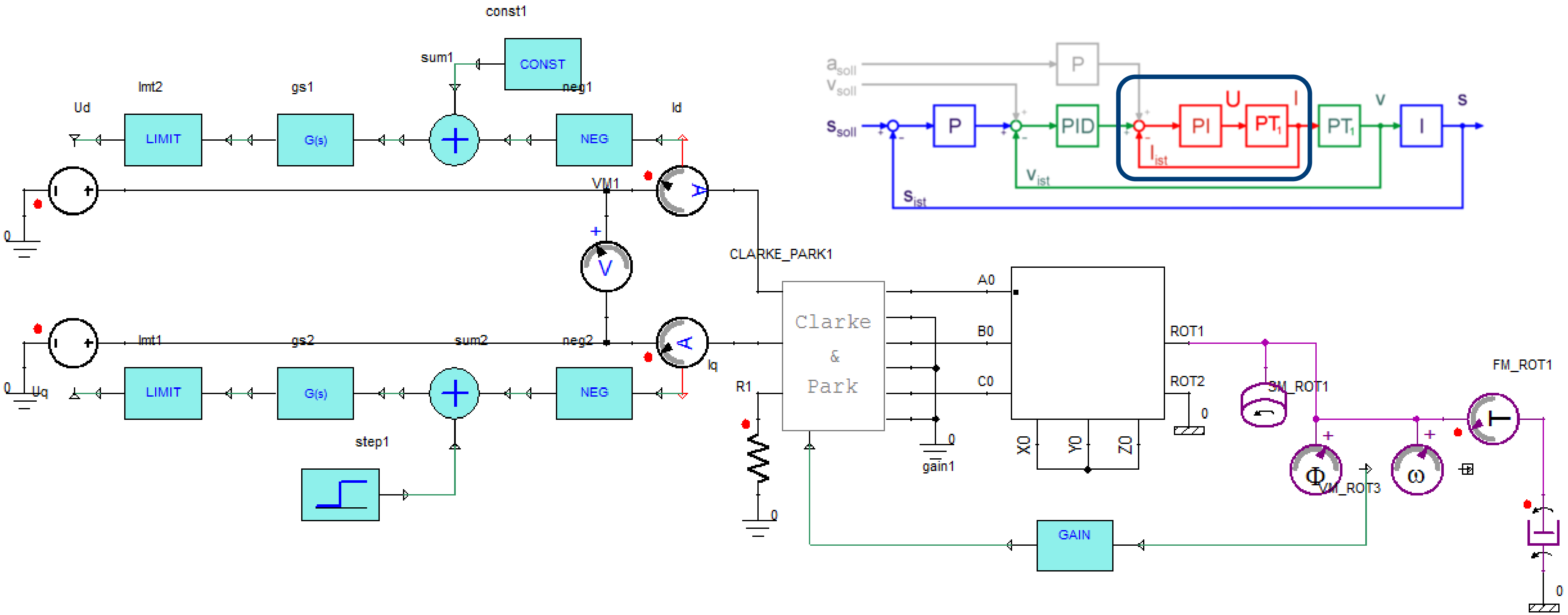
- time t_{Tol} to settle in tolerance band
- Oscillation amplitude at t_{End}
- Maximum control deviation e_{max}
- Persistent control deviation e_{end}
- Integral quality factors:

$$J_{L1} = \int_0^{t_{end}} |e(t)| dt \rightarrow \min \qquad J_{L2} = \int_0^{t_{end}} e(t)^2 dt \rightarrow \min$$

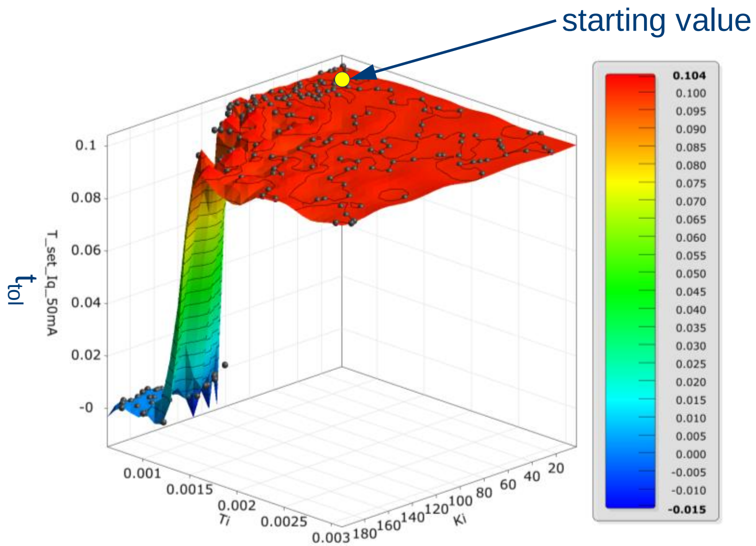
$$J_{ITAE} = \int_0^{t_{end}} |e(t)| \cdot t dt \rightarrow \min$$

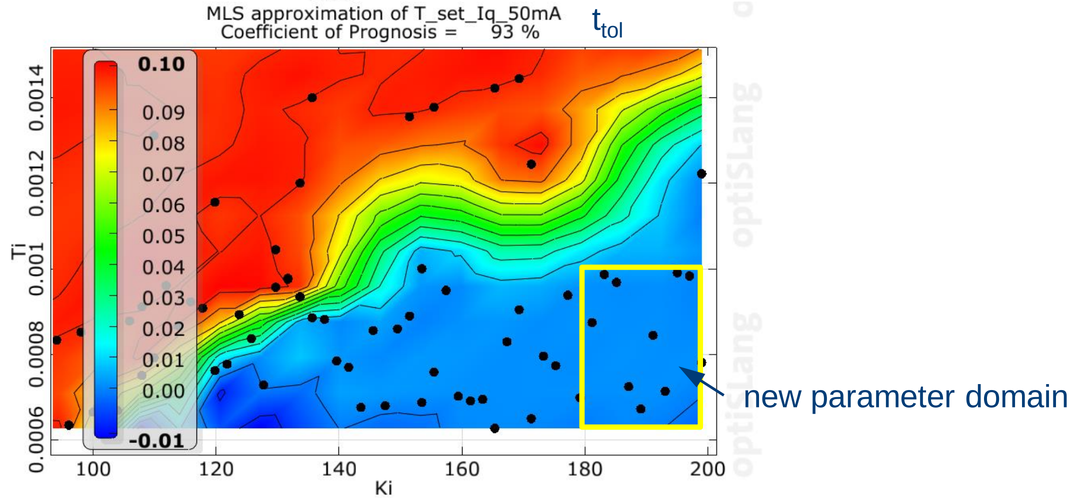
1: Current controler– pre-selection of fast designs

- Take a look at the motor
- DOE: Control parameters gain and integration time constant
- Starting point: parameters derived from analytical solution
- Output parameters: t_{tol}



1: Current controler– pre-selection of fast designs



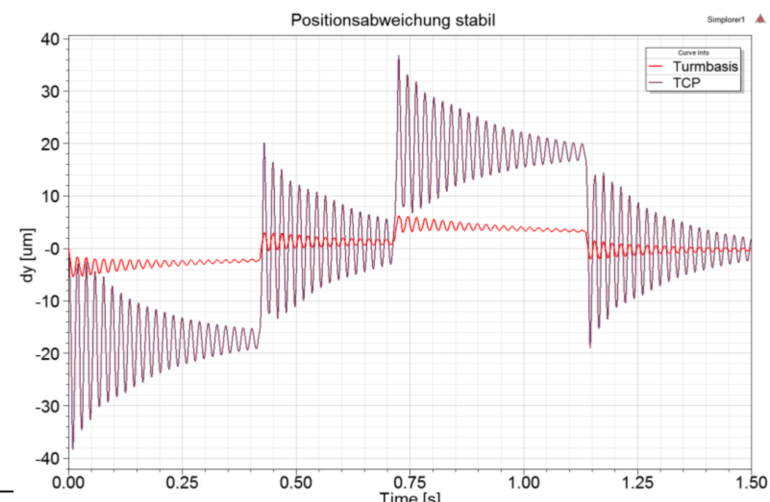


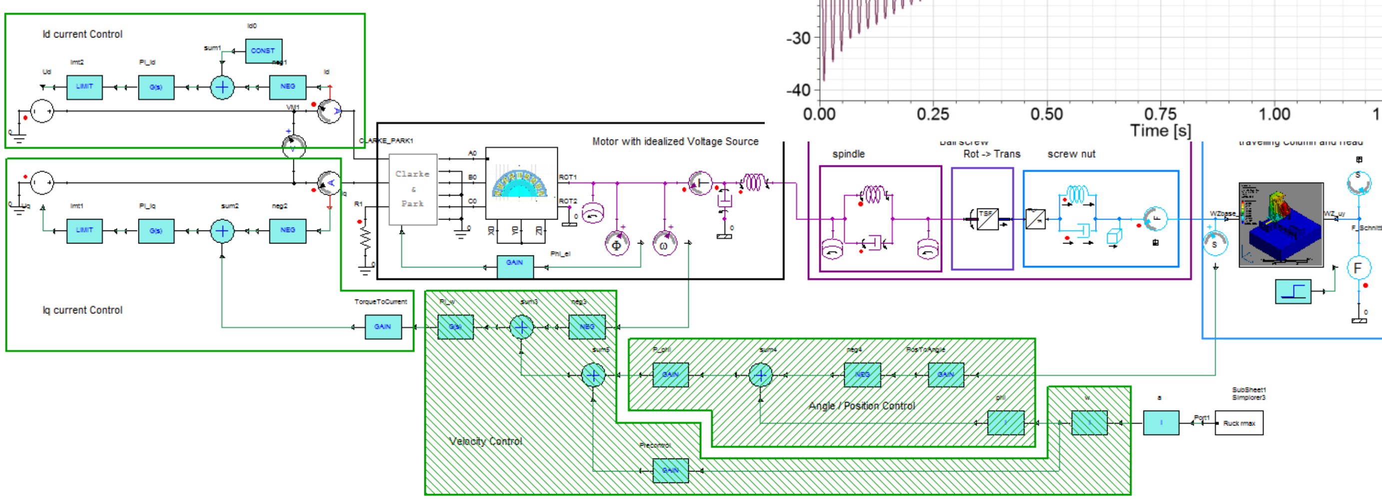
- steep gradient
- separation between fast and accurate and slow and or inaccurate designs

→reduction of parameter range

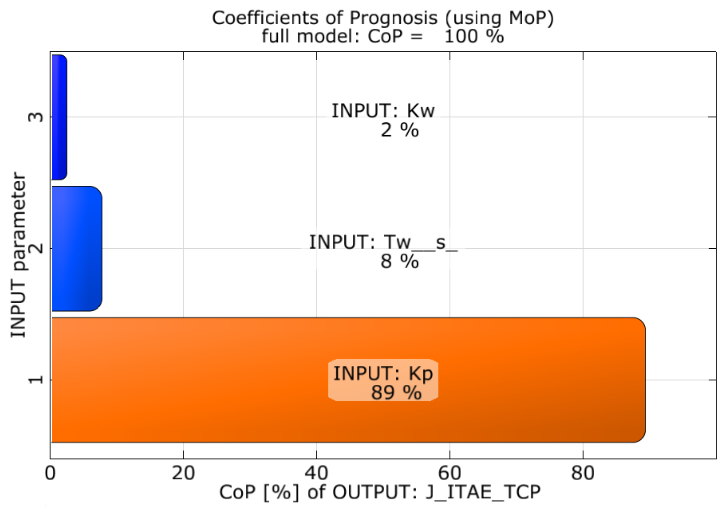
2: Control of the entire system

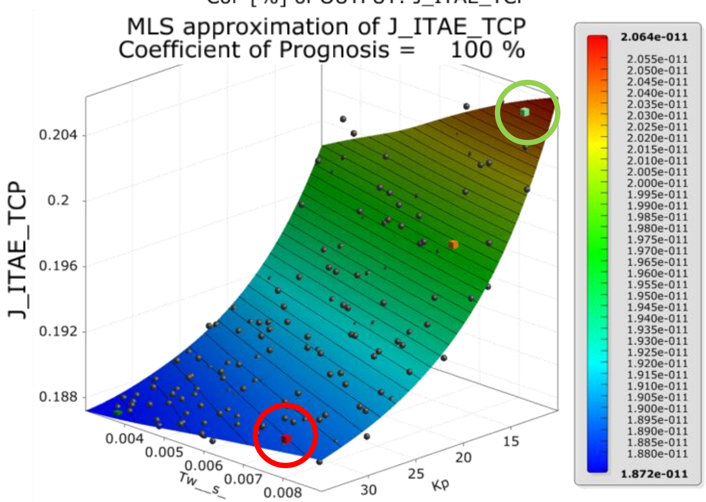
- DOE: control parameters for all 3 cascades:
  - PI current control: reduced parameter domain from 1. iteration
  - PI velocity control: from analytical solution
  - P position control: from analytical solution
- Results:
  - Integral quality factor ITAE
  - Amplitude of oscillations
    - At column basis
    - At TCP





Integral quality factor ITAE

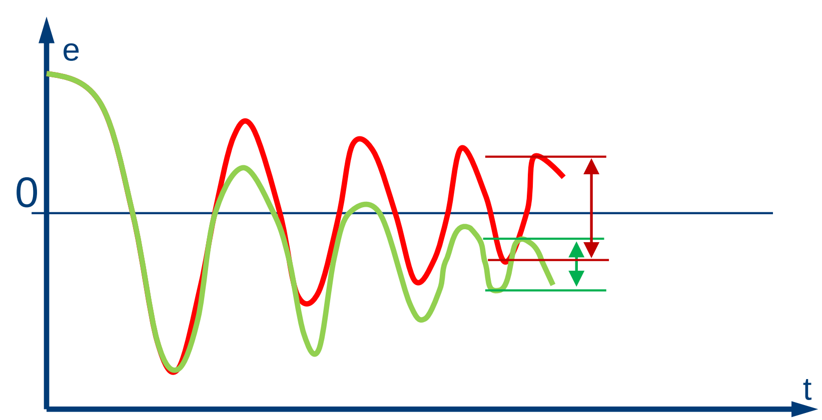




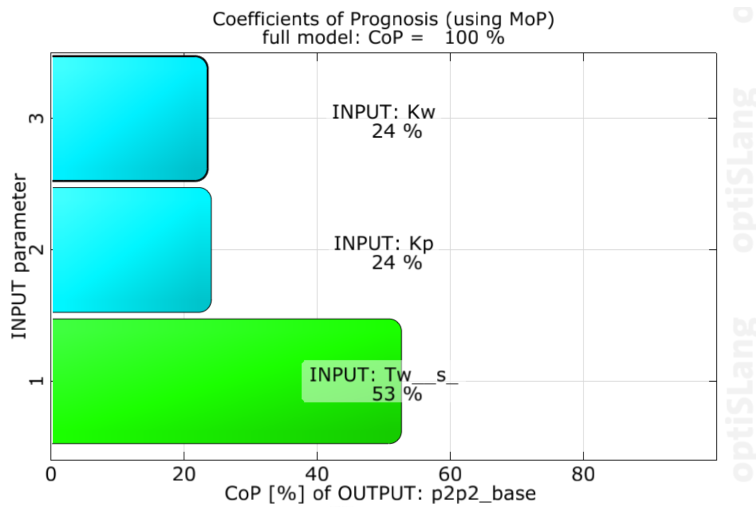
$$J_{ITAE} = \int_0^{t_{end}} |e(t)| \cdot t dt \rightarrow \min$$

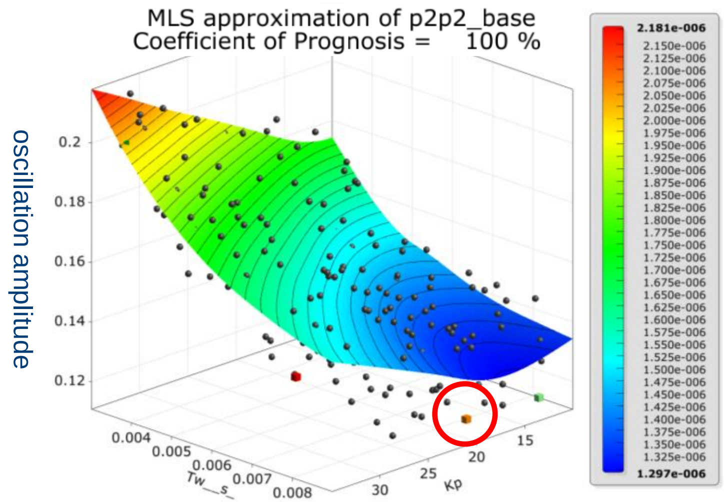
- Dominated by position controller gain
- Steady state control deviation penalized stronger than oscillation
- Difference between min and max value small

→Criterium here no good choice

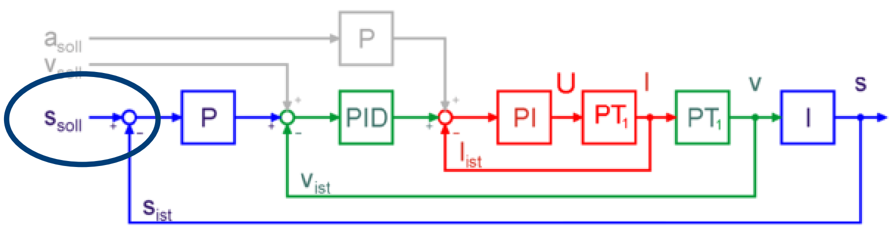


Oscillation amplitude at column basis

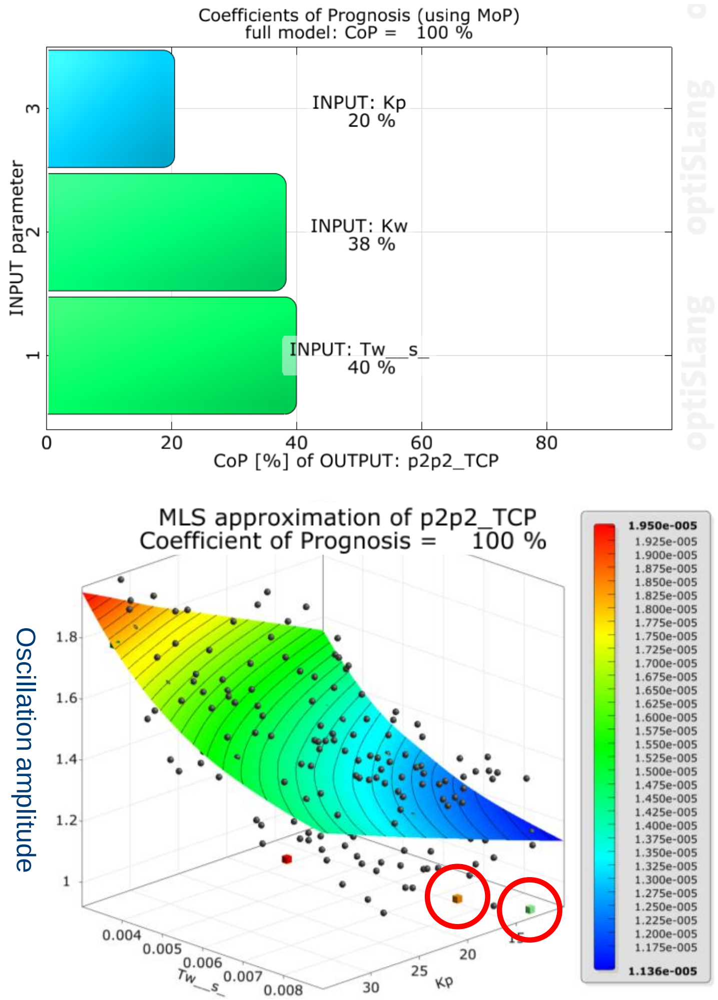




- Complete systems behavior at column basis == position of measurement device
- Position control: k_p ↑ oscillation amplitude ↑
- Position oscillation amplitude dominated by velocity control



Oscillation amplitude at TCP



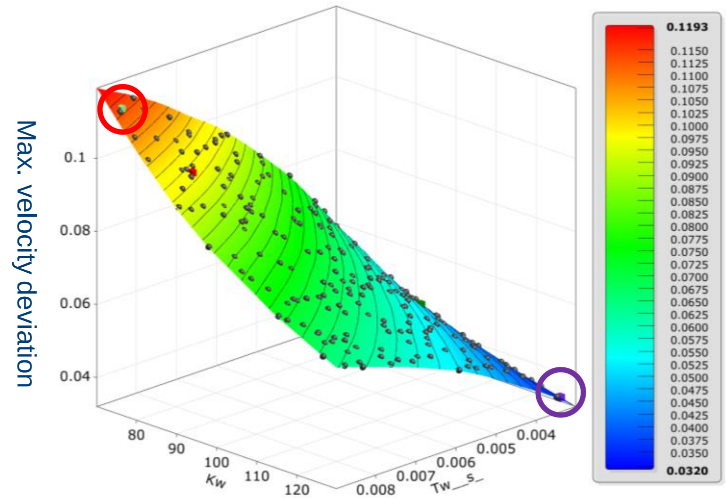
- Investigation of systems behavior at TCP
- In most machines no possibility to measure this behavior
- Relevant for machining results
- Behavior similar to behavior at coulmn basis but not equal → tuning potential

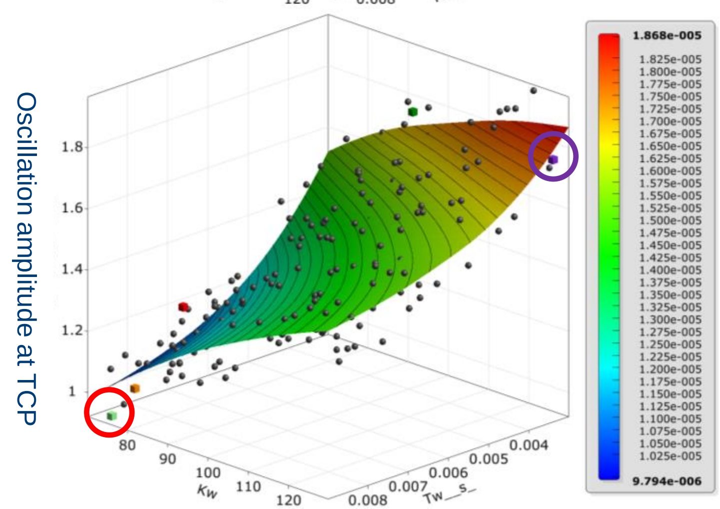
- Position oscillation amplitude dominated by velocity control

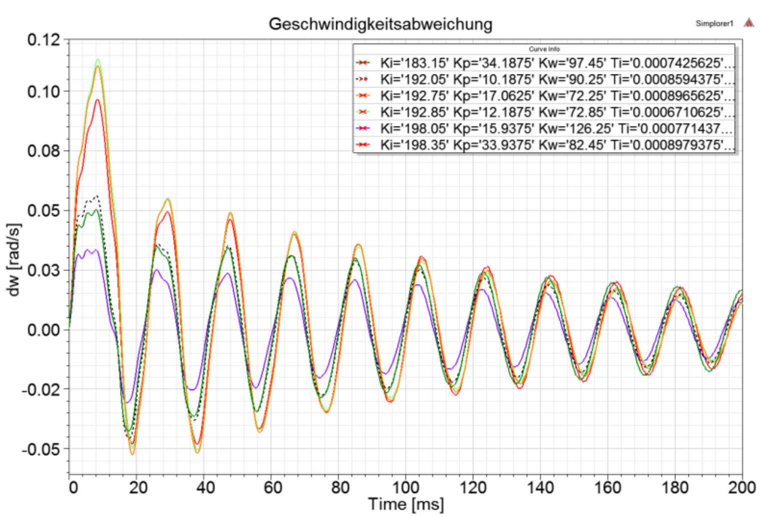
Best velocity control = best positioning behavior?

- No!!!
- Parameter (low oscillation @ TCP) ≠ parameter (low velocity deviation)!
- agressive behavior of velocity control leads to high oscillation at

→Best results trough optimization of position and velocity control in one step







Optimization

- Sensitivity analysis results:
- Position control performance dominated by position and velocity controller
- Current controller in preoptimized shape does not influence position control (as control theory predicts)

Optimization:

- ARSM
- Objective: minimize oscillation at TCP (< 2 µm p2p)
- Constraints: maximum stationary control deviation 1 µm
- Handle controller parameters for position and velocity control in one optimization run, leave current controller parameters constant

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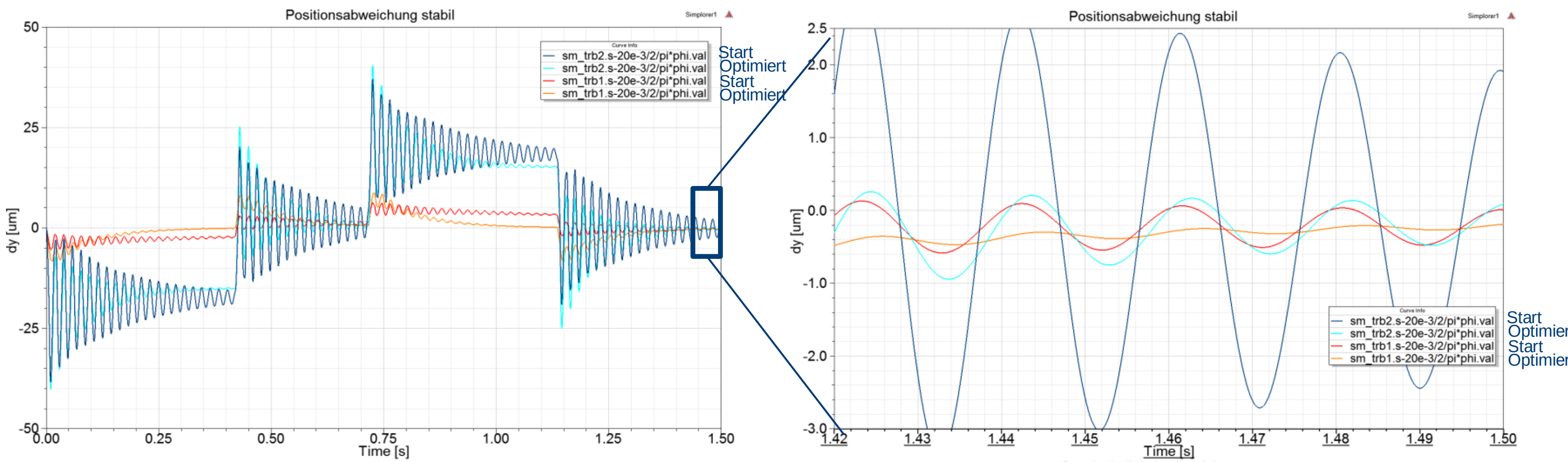
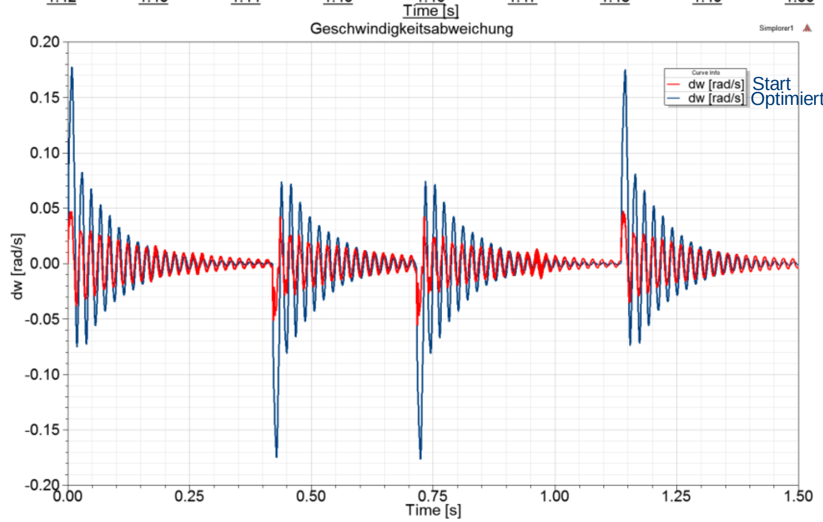
Machine tool behavior at TCP for start values and optimized values



- Automatized optimization of control parameters
- 0.5µm p2p Oscillation at TCP after 1.5s with a stationary position deviation of 0.1µm
- Optimal position control achieved by accepting slight performance losses for velocity control
- Pairing developer know-how with sensitivity analyses and optimization: in very short time excellent results



Conclusion

- Systems simulation: bidirectional interaction of components across different physical domains together with controller interaction
- Reduced order models: Excellent balance between speed and accuracy

- Parameterized Systems: automatized determination of optimal parameters
- Taking into account the nonlinearities of the system

→ Better understanding of the systems behavior
→ Avoid late stage integration failure
→ reduce costs for physical testing

Contact

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