TECHNISCHE UNIVERSITÄT DRESDEN

Institute of Machine Tools
and Control Engineering
Prof. Dr.-Ing. S. Ihlenfeldt

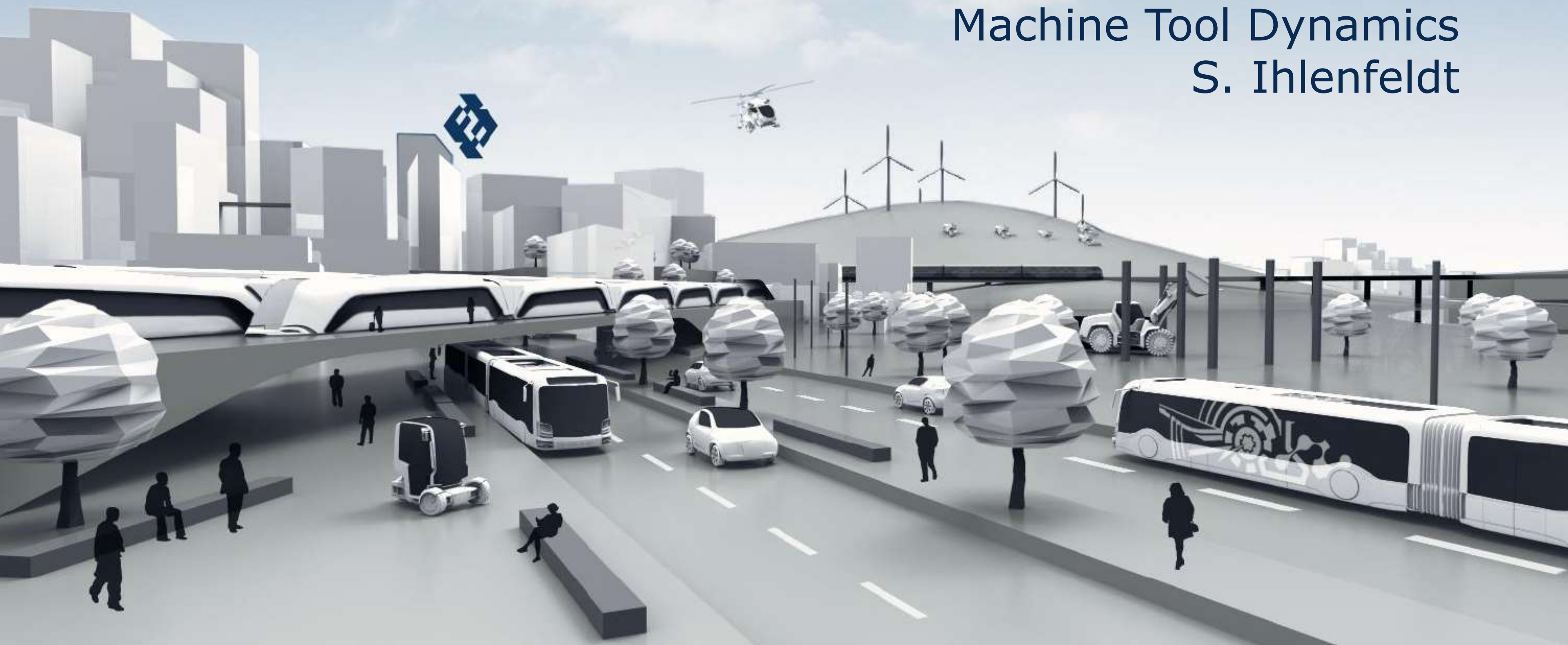
Faculty of Mechanical Science and Engineering, Institute of Machine Tools and Control Engineering

Faculty of Mechanical Science and Engineering
technology without borders

Machine Tool Dynamics

New Concepts for Increasing Machine Tool Dynamics

S. Ihlenfeldt



Institute of Machine Tools and Control Engineering

Historie

- established in 1954 as Institute for Machine Tools at the TH Dresden
- in 1968 integrated into the “Department Workshop Facilities and Machine Tools”
- reestablished as Institute for Machine Tools in 1991; Executive Director:
  Doz. Dr.- Ing. habil. R. Neugebauer
- 1994 renamed to “Institute for Machine Tools and Fluid Power”
  Director: Prof. Dr.- Ing. habil. K. Großmann
- since 1997: “Institute for Machine Tools and Control Engineering”
- since 2015: Chair of „Machine Tools Engineering and Adaptive Controls“
  Prof. Dr.-Ing. S. Ihlenfeldt

Institute of Machine Tools and Control Engineering

Facts

Institute (28 Research associates)

	Machine- and Process-Analysis	Mechatronic Motion Systems	Adaptive Control	Information Management for Production
Research	Analysis of components Modeling of structures an processes Coupled simulation Measurement technology for machine tools	Lightweight design Dimensioning and control of drives Drive concepts Energy management	Correction algorithm Model integration Process data acquisition Condition Monitoring	Modeling of process chains Structuring and storage of process data Analysis of process data Assistance systems
Lectures	Machine tool development Fundamentals Analysis of motion controlled machines	Machine tool development Concepts and design of Machine Tools	Fundamentals of machine tool controls	Design of Experiments

Machine Tools Dynamics
Outline

1. **Motivation**
2. **Materials for Machine Tools**
3. **Drive Structures**
4. **Machine Structures**
5. **Process Stability**
6. **Summary**

Motivation

Trend 1: **customized** products

number of variants ↑
lot sizes ↓
development times ↓

Trend 2: **complex** products

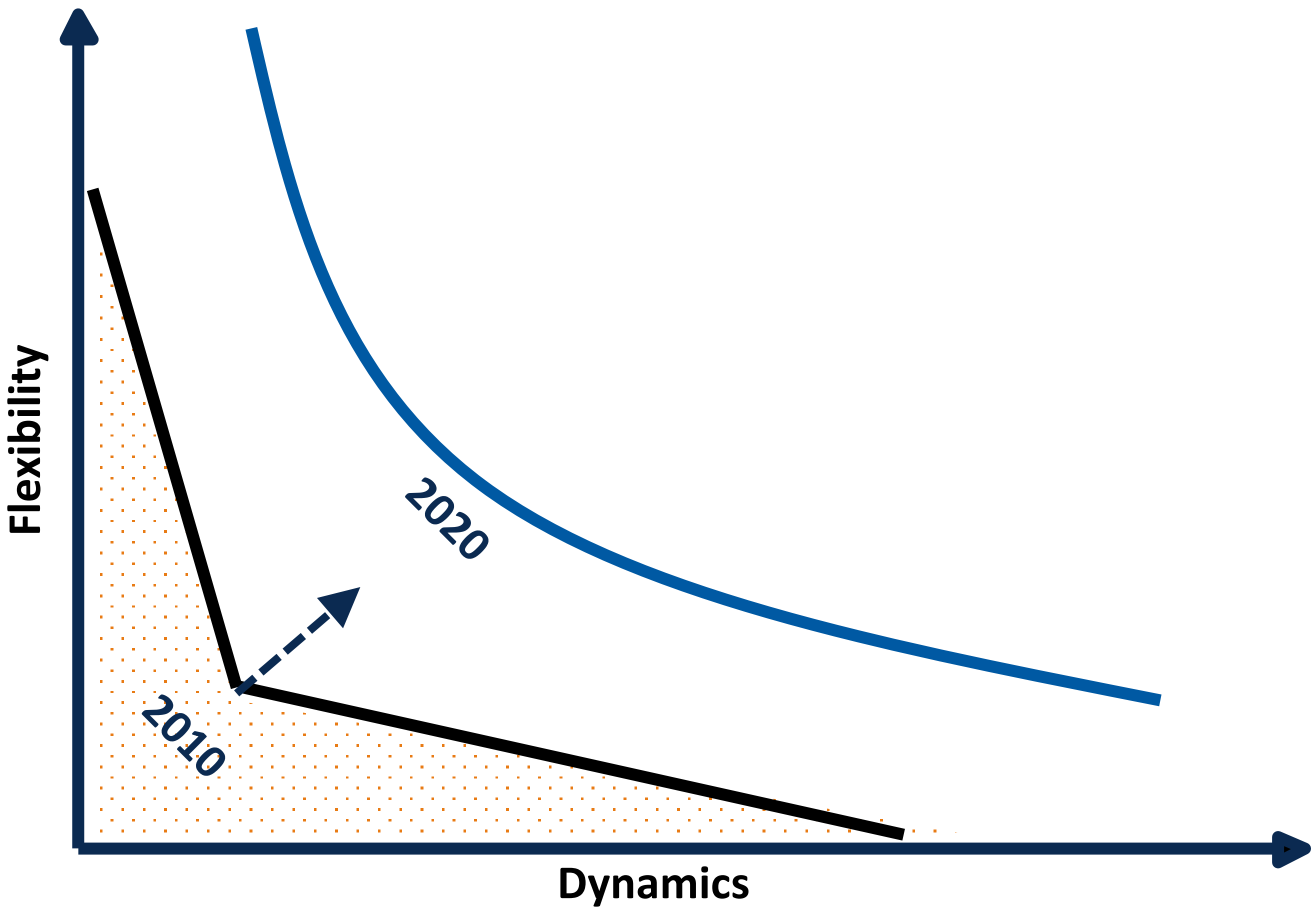
miniaturization ↑
functional integration ↑
functionality ↑

dynamics ↑

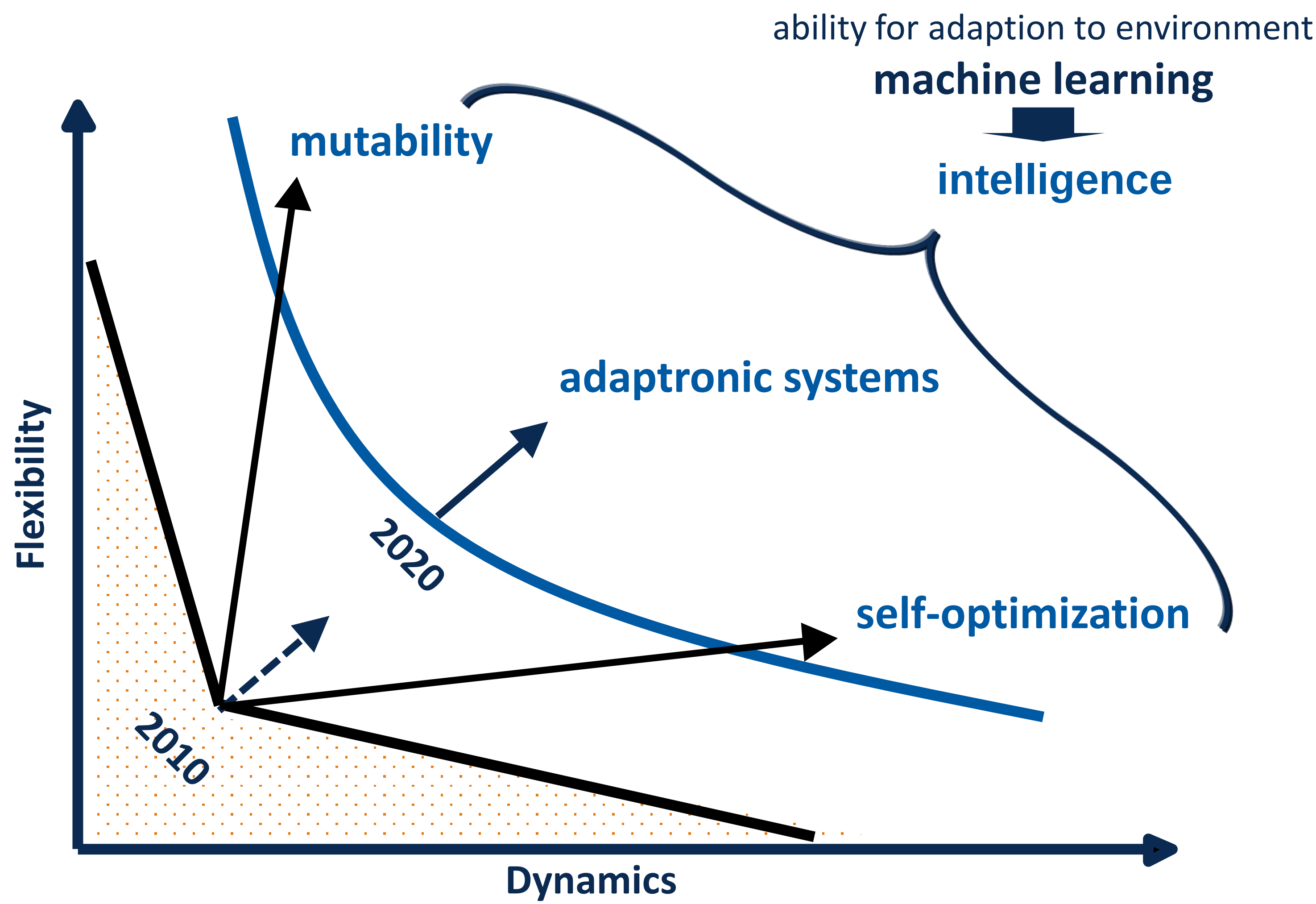
accuracy ↑

flexibility ↑

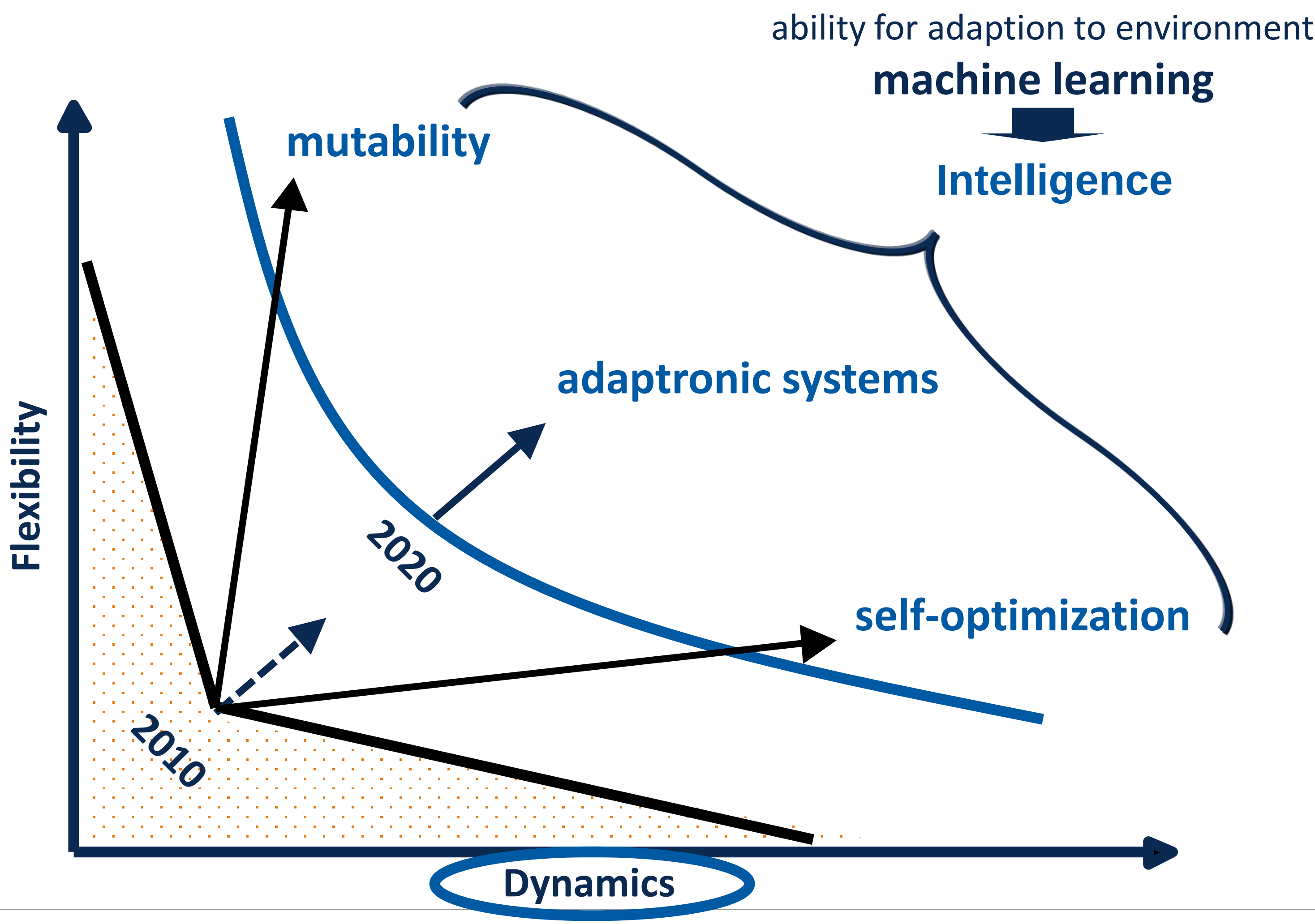
Conflict of aims



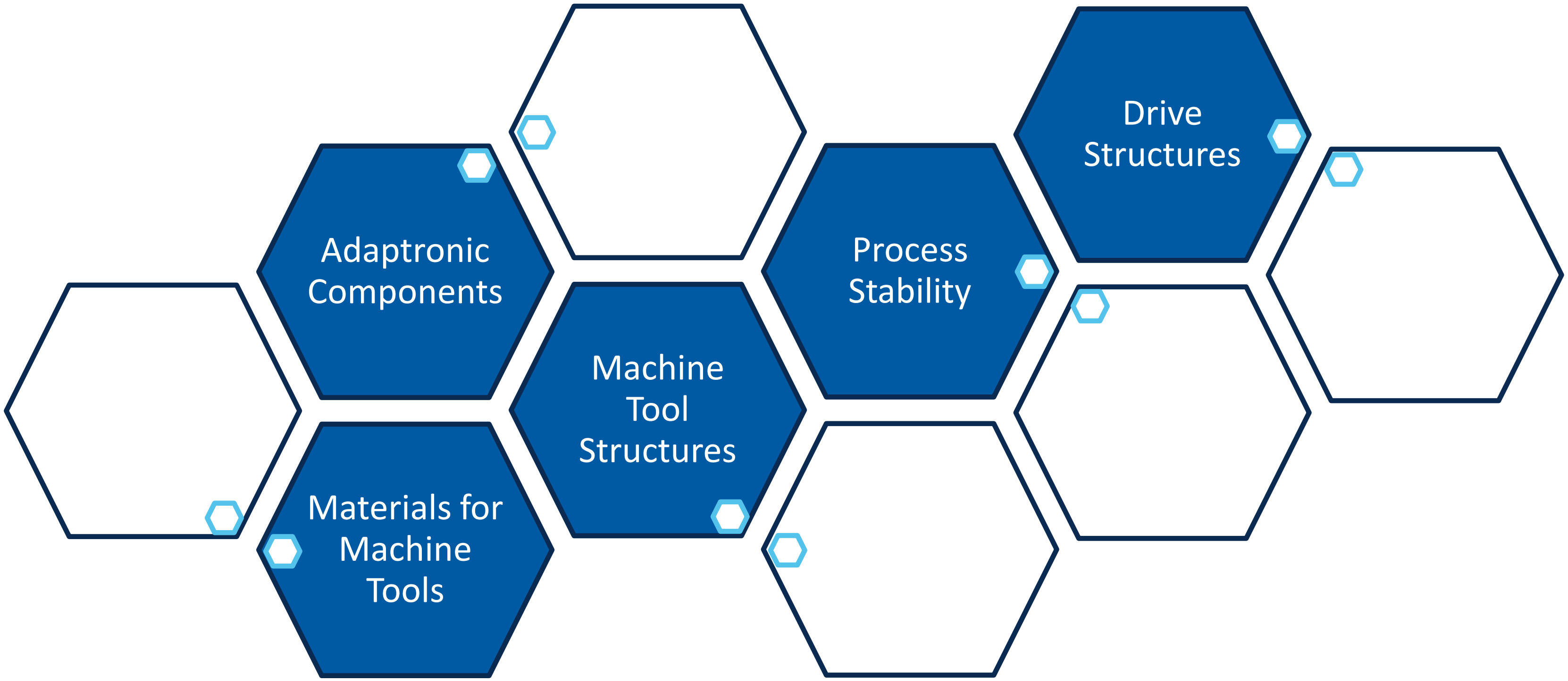
Conflict of aims and fields of actions



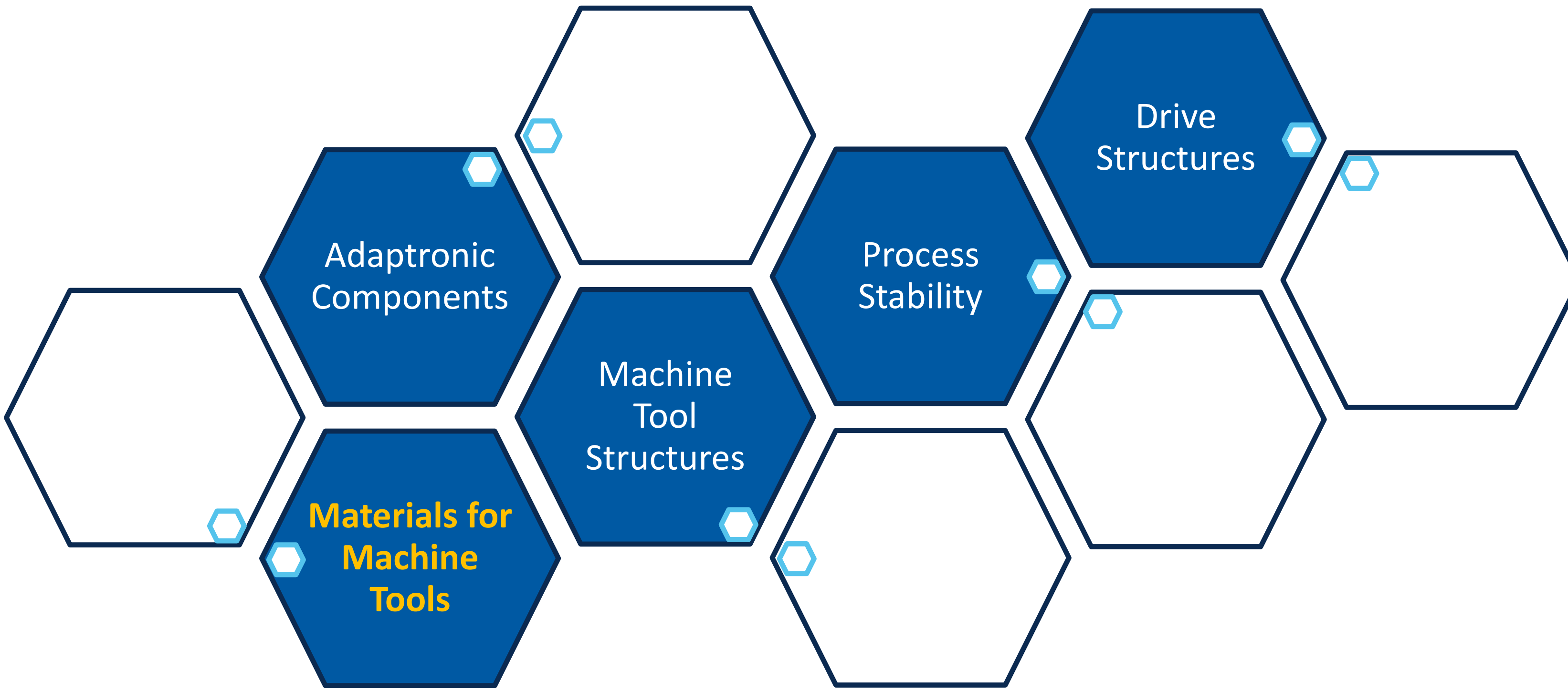
Conflict of aims and fields of actions



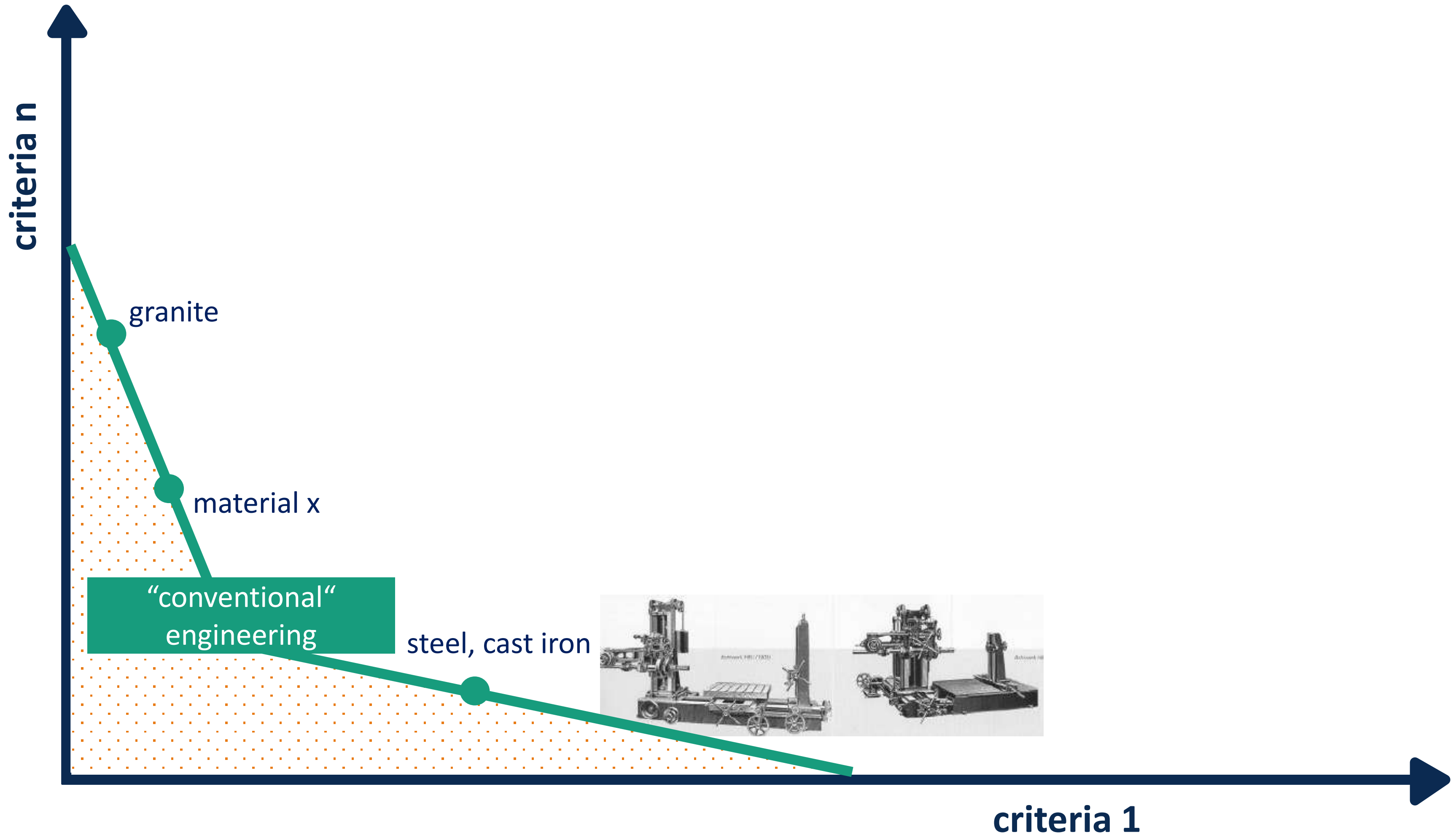
Machine Tools Dynamics



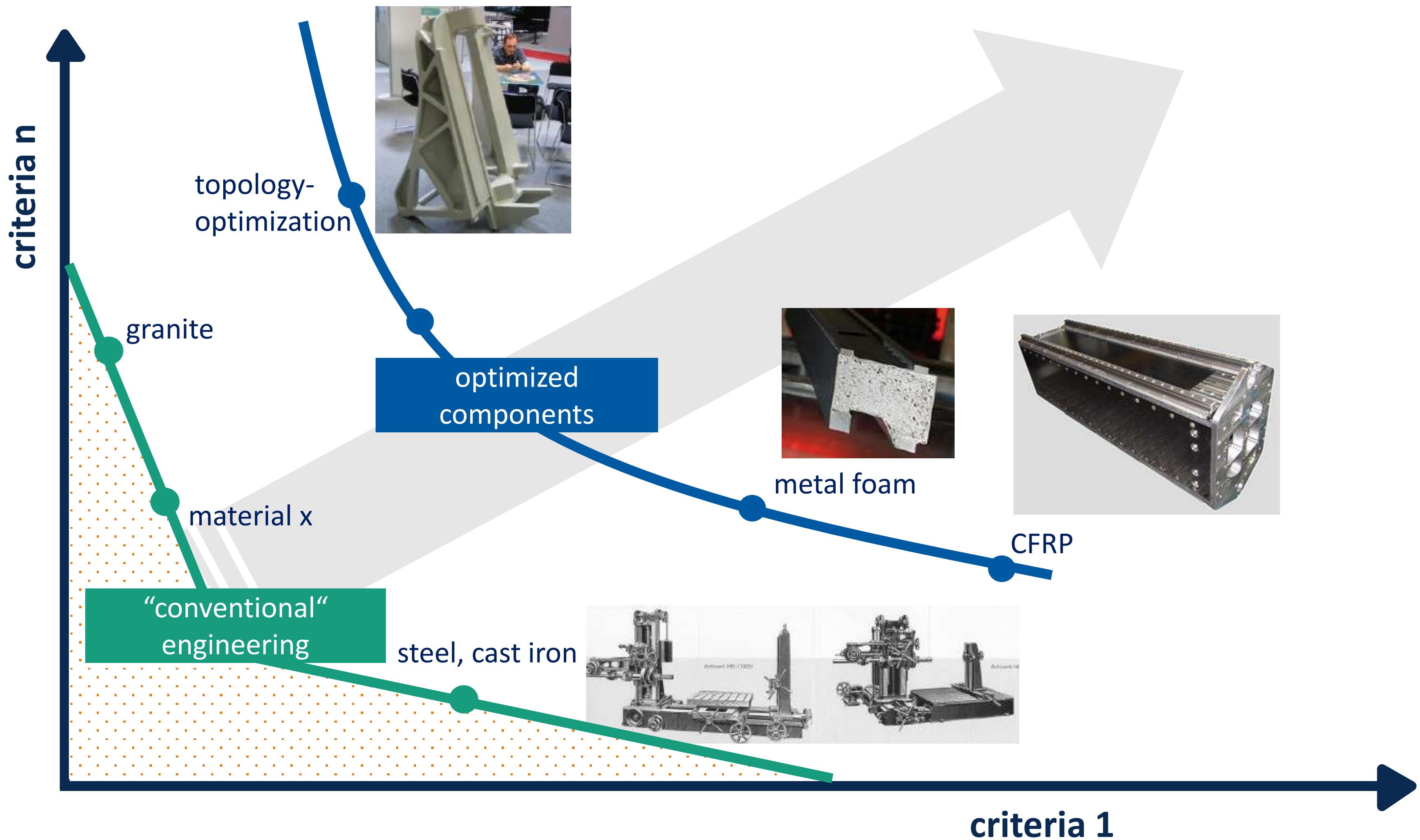
Machine Tools Dynamics



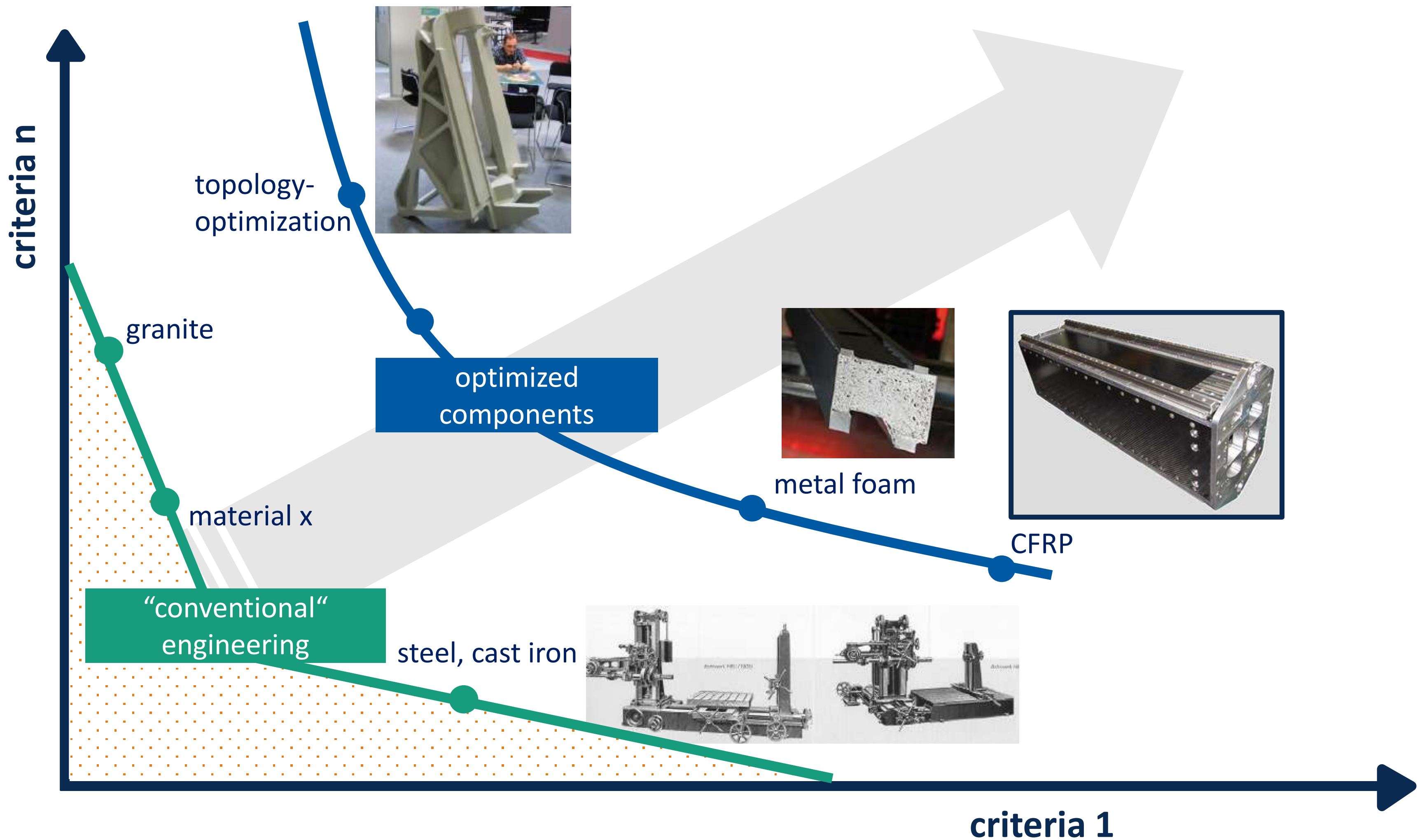
Materials for machine tools



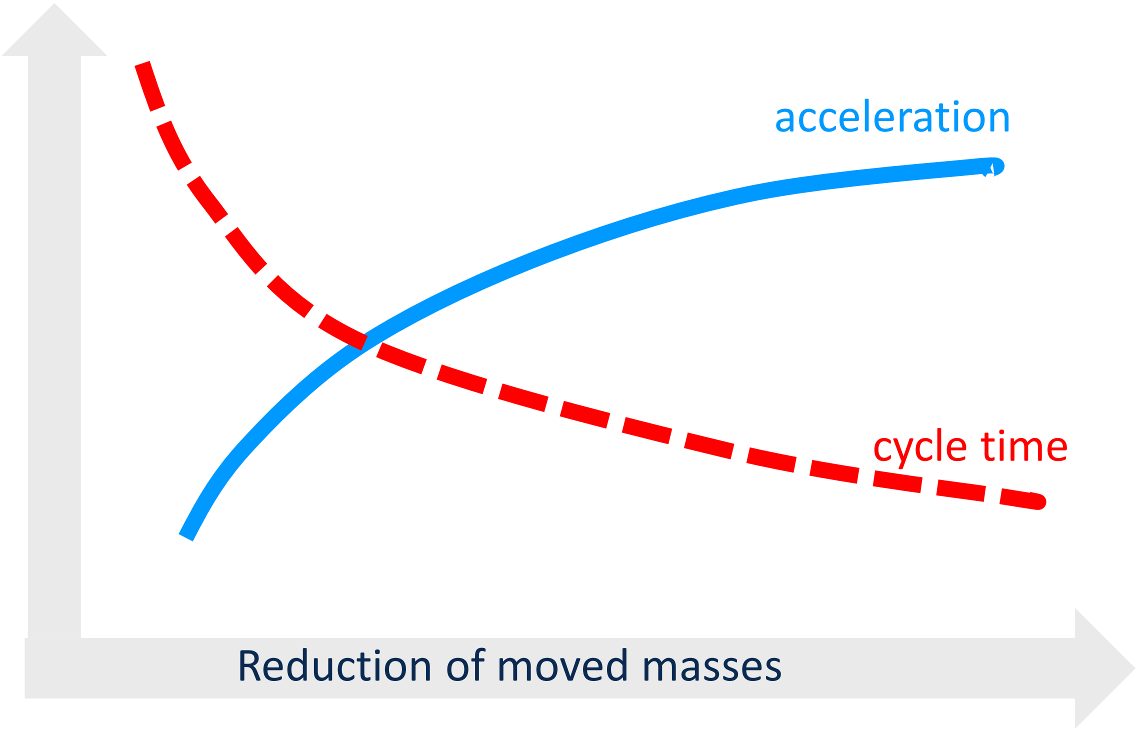
Materials for machine tools



Materials for machine tools

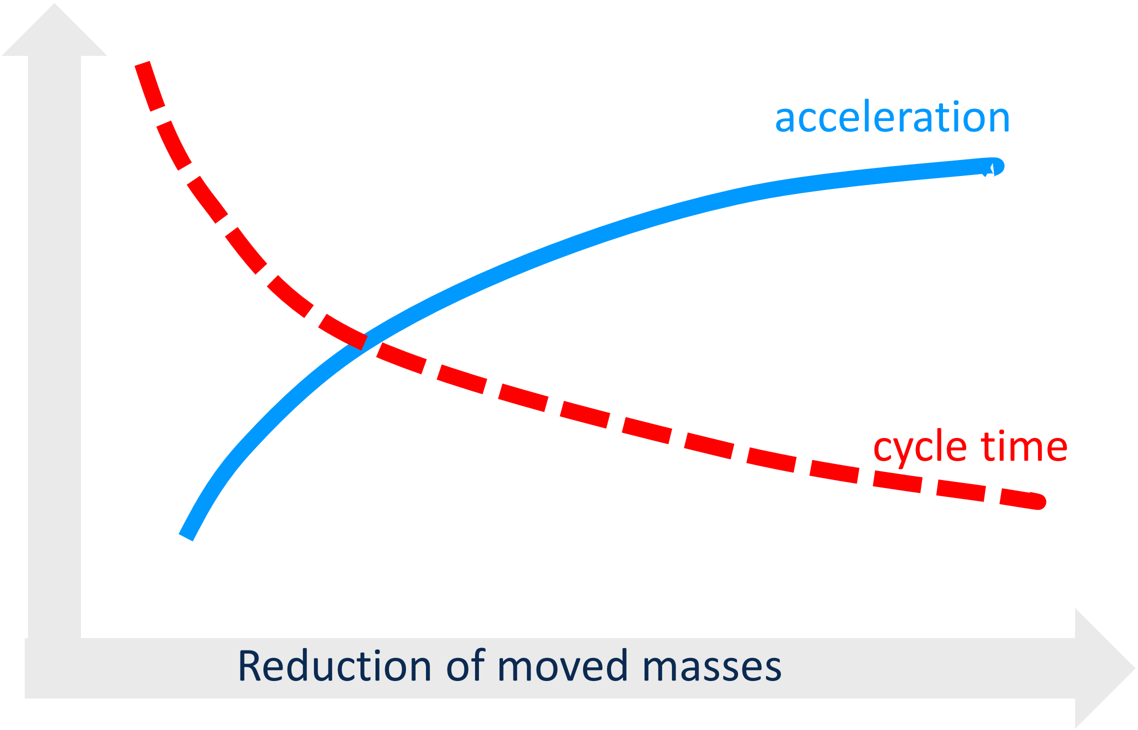


Materials for machine tools - lightweight design



1) Higher acceleration → shorter cycle times
2) Shorter cycle times → better global competitiveness
3) Shorter cycle times → effective way to energy efficiency

Materials for machine tools - lightweight design



Carbon fiber structures for machine tools

1) Higher acceleration → shorter cycle times
2) Shorter cycle times → better global competitiveness
3) Shorter cycle times → effective way to energy efficiency

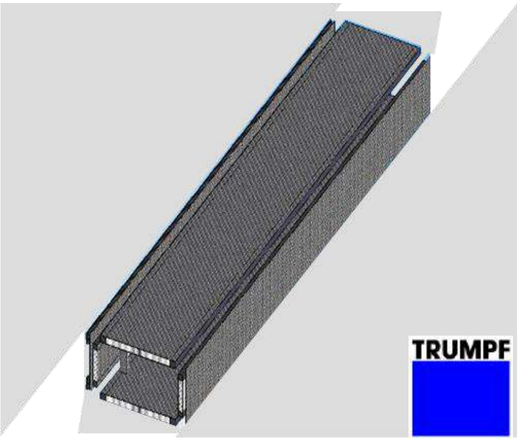
Example: CFRP traverse laser cutting machine

Machine characteristics :

- 2 parallel working laser units
- High dynamics: Acceleration 2,5g

Design principle

- CFRP aluminum honeycomb sandwiches
- CFRP-belts
- Steel support
- Joining by gluing



Advantages over steel concept

1) mass reduction 50 %
2) Increase of stiffness by 100%
3) Increase dynamic stiffness by factor of 4

70% increase of productivity

(amortization after 3,5 month)

Quelle: TRUMPF (TruLaser 7040)

Example: CFRP Z-Slide machining center

Machine characteristics :

- HSC machining center
- Tool and die making

Design principle

- CFRP semi-finished parts
- Steel support
- Joining by gluing

Fraunhofer IWU

NILES CHEMNITZ

Advantages over steel concept

mass reduction structural parts 60% (775 → 305 kg)

mass reduction overall 41% (1143 → 673 kg)

increase of productivity

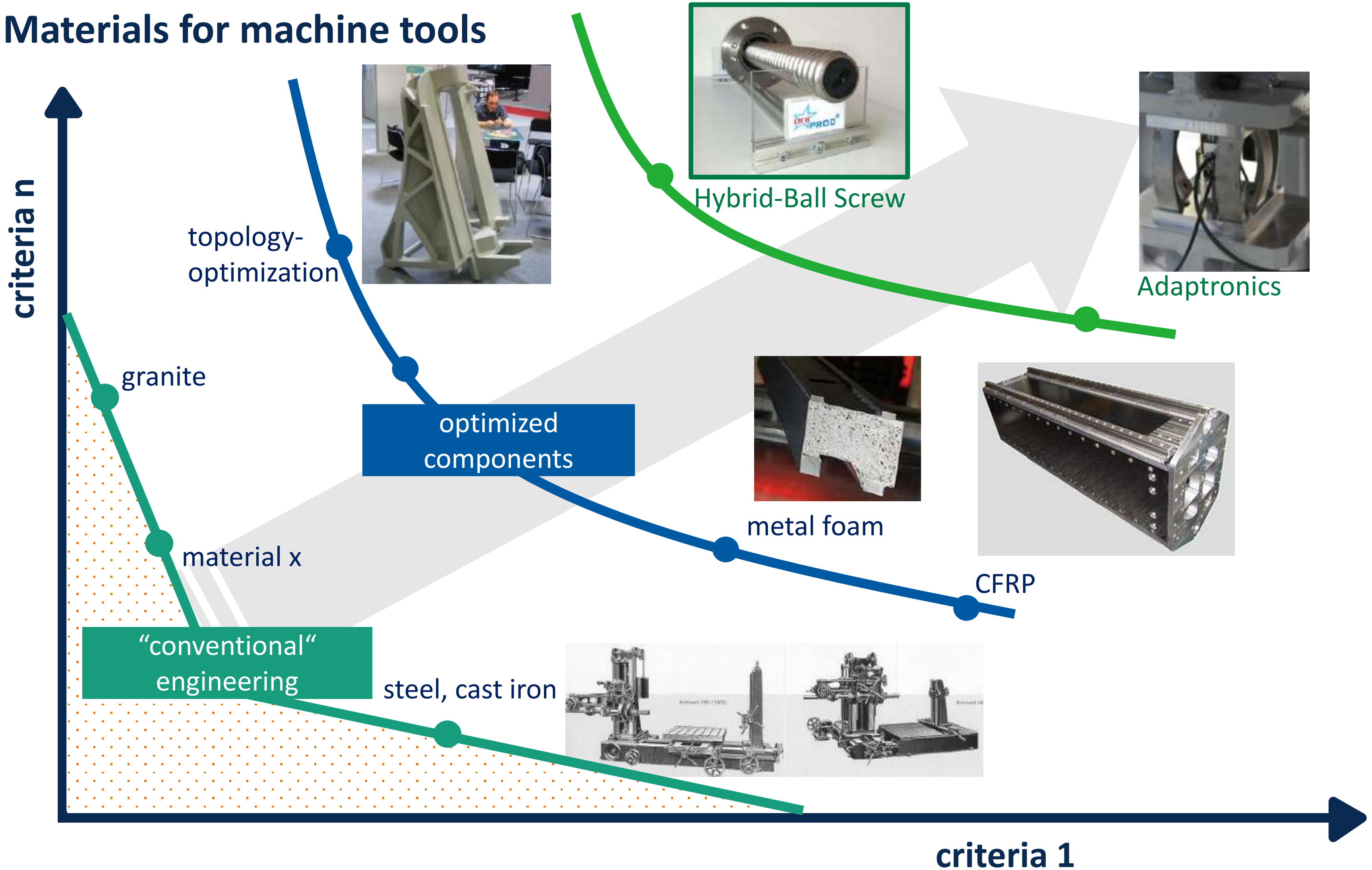
improvement of quality (surface)

Carbon fiber composite structures

Challenges:

- Where are CFRP structures useful?
- Complex design and engineering due to anisotropy of CFRP
- Lack of knowledge in CFRP component design
- Design of combination metal – CFRP
  - different Youngs' modulus
  - different expansion coefficient
- Economics

Materials for machine tools



Hybrid CFRP-Metal ball screw drive

Motivation for hybrid carbon-fiber reinforced ball screw spindle

1. **Guide bandwidth** determined by lowest eigenfrequency
   → Axial stiffness of ball screw spindle is often the major elasticity
2. **Rotational inertia** limits feed drive dynamics
3. **Thermal lengthening** of spindle demands fixed-free axial bearing (especially in high dynamic feed drives with high local thermal loads)
   → Reduced feed drive stiffness compared to a fixed-fixed axial bearing
   → Thermal lengthening is not recognized by indirect measuring systems
4. **Feed drive dynamic limitation by critical speed of the spindle**

Need for action ball screw spindles

Higher stiffness (axial, bending, torsion)

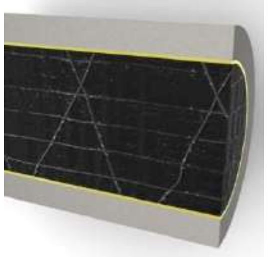
Reduced rotational inertia

Reduced thermal lengthening

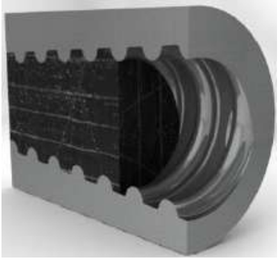
Hybrid CFRP-Metal ball screw drive

General Approach: Hybrid Spindle consisting of carbon-reinforced core and metallic layer for the bearing surface

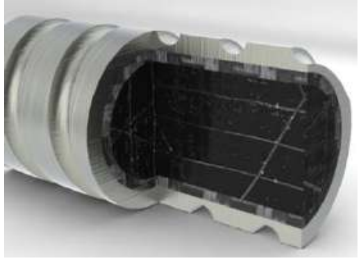
Adhesive joint



Form closure



HV arc spraying



Adhesive joint / Form closure:

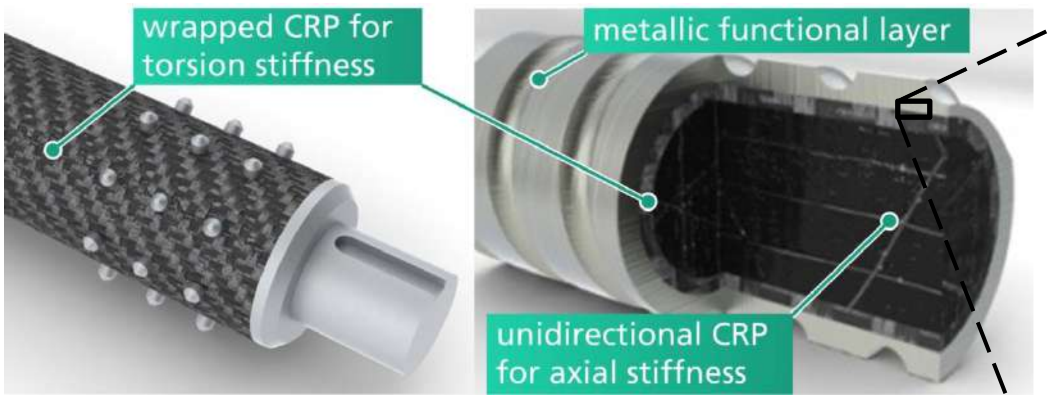
+ material variability
+ technological potential for higher manufacturing numbers
+ standard finishing technology
– extremely sensitive for tolerances
– not well-suited for large dimensions (e.g. unbalances)

HV arc spraying:

+ flexible realization for prototype
+ reliable contact between carbon core and metallic layer
– restriction for material variability
– specific finishing technology necessary
– multi-layer metallic film necessary (thermal induced residual stress)

Hybrid CFRP-Metal ball screw drive

Structure



Structural layers CFRP-steel

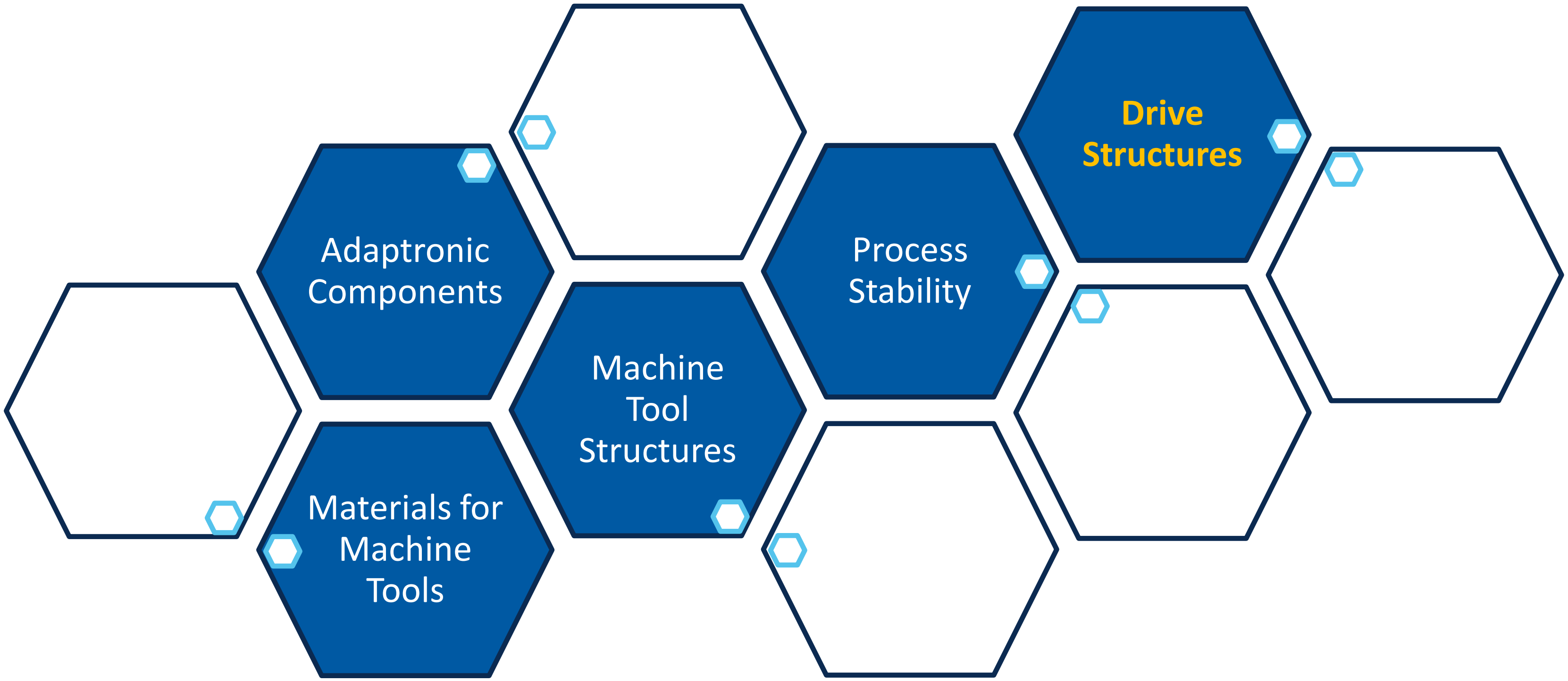
Simulation results for functional prototype

Thermal lengthening	Axial stiffness	mass
-87 %	-10 %	-54 %

- CFRP core: unidirectional high-modulus fibre for axial stiffness
- +/-45°-wrapped CRP for torsional load and stiffness
- Functional metallic layer for bearing surface realized through thermal spraying

eniPROD Fraunhofer IWU

Machine Tools Dynamics



Application with high dynamics

Movements with high dynamics and high acceleration

Tool- and die making

Dynamic and high-precision positioning

Pick- and Place

Surface quality stick-slip-free behavior

Micromachining

High feed rate

Laser cutting

Comparison of different drive systems

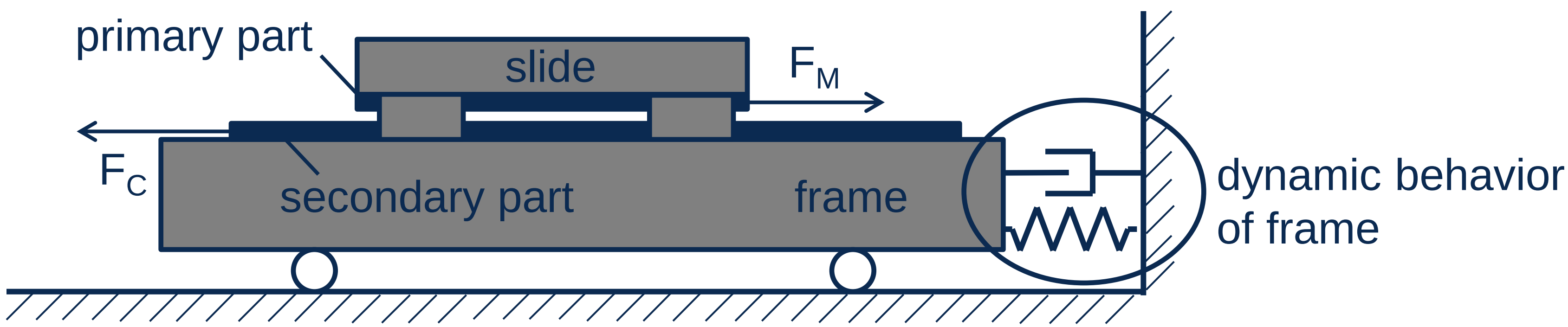
	Linear direct drives	Ball screw drives	Belt drives	Rack and Pinion drives
Velocity	++	O	+	+
Acceleration	++	+	-	O
Accuracy	++	+	-	-
Max. Force	O	++	O	+
Max. Traverse	++	-	+	++
Wear	++	O	O	O
Stiffness / 1 EF	++	O	-	+

Linear direct drives

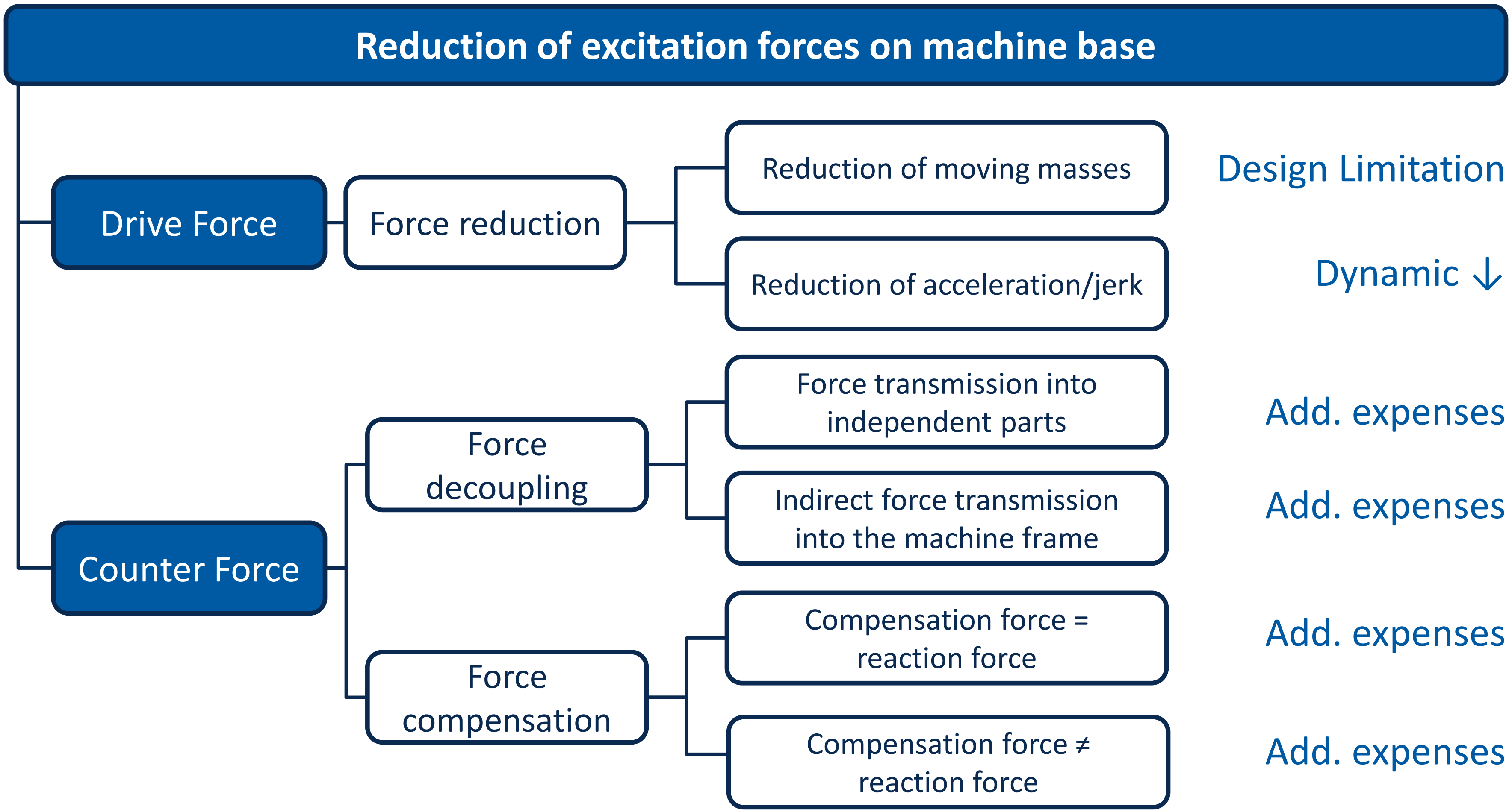
High forces and high force gradients
enable
High feed rate, acceleration and acceleration gradient (jerk)

Counterforces
cause
Excitation of frame oscillation, limited control parameters and jerk limitations

Principle (simplified) model



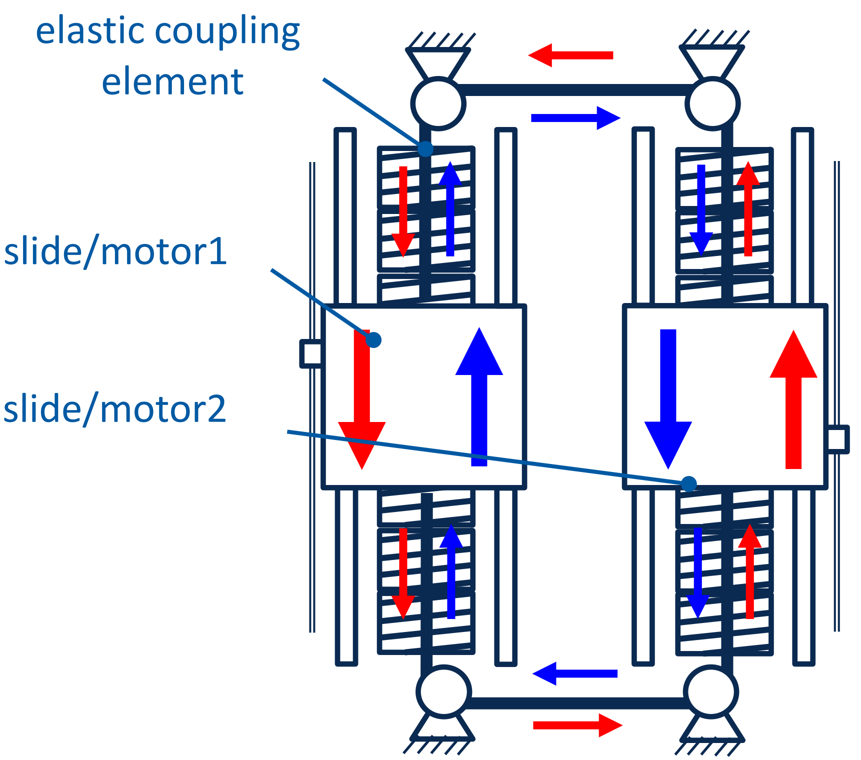
Systematic Approach



New Concept

Force compensated linear motor direct drive system

1. Force compensation by opposite movement of motors
2. Using counterforce as feed force
   → downsizing of motors
3. Enabling of energy storage by the use of elastic coupling elements



New Concept

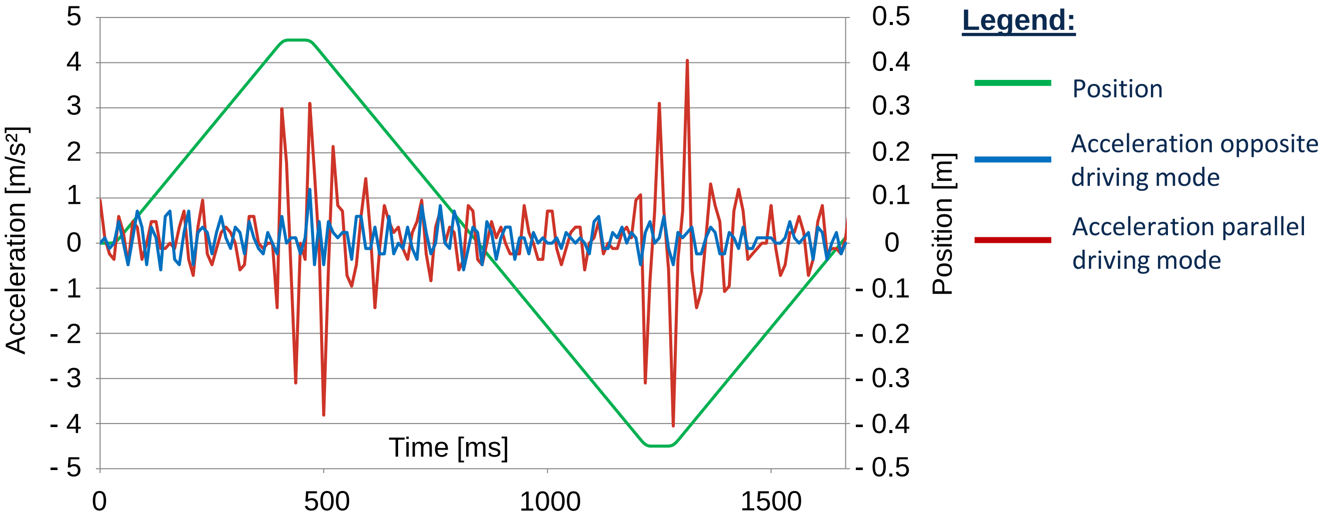
Force compensated linear motor direct drive system

1. Force compensation by opposite movement of motors
2. Using counterforce as feed force → downsizing of motors
3. Enabling of energy storage by the use of elastic coupling elements

New Concept - Results

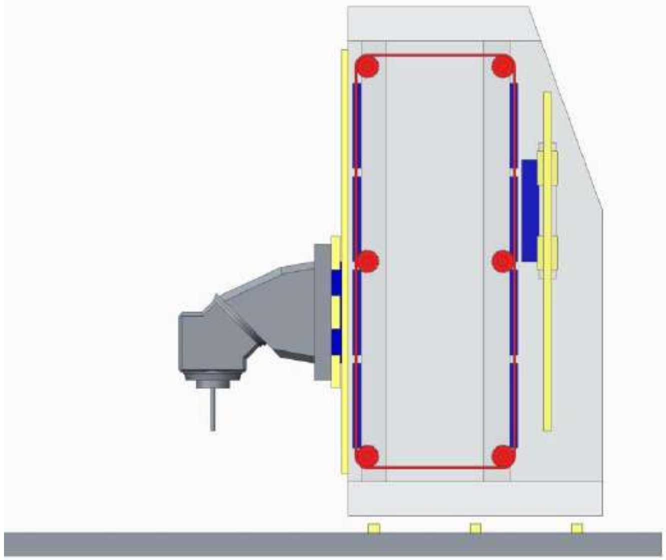
Excitation of the machine structure

- Comparison between opposite and parallel driving linear motors
- High dynamic positioning motion (900 mm, 2000 mm/s, 10.000 m/s²)
- Machine structure acceleration measured in feed direction
- **On average 75 % less vibration excitation into machine structure**

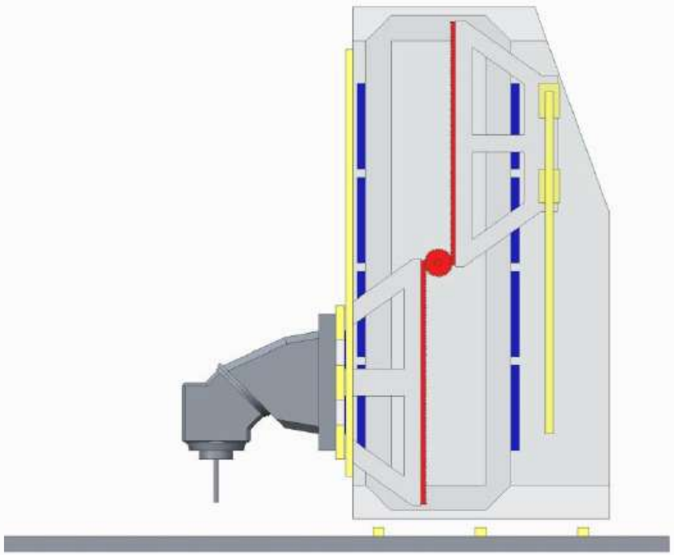


New Concept - Results

Design Concepts

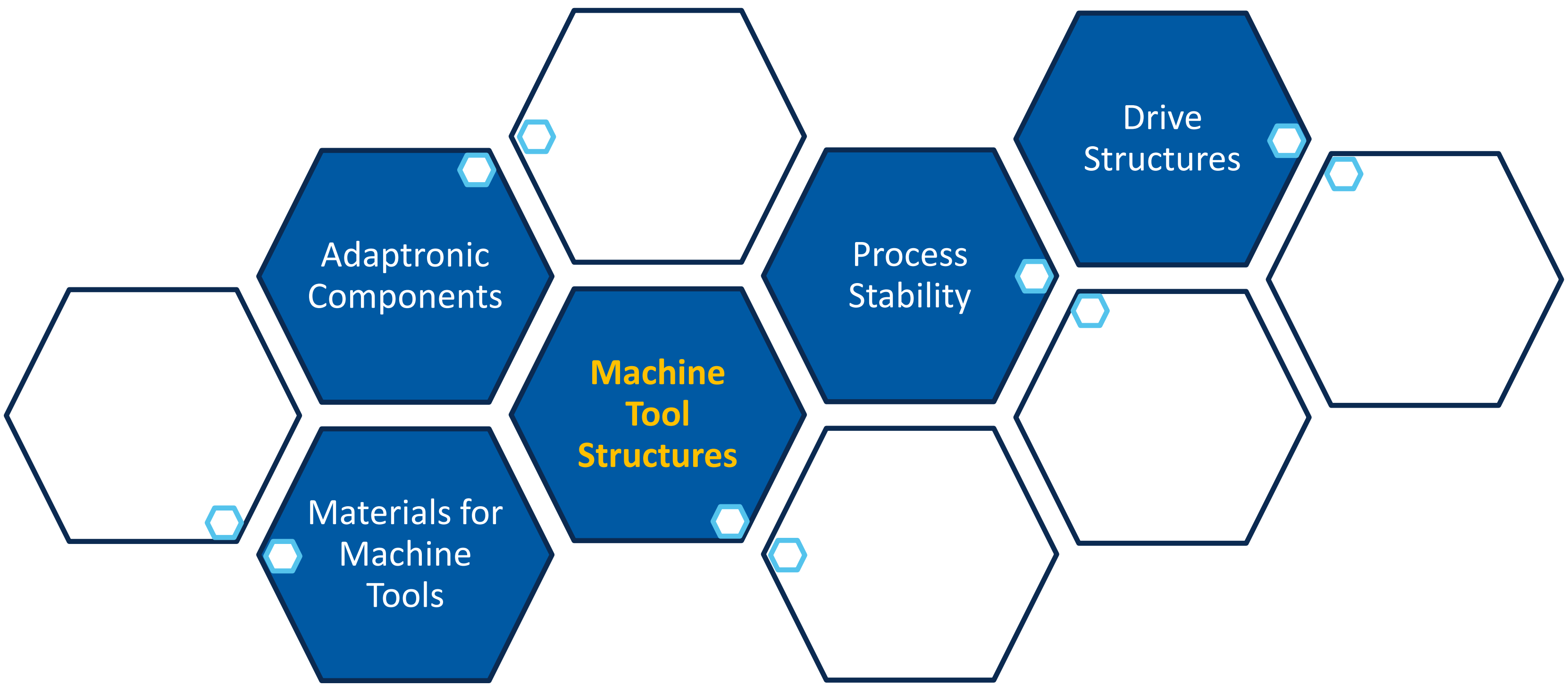


Design concept with belt-coupling

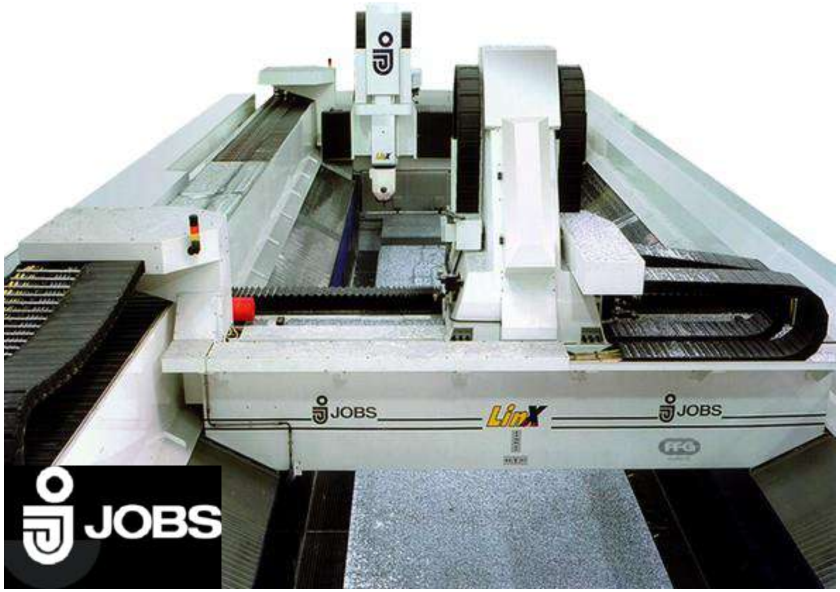


Design concept with rack-and-pinion

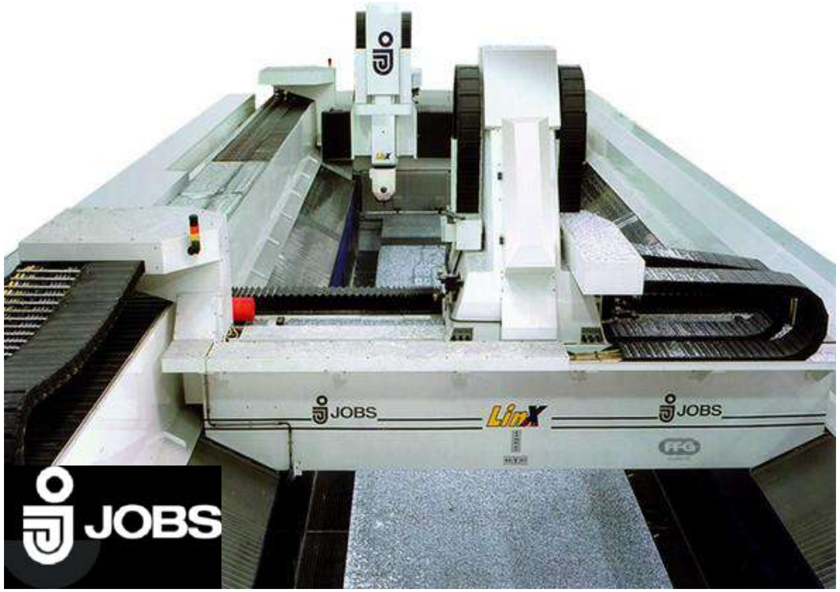
Machine Tools Dynamics



Machine Tool Structures
Machining of large parts



Machine Tool Structures
Machining of large parts



Hypothesis:
The solutions in nature are based on a long-time optimization process by evolution

Bionic Analogies:
Short-time optimization of technical systems by learning from nature

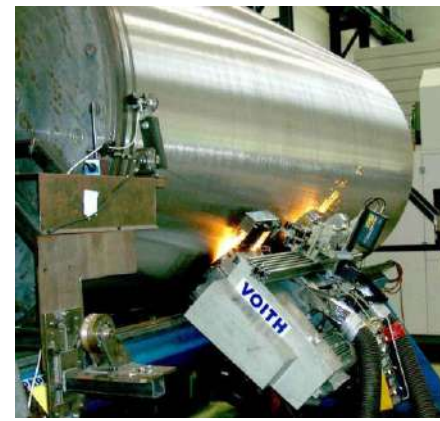
Machine Tool Structures

Mobile machine tools

Example: Machining of large workpieces with small mobile machine tools

Mobile Milling unit for maintenance of turbine drive shafts (METROM / IWU)

Pecker



Mobile Grinding unit for maintenance of rolls for paper drying (Voith Paper Services / IWU)

Analogies:
- **Orientation** on the workpiece coordinate system
- workpiece is part of the **machine structure**
- high **dynamic**, high **energy-efficient** technologies with low **machining forces**

Machine Tool Structures

Redundant drive structures

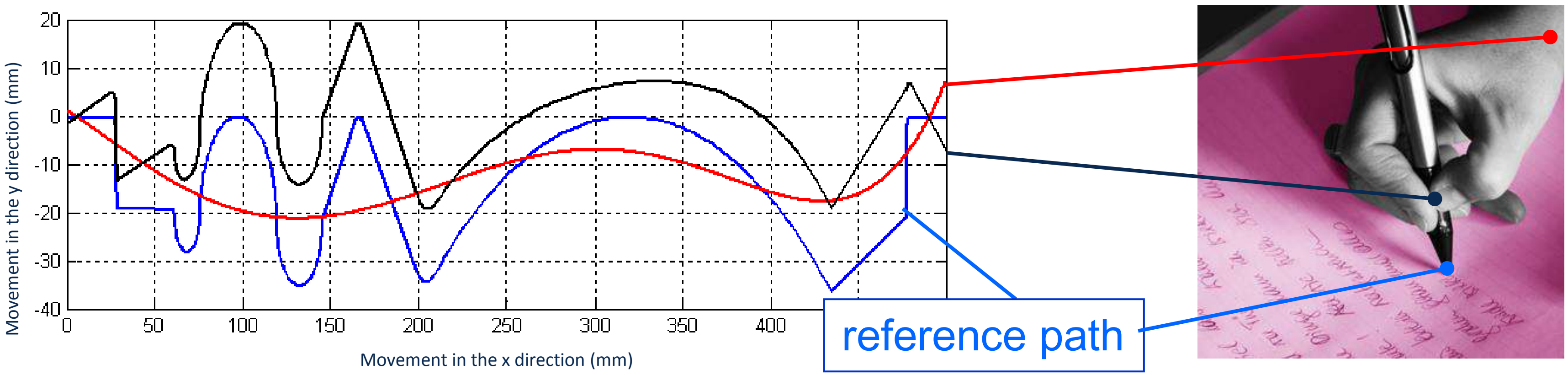
Challenge in Tool and Die Machining

Large working space *versus* local high dynamic requirements

Bionic Analogy

Redundancy as energy efficient movement principle

Examples in nature: frog (tongue), elephant (trunk), human (hand)



Analogy: Writing

Global – low dynamic (arm axes / serial)

Local – high dynamic (hand axes / parallel)

Machine Tool Structures

Redundant drive structures

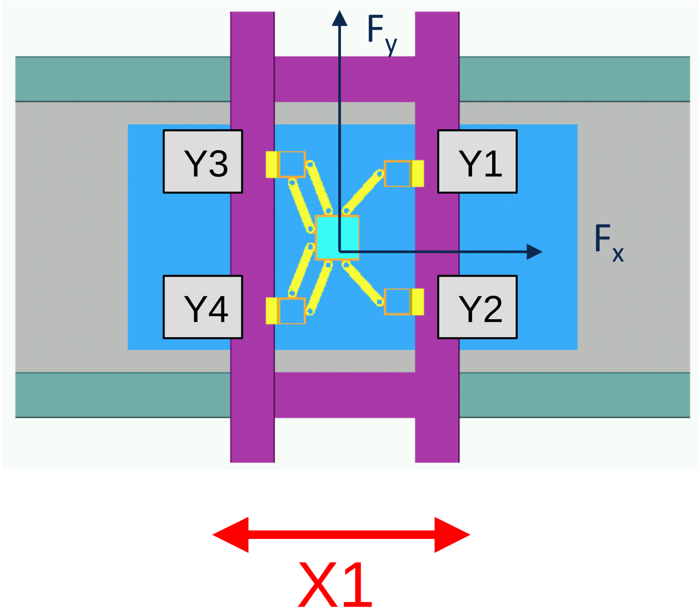
Rough Milling / HPC

- Machining Forces
- Process Stability / Volume Removal Rate

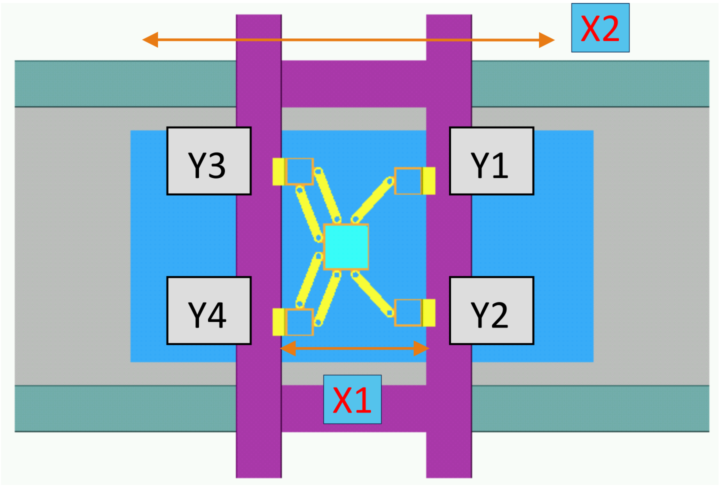
Finishing / HSC

- Dynamics
- Accuracy

Actuation Redundancy



Motion Redundancy



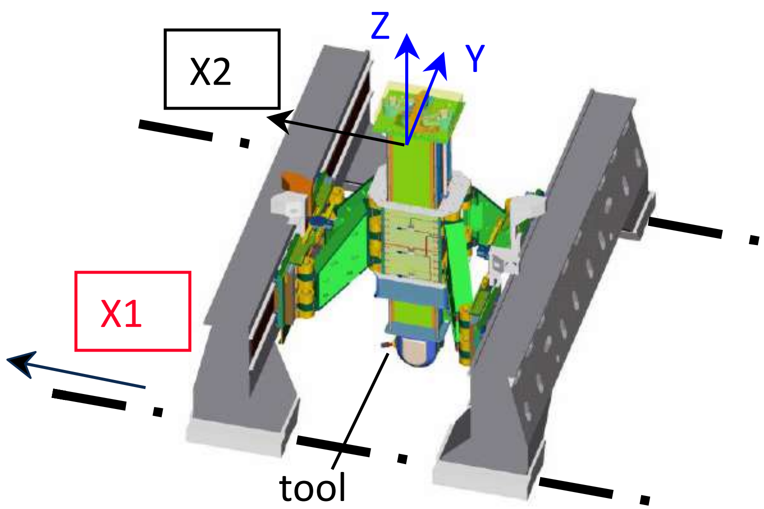
Machine Tool Structures
Redundant drive structures

→Suitable for HPC + HSC

→Motion redundancy for the heaviest axis

→High stiffness by actuator‘s redundancy

→High accuracy by sensor‘s redundancy

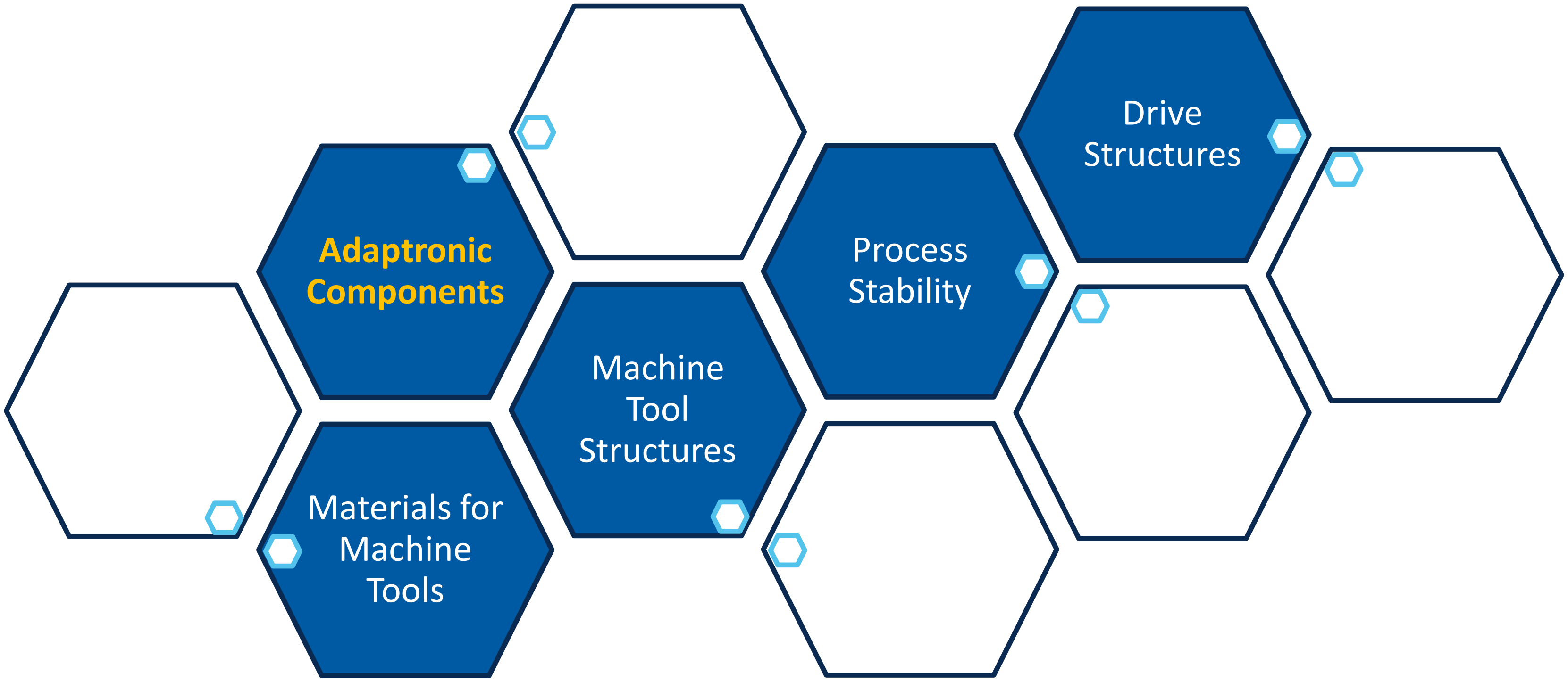


Prototype / Cooperation Project
VW, Niles-Simmons, IWU

Machine Tool Structures

Redundant drive structures

Machine Tools Dynamics



Adaptronic Components

Motivation

Machining of energy-efficient components

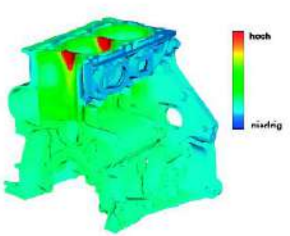
Active control cutting edge

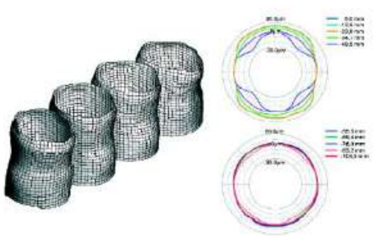
Concept

Ultra-precise sub kinematics Based on piezo actuators

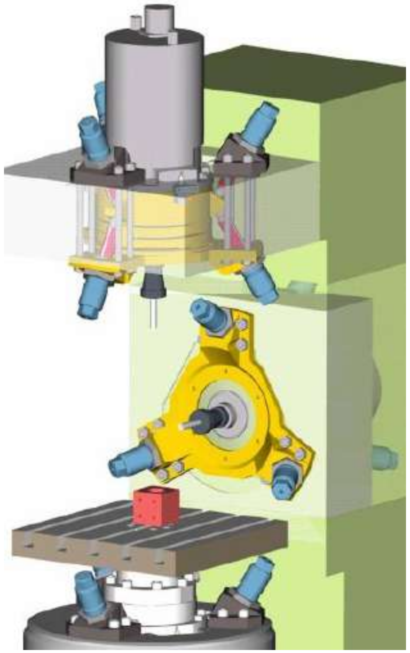
1. Pre-compensation of thermal effects by inverse contouring

2. Optimal friction behavior through micro structuring





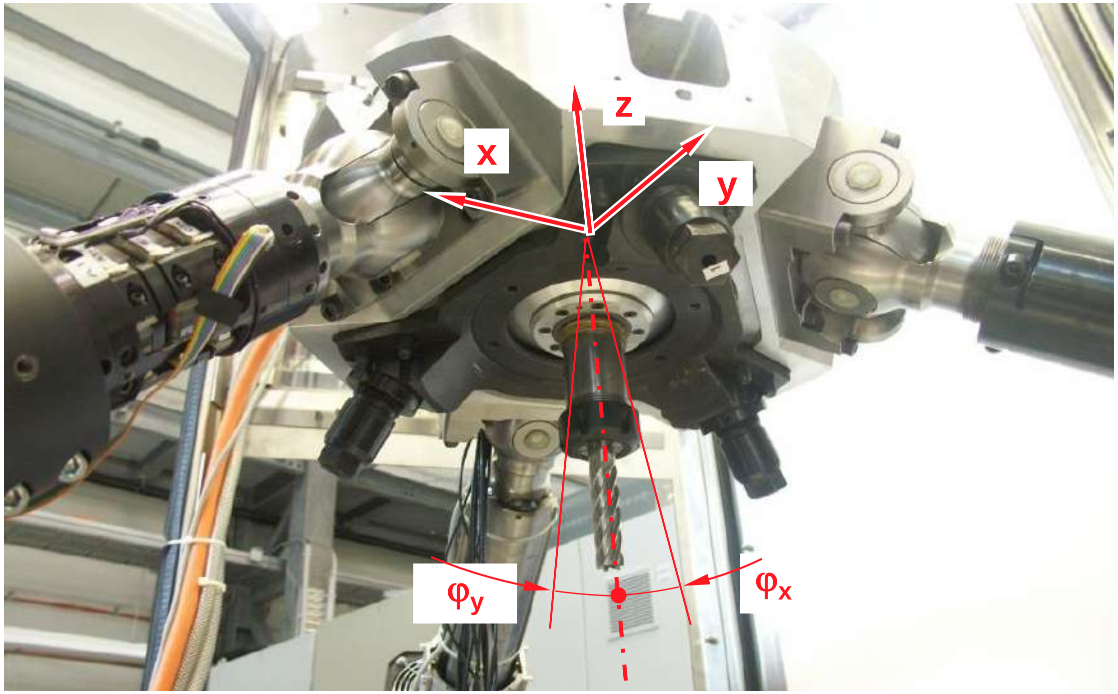
Source: Grunow et.al.
Das Zylinderkurbelgehäuse der neuen R4-TFSI Motorengeneration von Audi MTZ 05/2007 Jahrgang 68



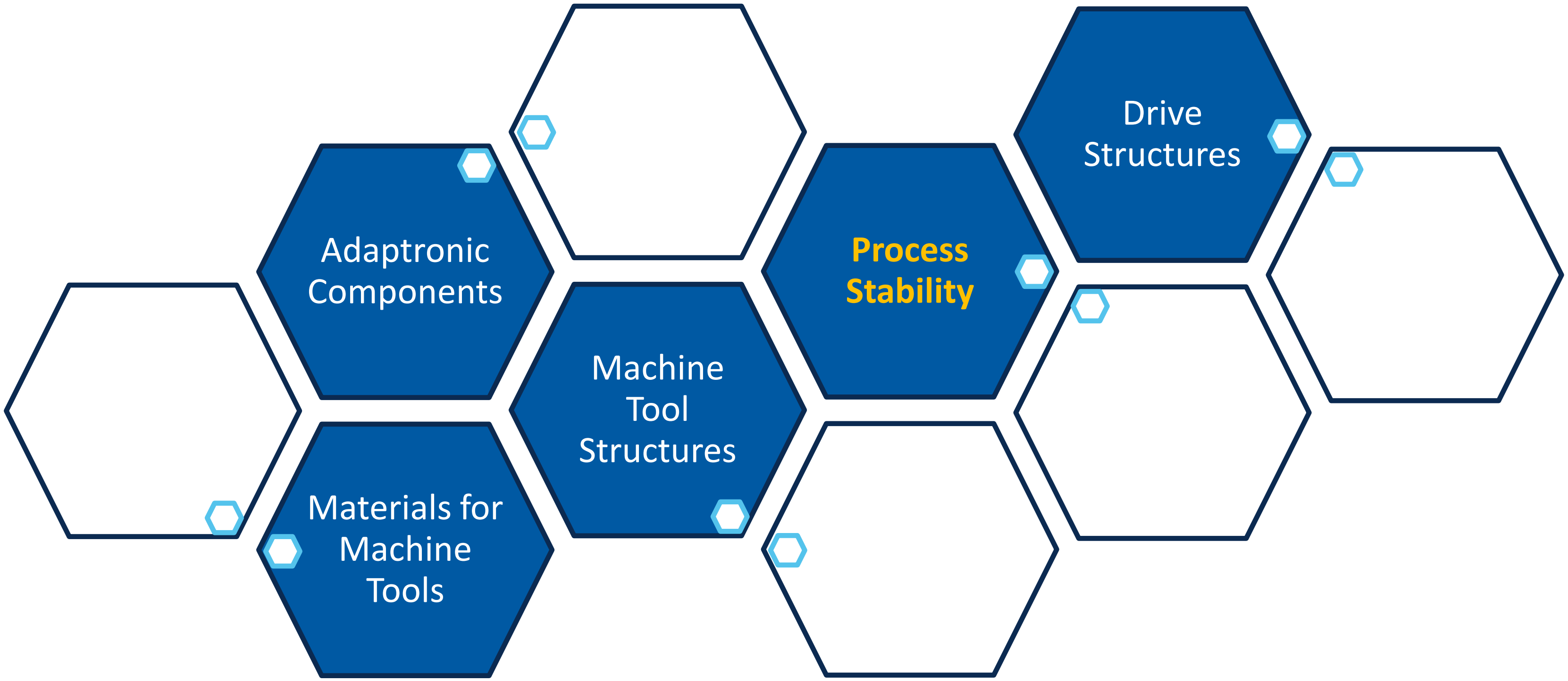
Adaptronic Components

Spindle mounting

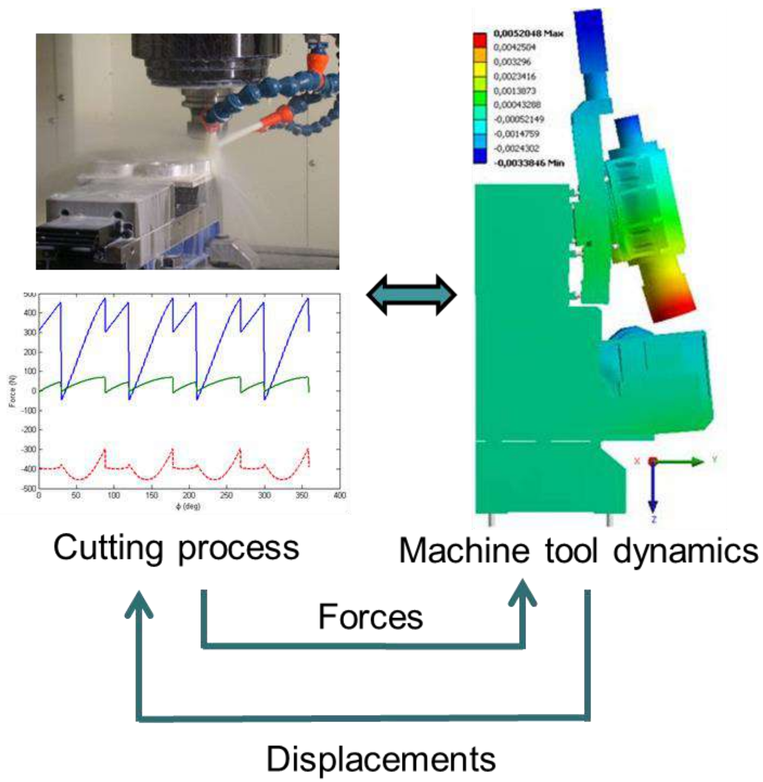
Integration into a machine tool

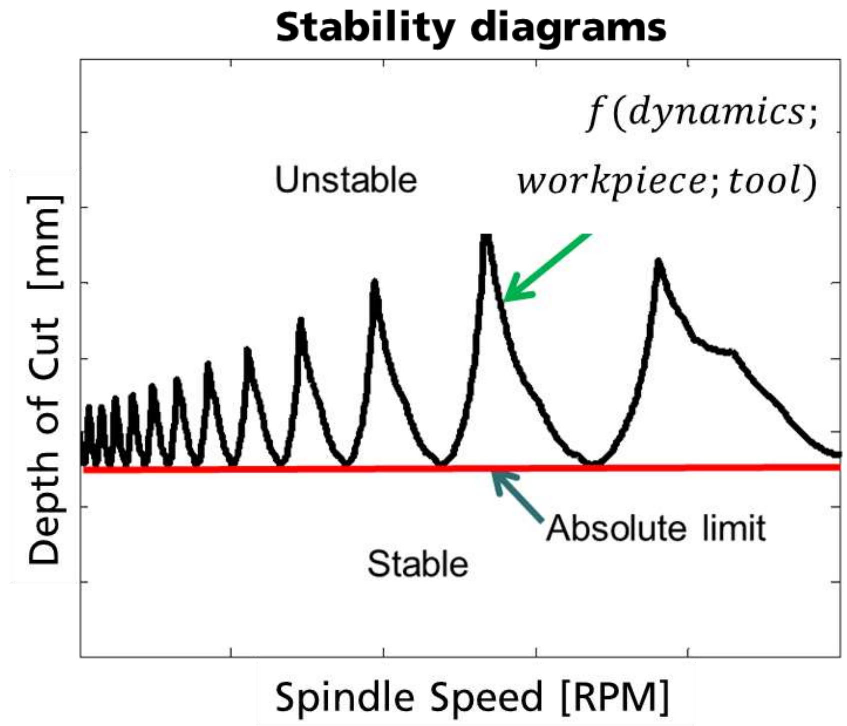


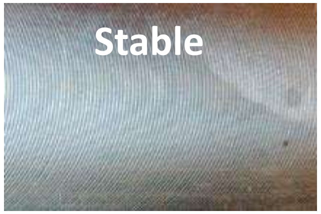
Machine Tools Dynamics



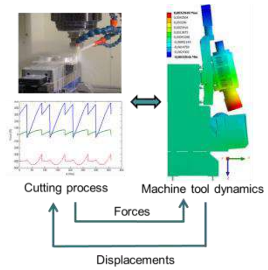
Introduction: performance characterized by stability







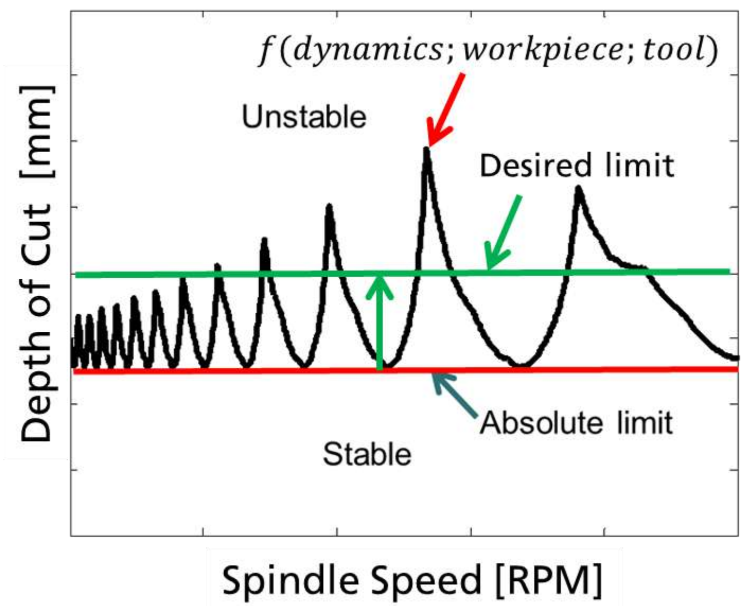
Motivation: improving machining performance

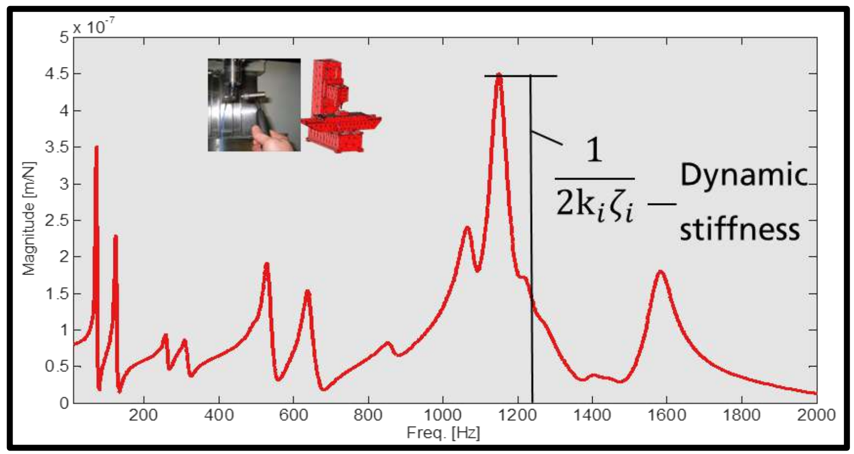


All other things being constant:

Absolute limiting depth of cut, a_{lim} :

$$a_{lim} \cong 2k\zeta$$





Increased dynamic stiffness → Increased productivity

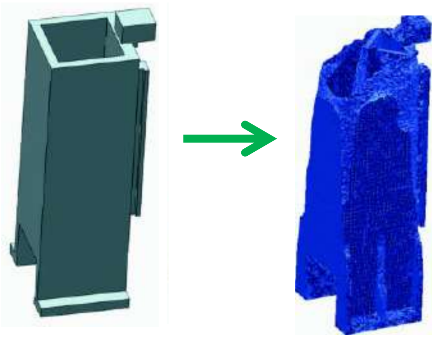
Increasing dynamic stiffness

Structural modification

$$a_{lim} \cong 2k\zeta$$

Stiffness:

$$k = f(Material\ modulus; Geometry)$$

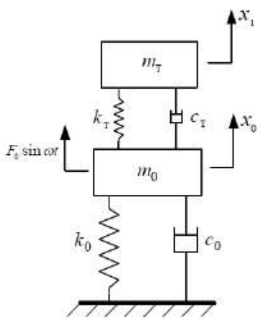


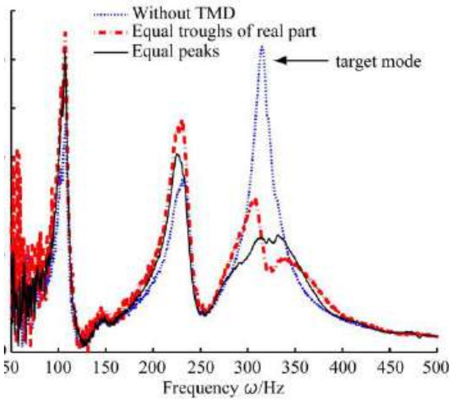
Law et. al. (2013)

Suitable at design stage

Increasing dynamic stiffness

Passive damping



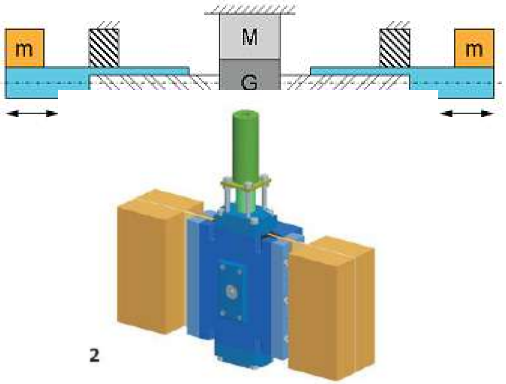


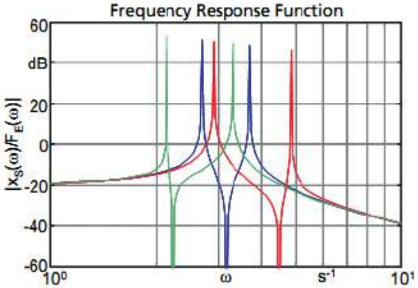
Yang et. al. (2010)

Not suitable for changing dynamics

Idea:

adaptive vibration damper only requires energy for frequency adaption

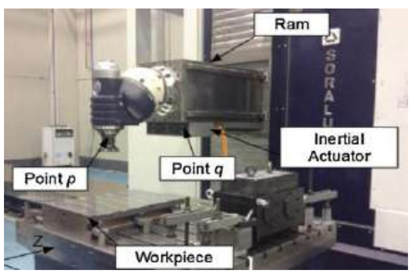




Increasing dynamic stiffness

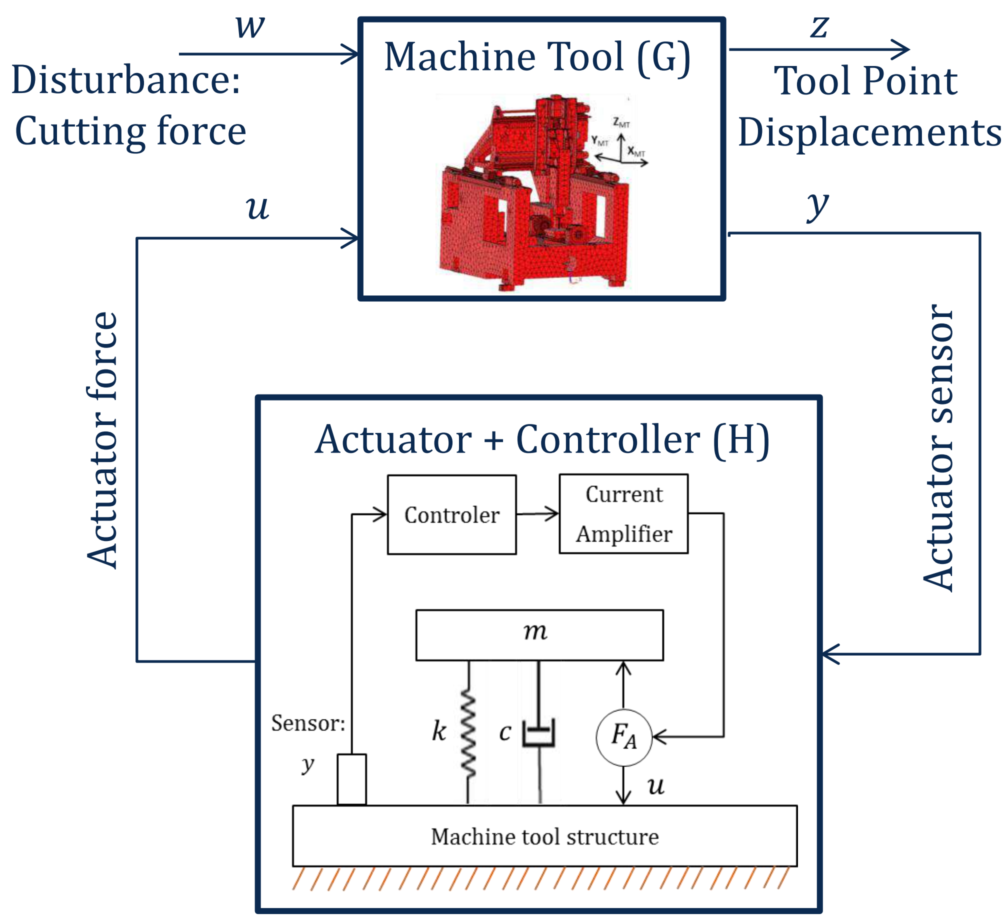
Active damping

Zäh and Baur (2011)



Munoa et. al. (2013)

Best suited, however:
No strategy for actuator sizing and selection for defined performance objectives



Combined effect: addition of viscous damping into the system

Machine Tools Dynamics

Outlook

- **New solution for machine tool design available**
- **Different approaches same objectives**
- **Combination reasonable**
- **Models for different degree of abstraction necessary**
- **Evaluation while design phases necessary**
- **Machine tools are agile**

Faculty of Mechanical Science and Engineering

technology without borders

Thank you for your attention!

Questions?

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