Machine tool precision determination and compensation approaches
Review on research at wbk Institute of Production Science

Daniel Brabandt
London, 5th Nov. 2014

wbk Institute of Production Science

Agenda

Karlsruhe Institute of Technology (KIT)

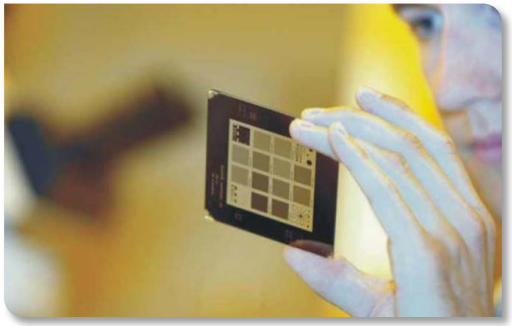
- Established: 1 October 2009
- Courses of Studies: 44
- Students: 24.500
- Staff: 9.439 (including 346 professors)
- Total budget: 795 m €

Objectives

- Positioning the Institute as an institution of internationally outstanding research and teaching in natural sciences and engineering that offers scientific excellence and world class performance in

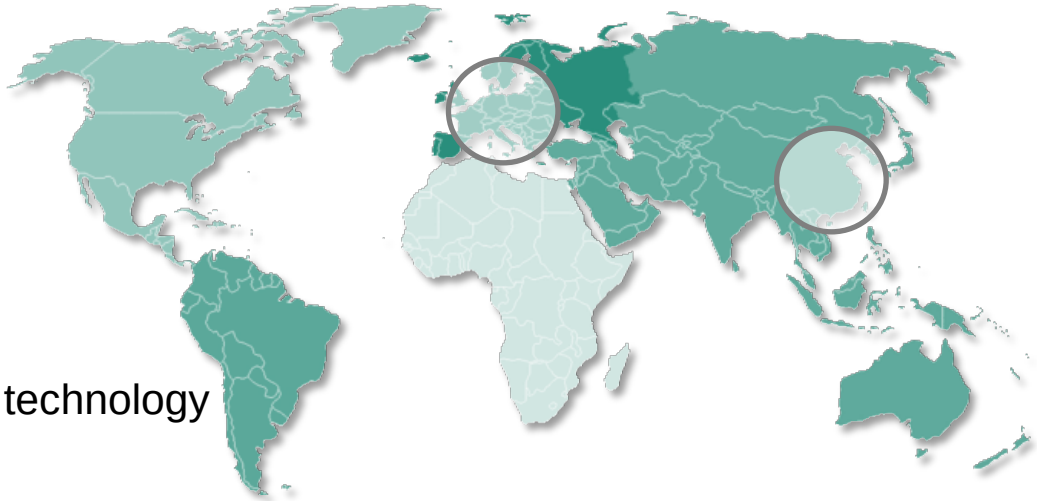
Research

Education



Innovation

Locations



- **wbk at Fasanengarten**
  - Production systems
  - Machines, equipment and process automation
- **wbk at Ehrenhof**
  - Manufacturing and materials technology
- **wbk at Campus Nord**
- **GAMI - Global Advanced Manufacturing Institute**
  - Suzhou, China
- **AMTC - Advanced Manufacturing Technology Center**
  - Shanghai, Jiading Campus at Tongji University, China

wbk, Fasanengarten, KIT

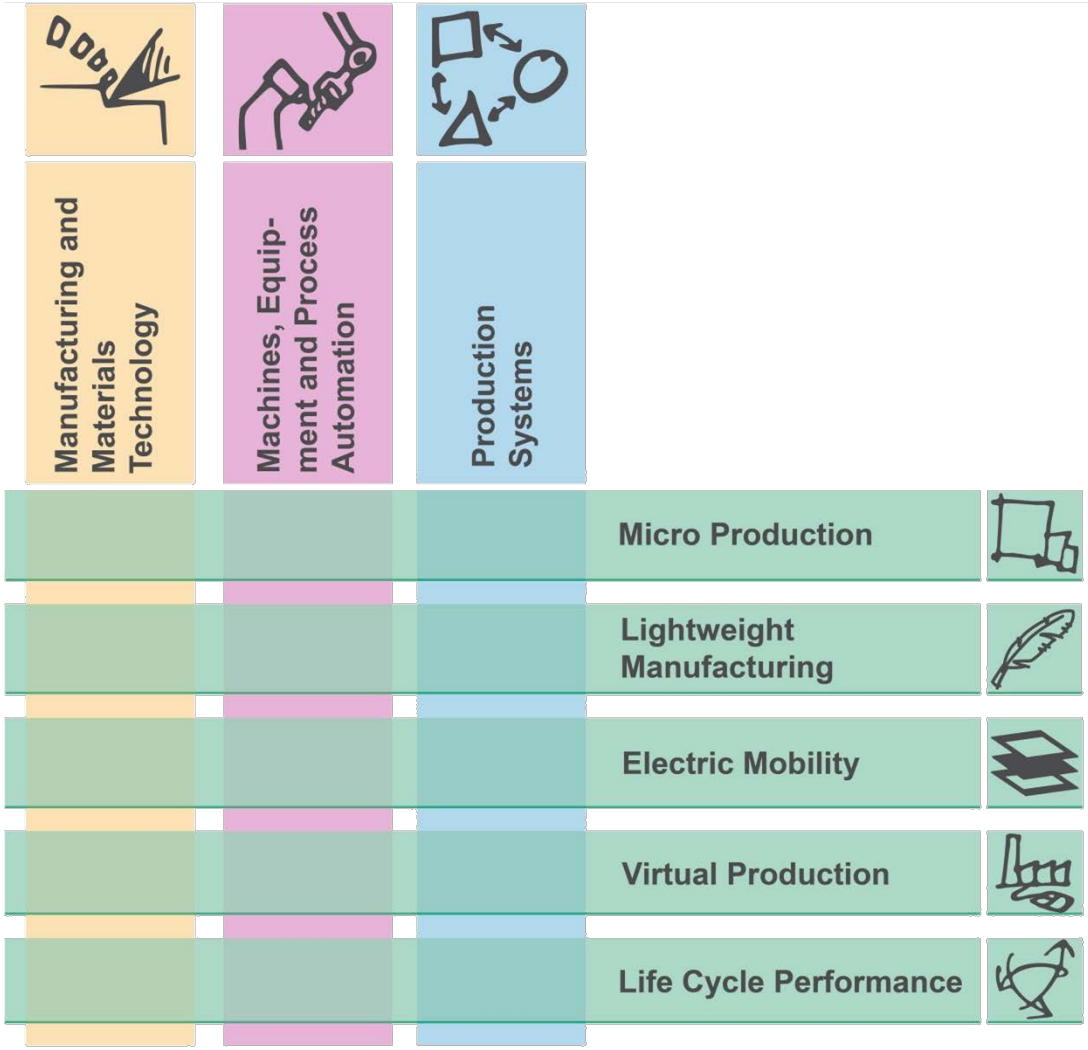
wbk, Ehrenhof, KIT

Building 276, KIT Campus Nord

Tongji University, GAMI, China

Prof. Dr.-Ing. J. Fleischer, Prof. Dr.-Ing. G. Lanza, Prof. Dr.-Ing. habil. V. Schulze

Research Portfolio



Prof. Dr.-Ing. Jürgen Fleischer
Prof. Dr.-Ing. Gisela Lanza
Prof. Dr.-Ing. habil. Volker Schulze

Introduction

Accuracy of machine tools

- Accuracies of machine tools is determined by all of the components and their errors
- Approaches to improve accuracies:

- Error compensation within machine tool structure:
  Adaptronic strut
- Error compensation at the tool:
  Compensation in tool clamping
- Workpiece orientation:
  Intrinsic part Scale

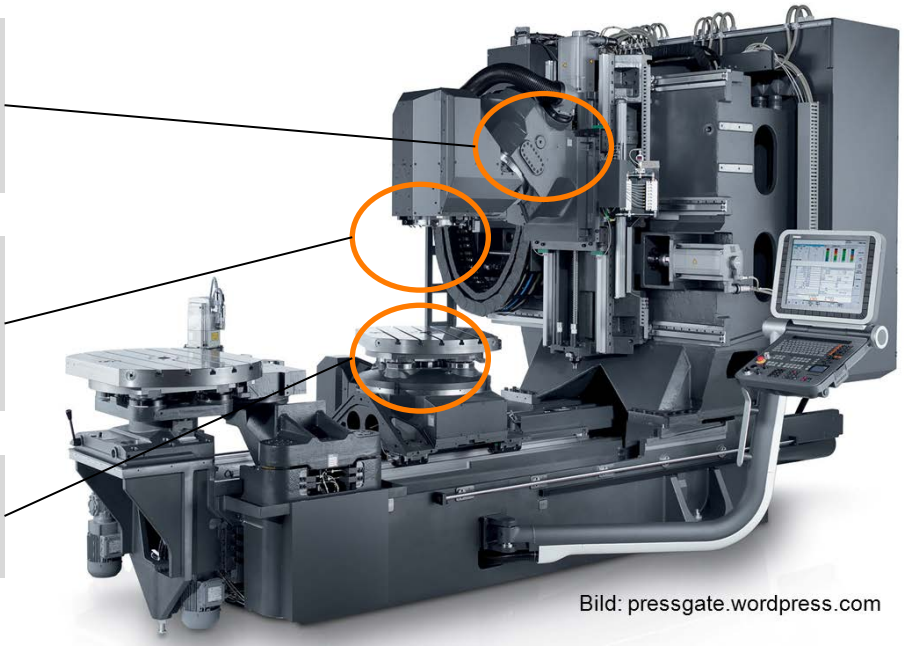


Bild: pressgate.wordpress.com

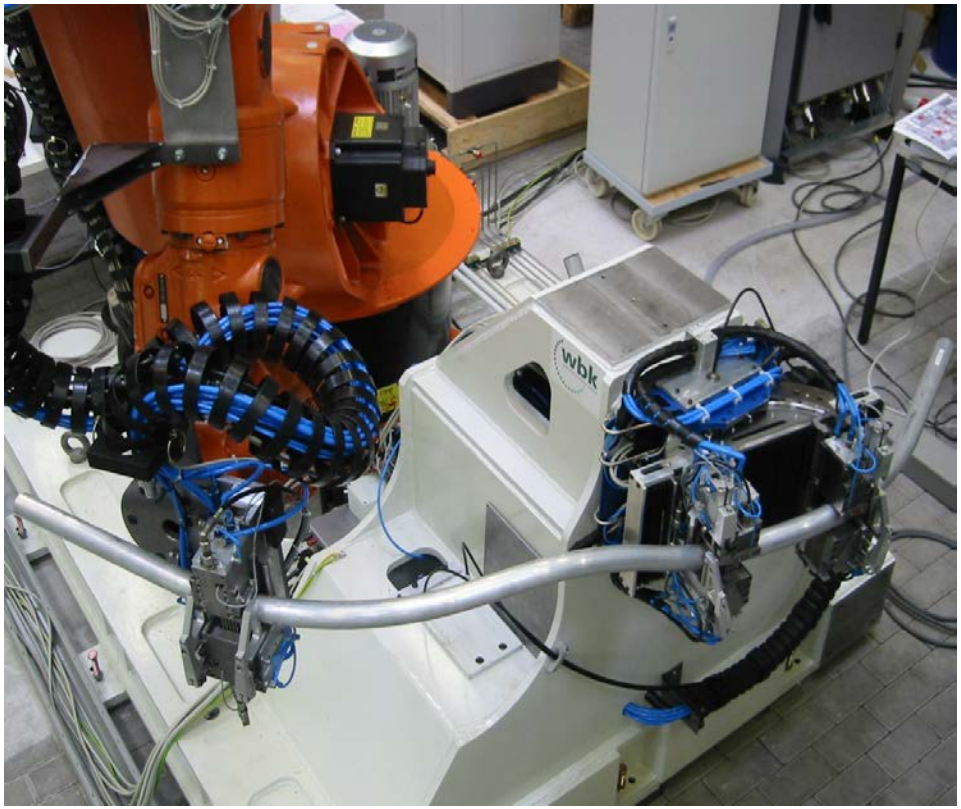
Agenda

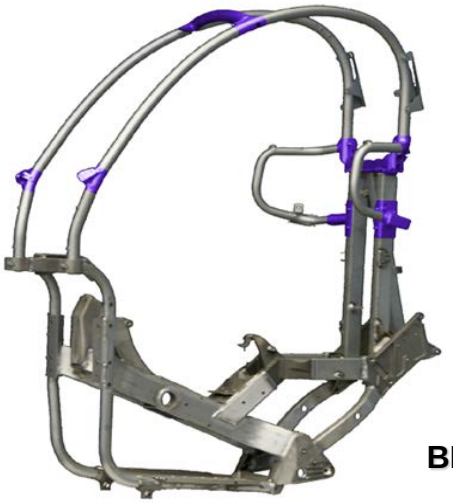
Intrinsic part scale

Motivation and Introduction

Aim

Flexible and exact machining of space-frame structures in automated **small batch production**





BMW C1

Process

- **insertion and positioning** the profile into the clamping fixture with an industrial robot (IR)
- **local clamping** of the profile
- **sequential machining**

Intrinsic part scale

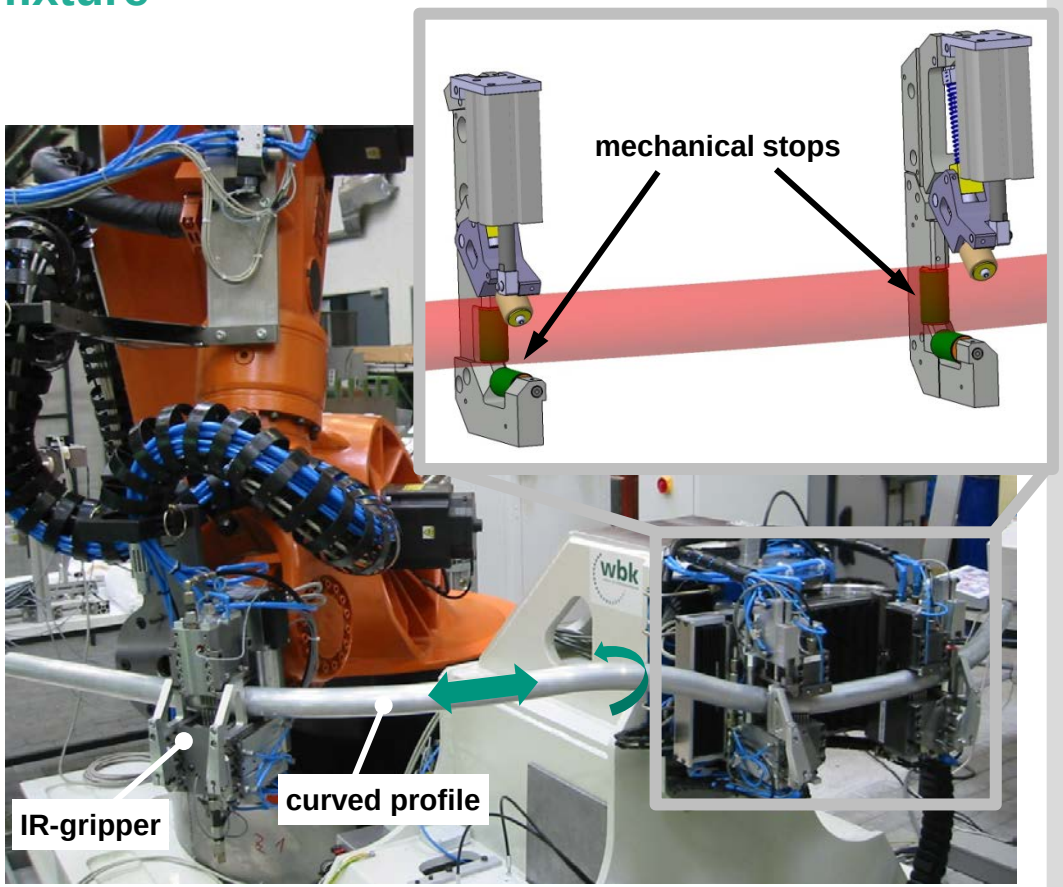
Profile positioning in the clamping fixture

Positioning

- 4 DOF are constrained with mechanical stops
- profile displacement and rotation along the longitudinal axis by the IR

Inaccurate positioning due to

- displacements inside the IR-gripper
- limited accuracy of the IR
- profile contour deviations



Metrological approach

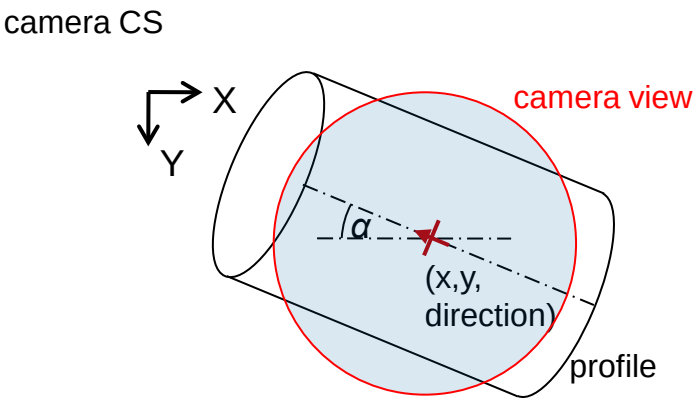
- individual **laser markings** on the profile surface for a **component-specific scale**

Intrinsic part scale

Component-specific scale

Required information in the marking

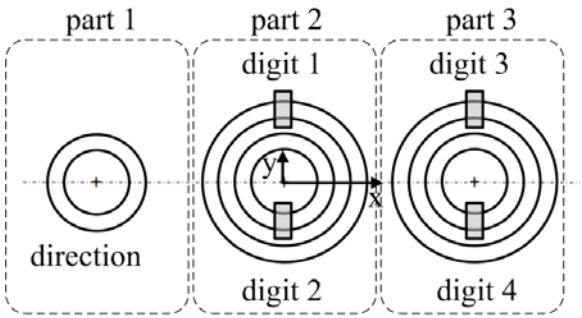
- x, y coordinates
- rotation-angle α (centerline – camera CS)
- orientation
- absolute allocation



Geometry derivation

- evaluation of simple ruled geometries and their combinations
- considered requirements
  - marking process
  - detection process

Scheme:



Binary image:

repeat accuracy of the position-detection of a single marking: ± 1.2µm (6σ)

Intrinsic part scale

Marking process

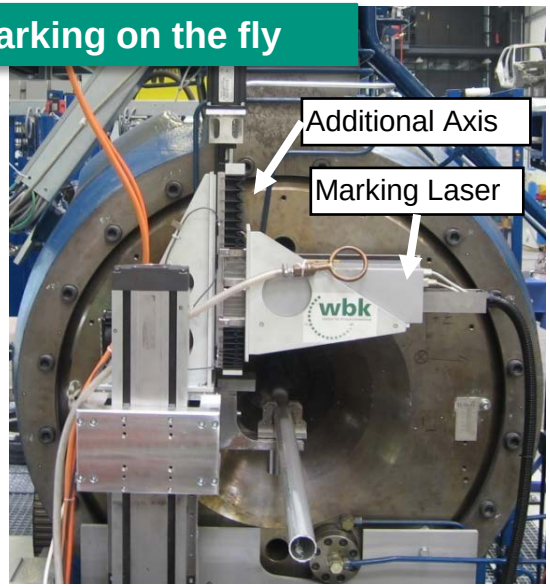
„Off-line“

- marking inside of a milling-machine
- positioning and focusing with axis and control of the milling machine
- during marking-process idle

„In process“

- synchronous with extrusion process (with marking laser)
- marking on the fly
- compensation of profile inclination
- real time control

marking on the fly



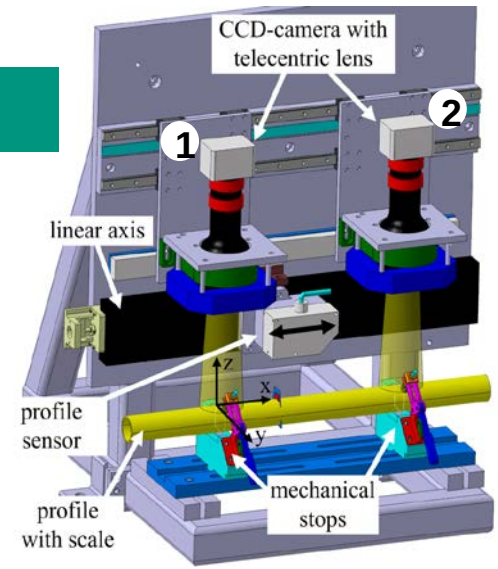
Intrinsic part scale

Measuring station

Profile positioning

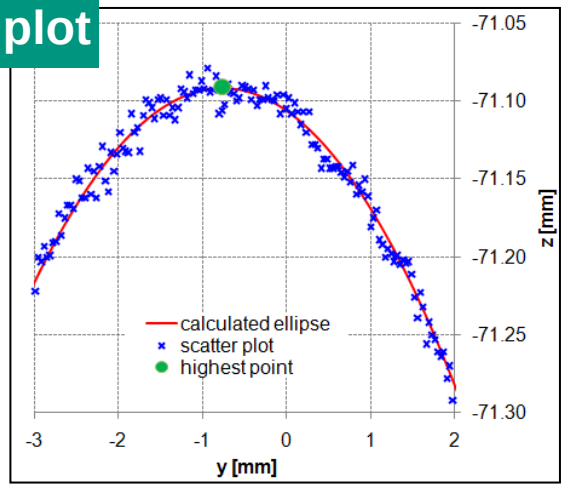
- **positioning of two markings**
  - calculation of deviation to the default marking position
  - calculation of projected distance

Setup



- **measuring the contour of the segment**
  - stepwise contour detection with a 2D laser-line triangulation sensor
  - calculation of peak coordinates (x,y,z) by fitting an ellipse with least square method

Scatter plot

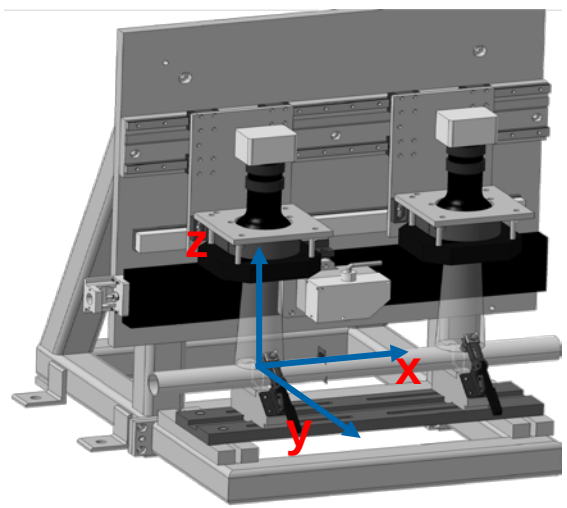


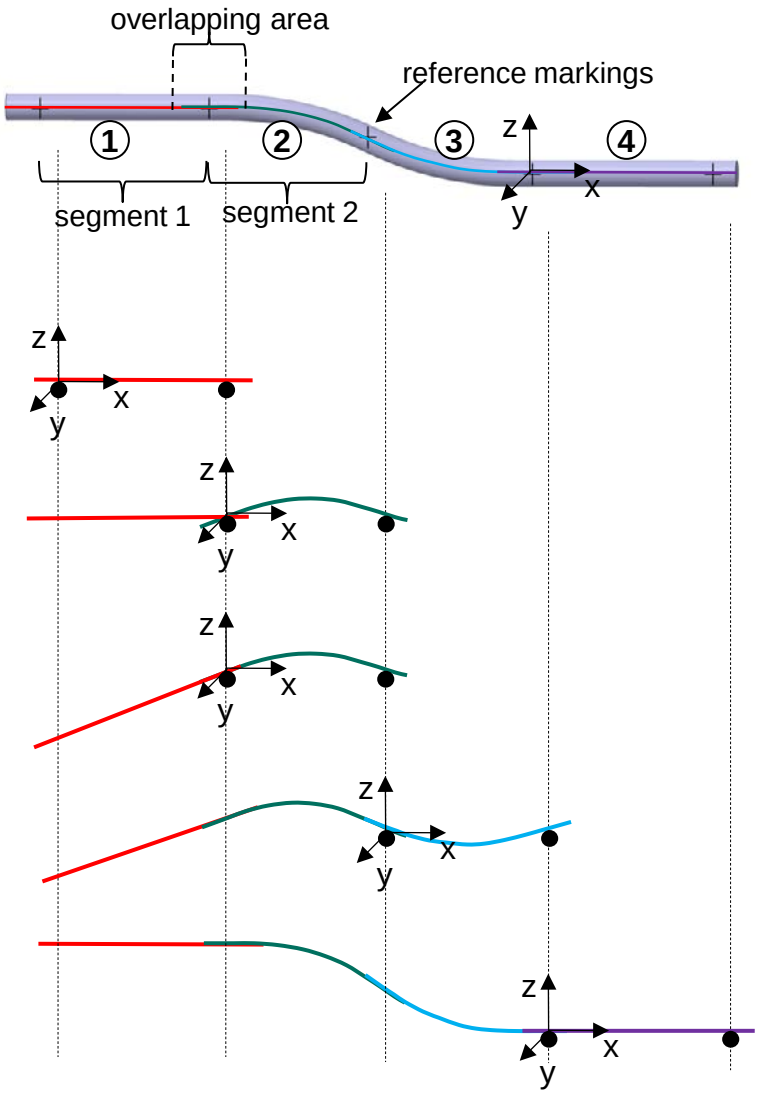
Intrinsic part scale

Metrological approach

Overall contour determination

- **generate overlapping areas** between two segments
- **align splines** in overlapping areas
- **calculate the overall contour** by means of cubic spline interpolation
- coordinate system located in last link



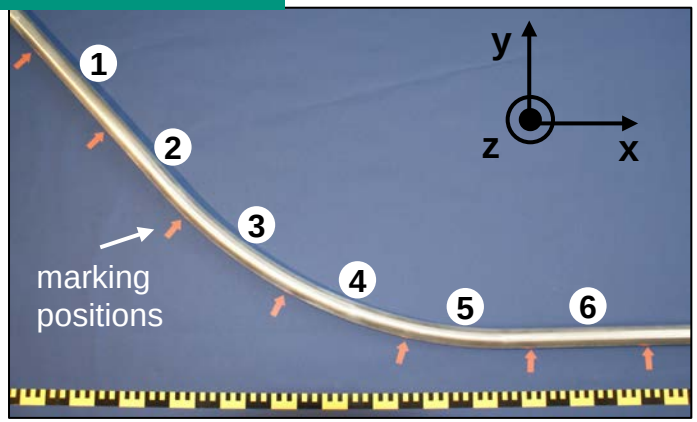


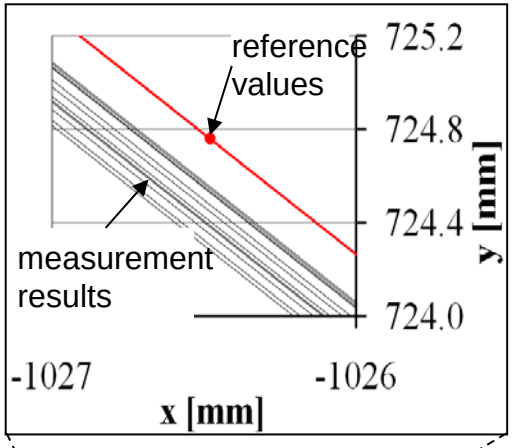
schematic determination of the entire profile contour

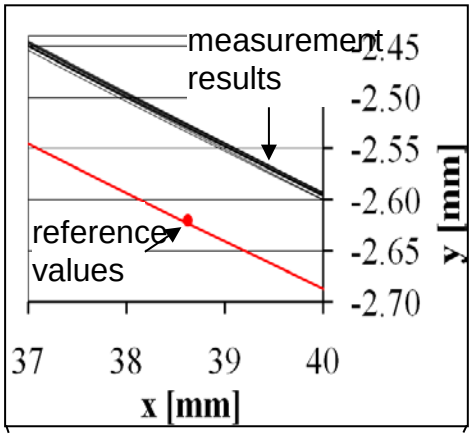
Intrinsic part scale

Validation (results of a planar curved profile)

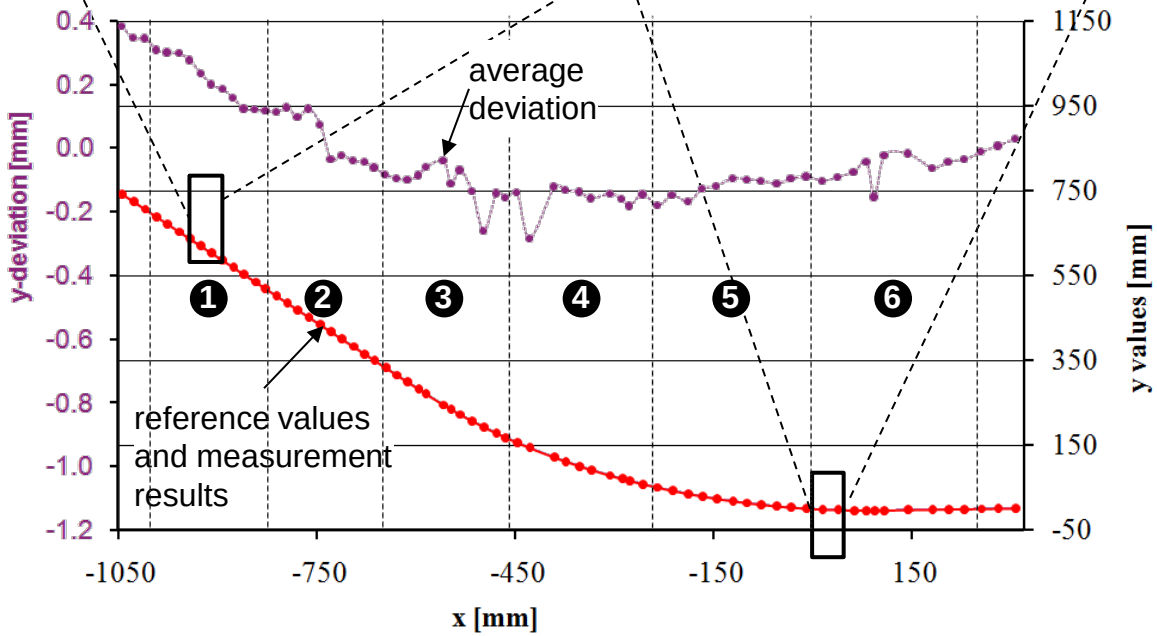
xy-plane







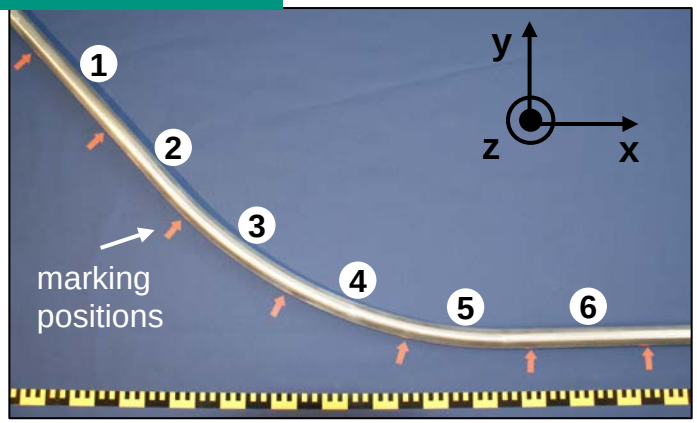
- circular cross-section Ø40x2mm
- profile with 6 Segments
- Segment length: 250mm
- total length: 1500mm
- overlap length: ± 60mm
- 12 measurements

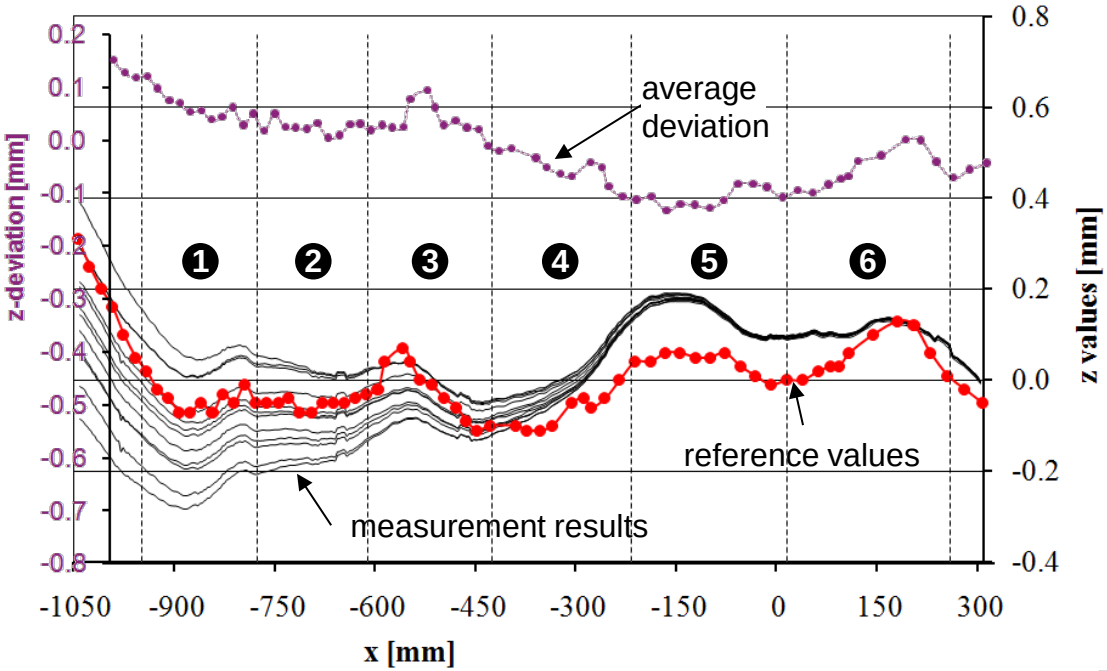


Intrinsic part scale

Validation (results of a planar curved profile)

xz-plane





max. contour deviation
xy plane: - 0.5mm; xz plane: - 0.4mm
maximum dispersion:
Δxy= ± 0.15mm Δxz= ± 0.25mm

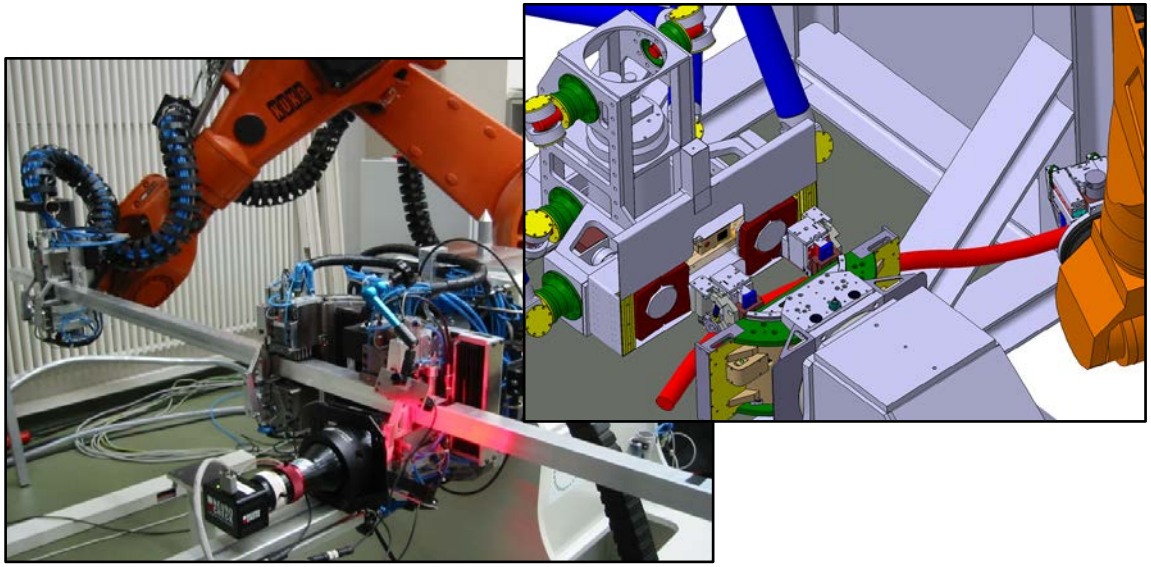
positioning accuracy over 6 segments
(Δl= 1502.05mm):
absolute: - 0.04mm
standard deviation: σ_x= 6µm

Intrinsic part scale

Summary

- approach for exact **profile positioning and contour detection** on the basis of a **component specific scale**
- metrological approach and design of single markings
- experimental setup and results of planar curved profile

➔ approach is usable for the precise and flexible positioning and contour detection of curved profiles (e.g. for machining processes)

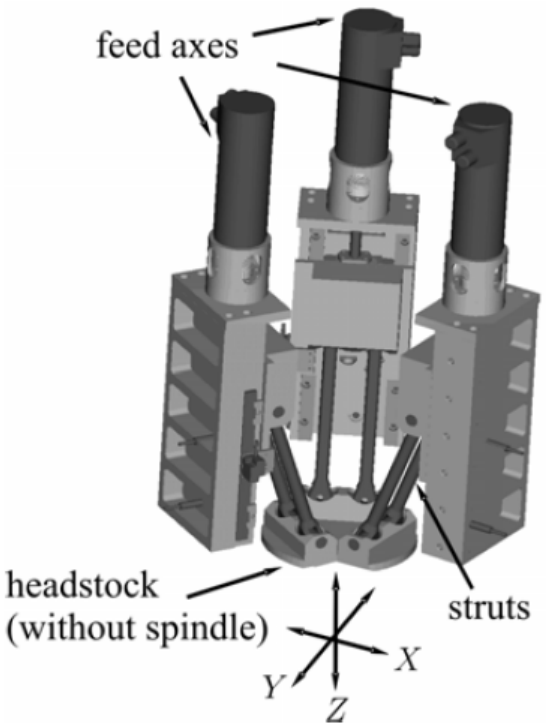


Agenda

Influences on accuracy of machine tools

- **Mechanical stiffness** and **production accuracy of machine components** are two main factors which **influence the geometrical accuracy** of machine tools.

- Process loads and errors in machine components lead to a **displacement of Tool Center Point**.
  → Negative impact on machining accuracy

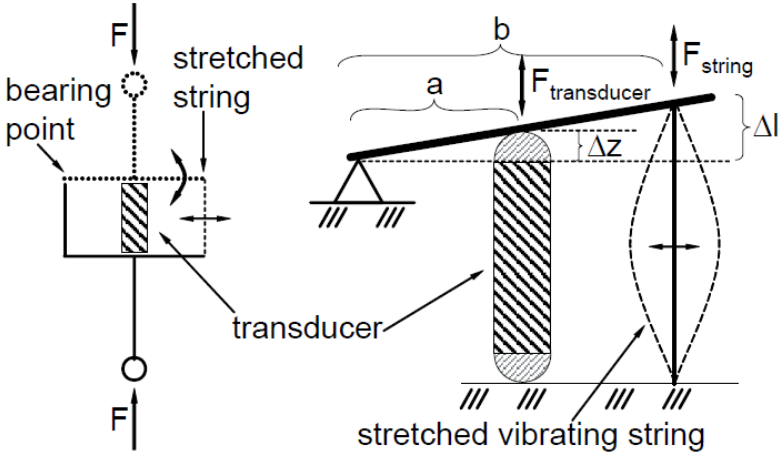


Parallel kinematic machine tool with three degrees of freedom

Approach:
Improvement of mechanical stiffness through adaptronics

Integration of an adaptronical strut

- The strut must be able to **compensate deformations** of the mechanical components **from external loads**
- To increase stiffness of a machine structure, the strut needs to
  - **detect a change in load**
  - **carry out correction movements**
- The Approach for the adaptronical strut is based on the **principle of oscillating-wire balance**.



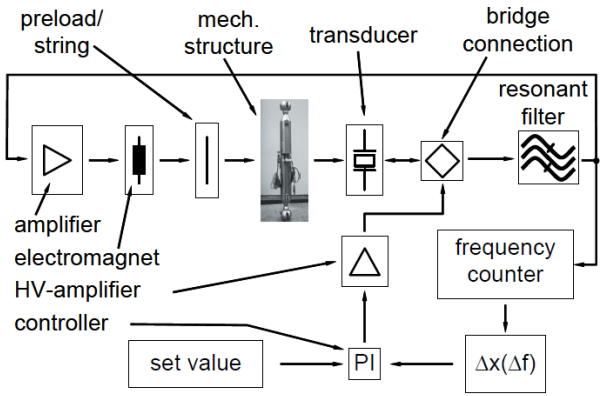
Concept of the adaptronical strut

Adaptronical Strut

Prototypical Realisation

Control concept

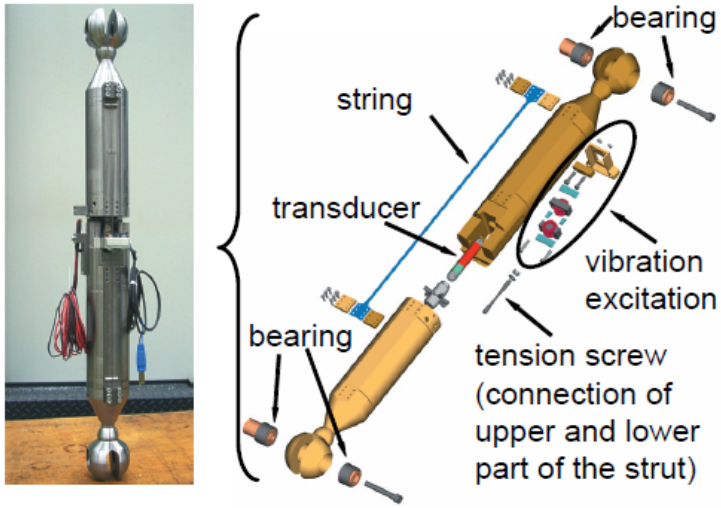
- To realize the functionality of the strut a **special control concept** is necessary
  - Separation of sensor and actuator signals
  - Stimulation of vibrating string
  - Control of actuator stroke



Simplified control concept

Prototypical adaptronical strut

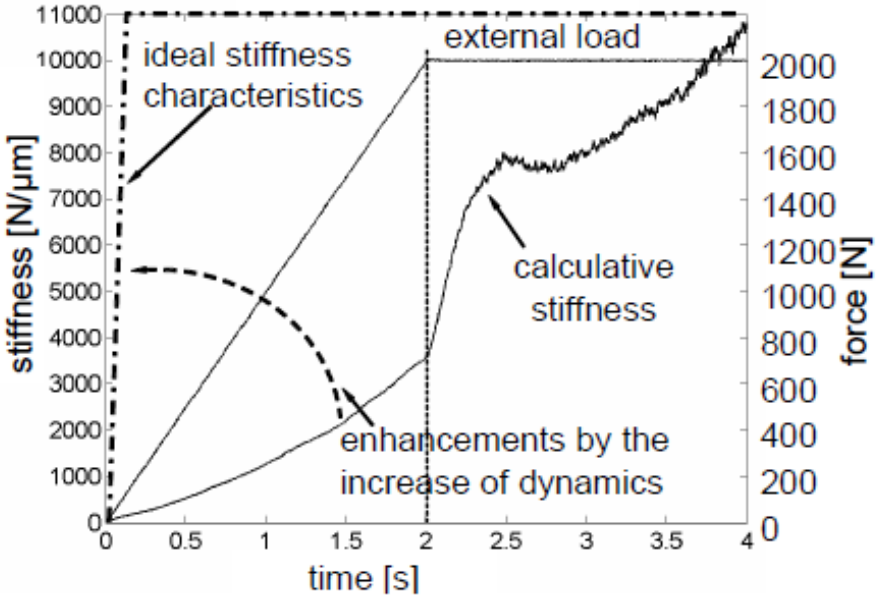
- The structure consist of an upper and a lower part
  - **Coaxially piezoelectric transducer**
  - **Vibration string**



Prototypical adaptronical strut

Measurements and Validation

- Frequency band
  - 2050 – 2350 Hz
- Response time
  - 300 – 400 ms
- Resulting stiffness
  - 11 KN/ µm

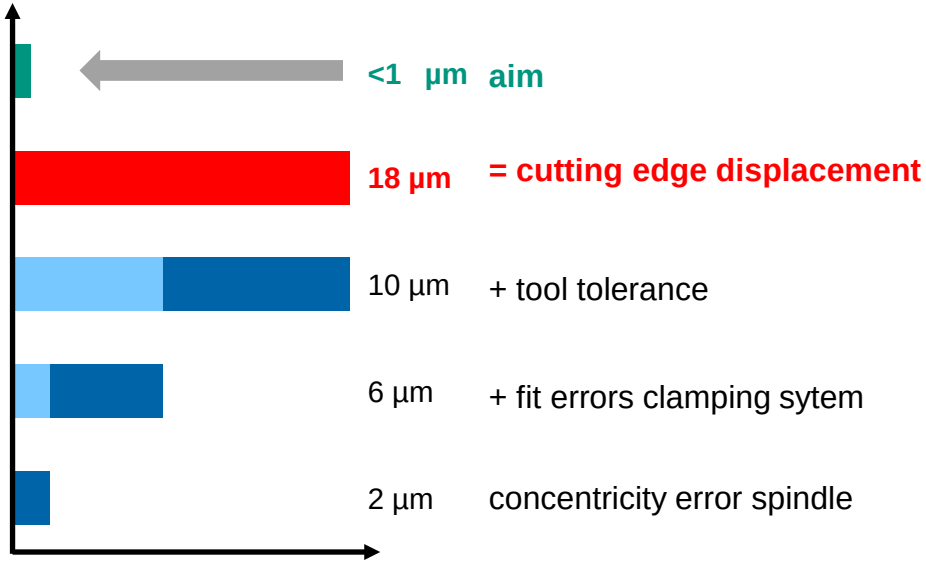


- An approach has been developed and implemented for **improving the mechanical stiffness of an strut structure** for parallel kinematics **through adaptronics**.
- The approach **can be applied to other structures** in machine tool manufacturing in principle

Agenda

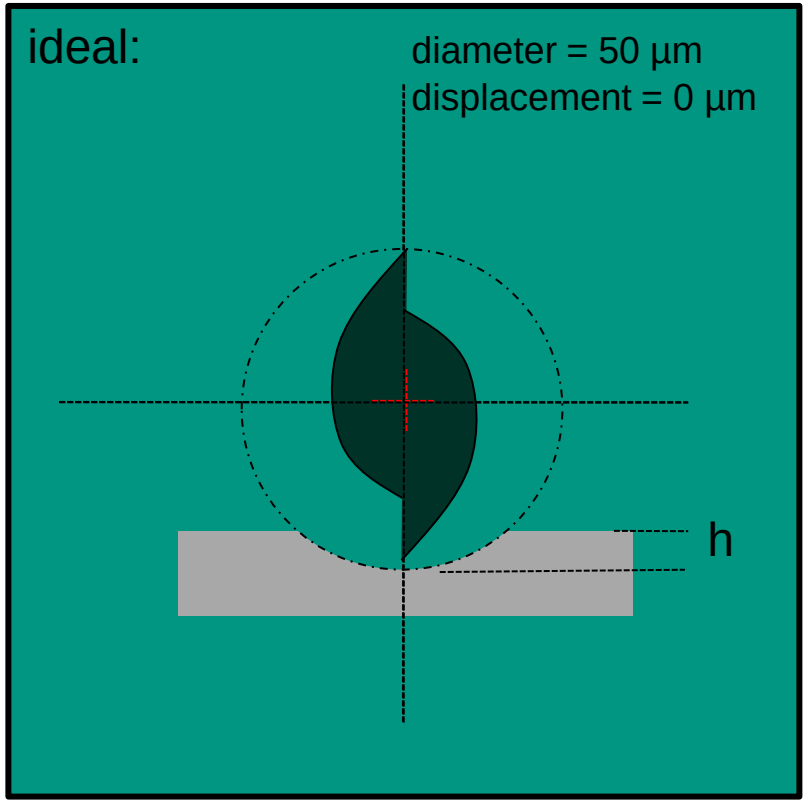
Micro-Milling

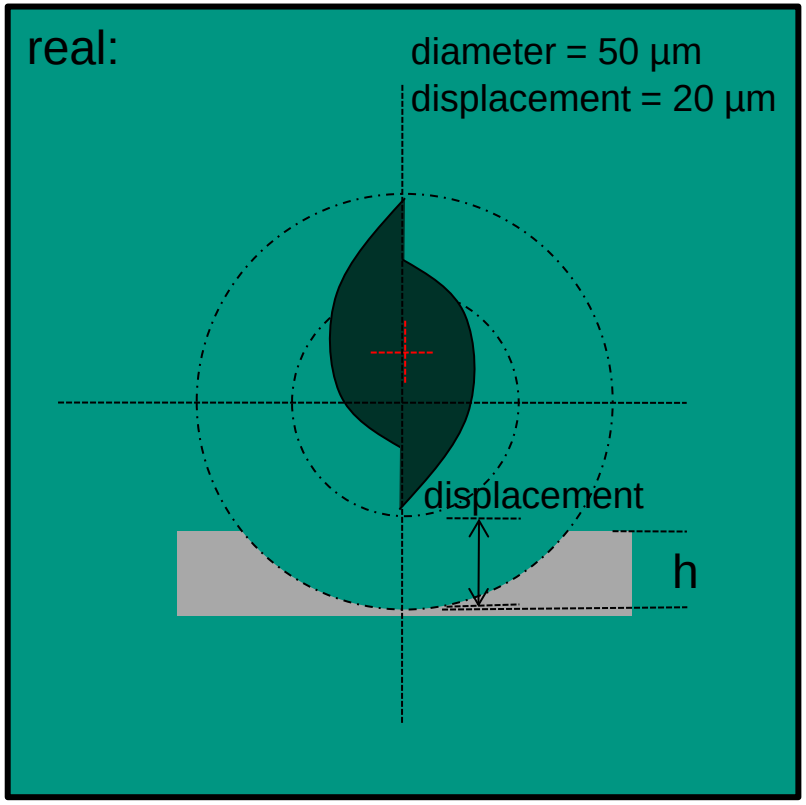
- **Application area**
  - Very small components
  - Ultra precise geometries
- **Micro specific challenges**
  - Tool deflection
  - Relatively high cutting edge radii
  - Cutting edge displacement



- **Cutting edge displacement** caused by concentricity errors in the spindle, fitting errors in the clamping system and material tolerances.
- The main problem is the **unpredictability of the wobbling move of the tool**.

Cutting edge displacement



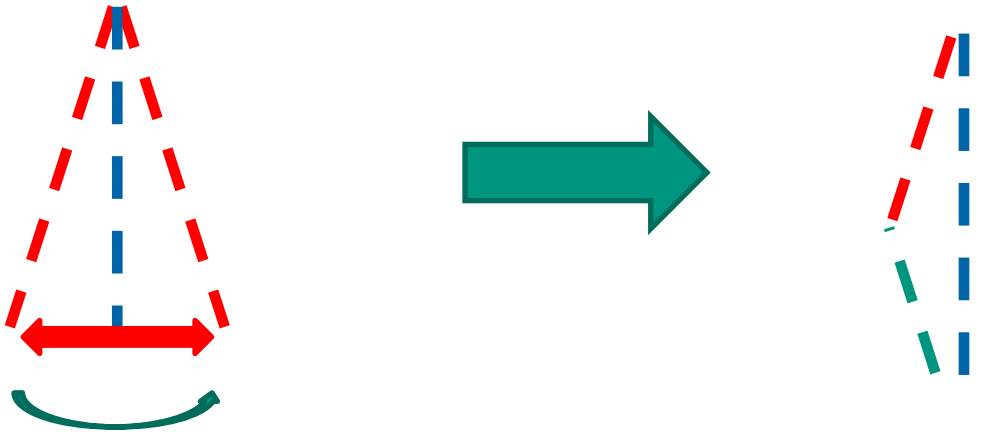


Worst case scenario: one cutting edge is completely unloded, the opposite edge however has doubled loads.

Compensation

- **Problems due to cutting edge displacement**
  - Doubled load for one cutting edge (→ tool with 2 cutting edges)
  - Therefore decreased tool lifetime
  - Decreasing process stability

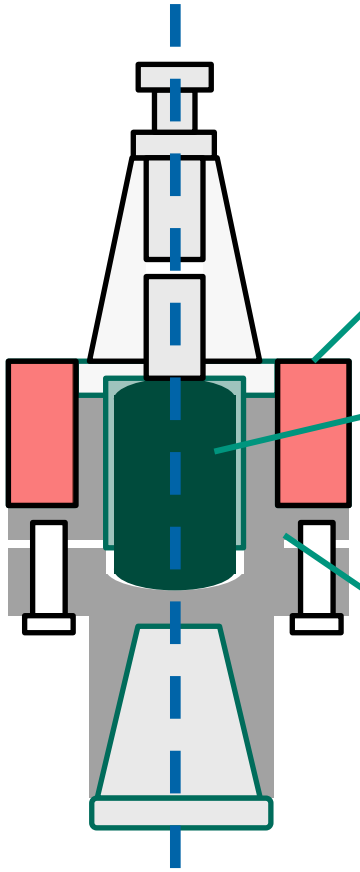
- **Approach**
  - Mechatronic clamping system for compensation at nominal speed
  - Idea:



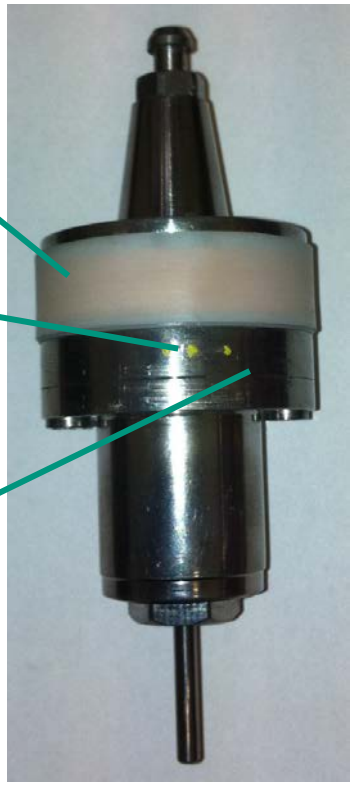
cutting edge displacement compensation

Mechatronic Clamping System

Compensation



- Coils for energy transfer
- Actuation through piezo actuators
- Flexibility with solid-state joint

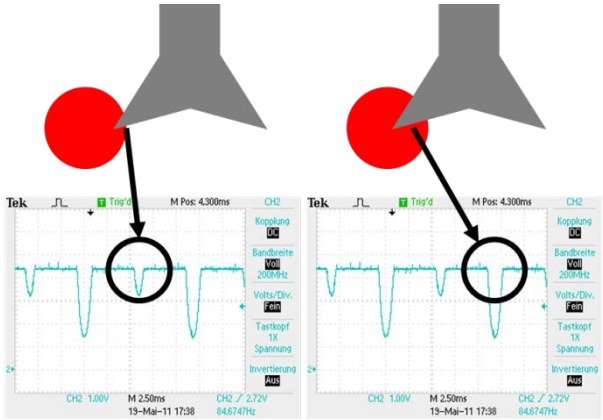


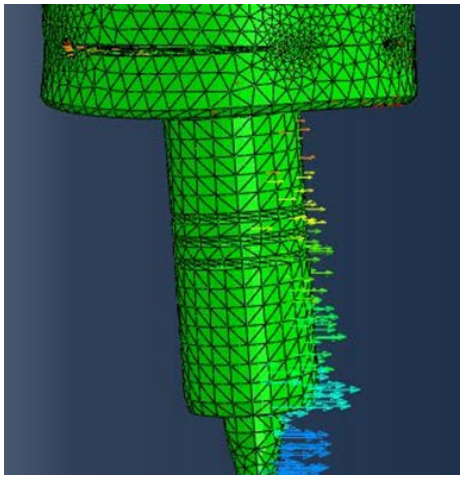
Contactless energy transfer runs a piezo actuater to tilt the flexible, lower part. The **solid-state joint enables the tilt ot the chuck** to direct the tool center point to its nominal point. A feasible maximum of **10-15 µm correction is possible**.

Prof. Dr.-Ing. J. Fleischer, Prof. Dr.-Ing. G. Lanza, Prof. Dr.-Ing. habil. V. Schulze

Mechatronic Clamping System

Operation





measurement

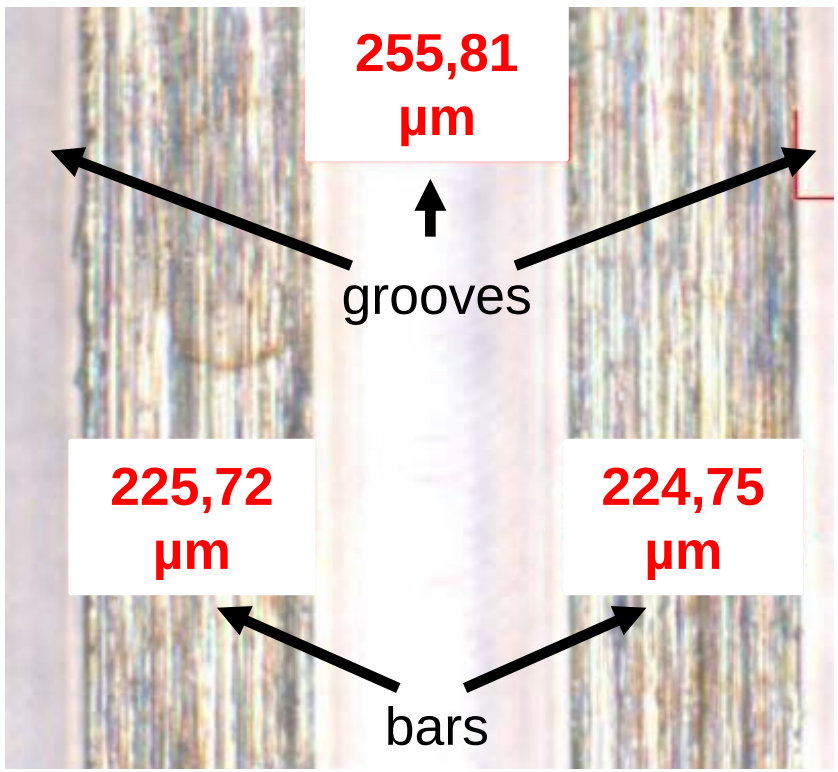
analysis

compensation

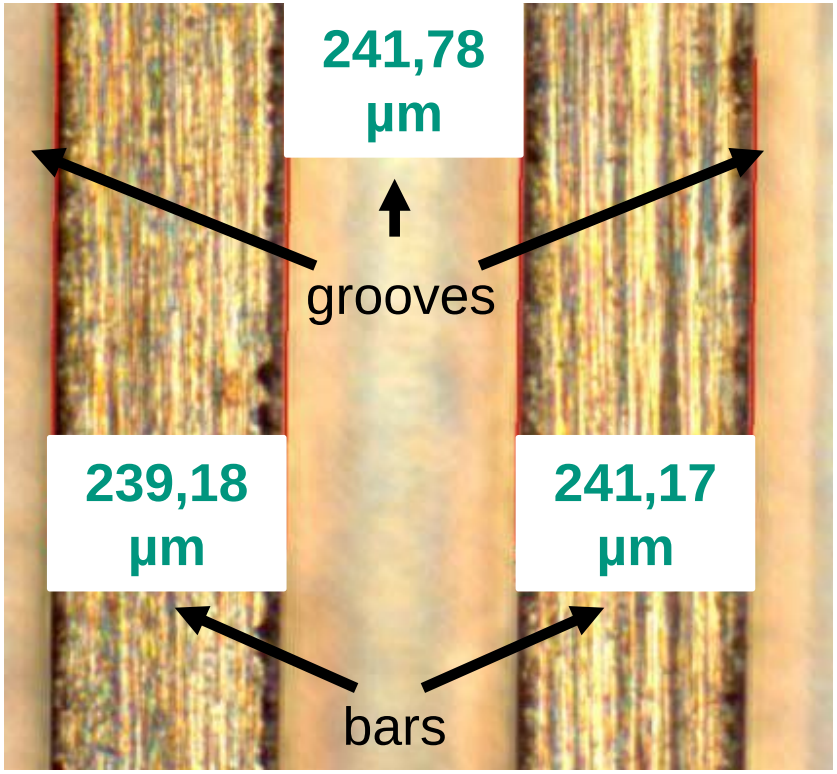
Detection of tumbling cutting edges with a Blum-laser. Alternating shading of the laser triggers compensation.

Mechatronic Clamping System

Validation and results



not compensated

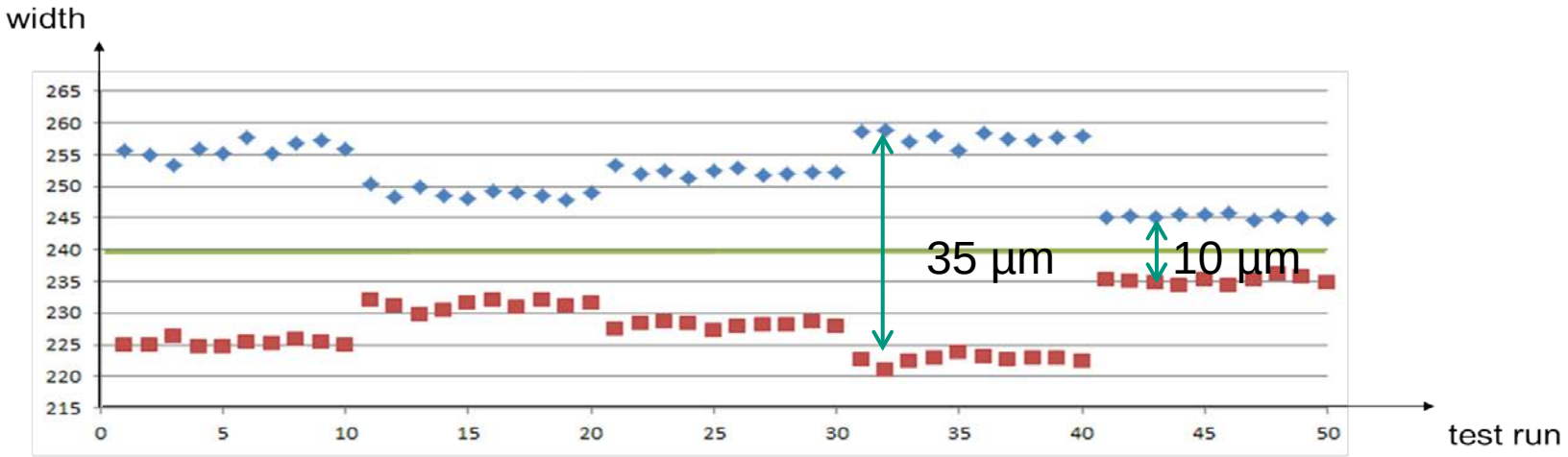


compensated

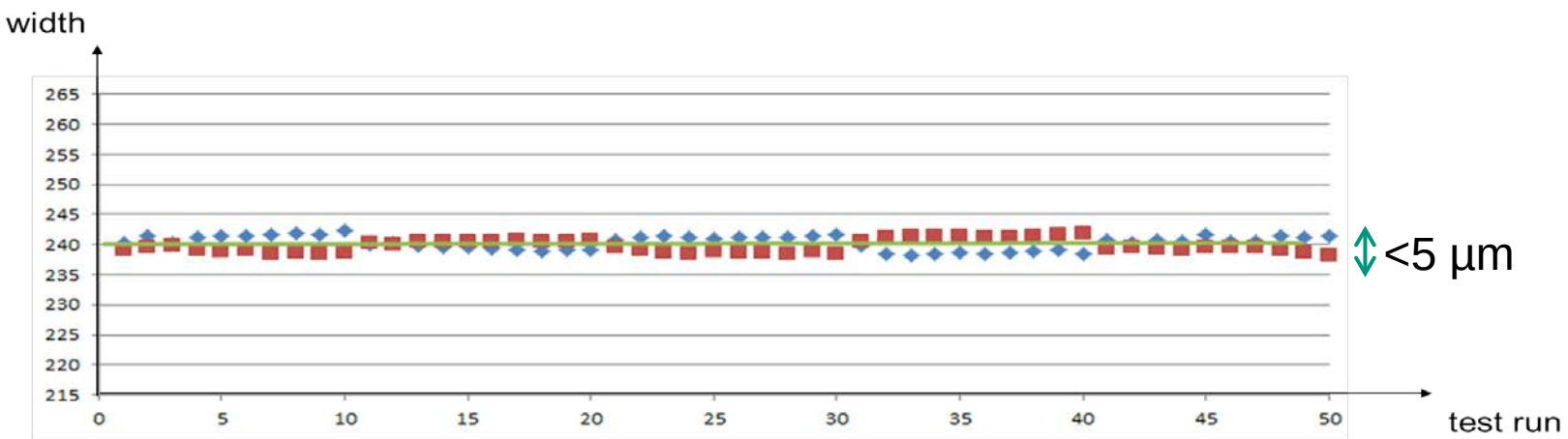
Nominal size: 240µm
Compensation enables manufacturability of tolerable deviations from the nominal size.

Validation and results

- 50 test runs uncompensated



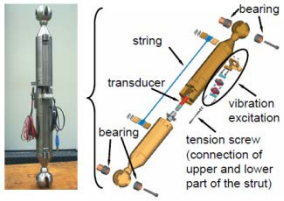
- 50 test runs compensated



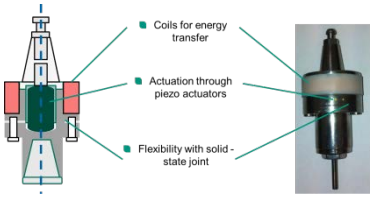
Agenda

Introduction

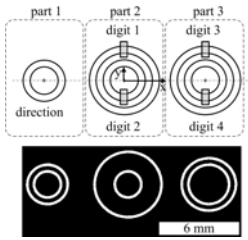
Accuracy of machine tools



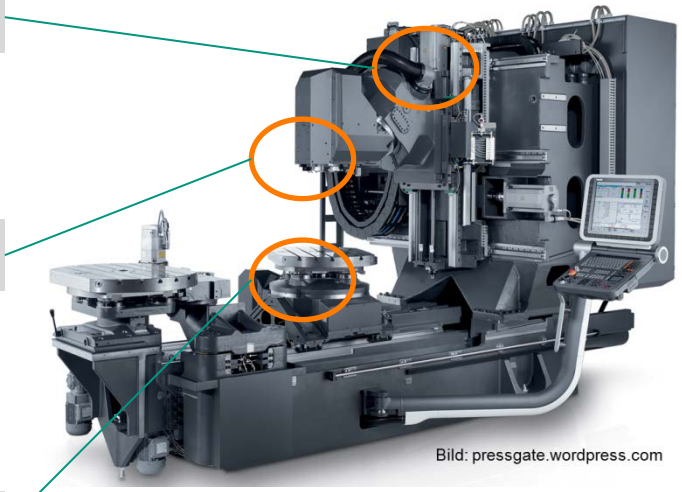
Adaptronic strut



Compensation in tool clamping



Intrinsic part Scale



- Accuracies of machine tools is determined by all of the components and their errors
- Increase of machine tool accuracy is possible by scientific approaches using measuring systems

Thank you!

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