Machine tool precision determination and compensation approaches

*Review on research at wbk Institute of Production Science*

Daniel Brabandt
London, 5th Nov. 2014
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
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
## Research Portfolio

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### Research Areas

- **Micro Production**
- **Lightweight Manufacturing**
- **Electric Mobility**
- **Virtual Production**
- **Life Cycle Performance**

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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**
Agenda

1. Introduction
2. Intrinsic Part Scale
3. Adaptronical Strut
4. Mechatronic Clamping System
5. Summary
Intrinsic part scale
Motivation and Introduction

Aim

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

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 $\alpha$ (centerline – camera CS)
- orientation
- absolute allocation

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

Repeat accuracy of the position-detection of a single marking: $\pm 1.2 \mu m$ (6$\sigma$)

Scheme:
- Binary image:
  - Camera CS
  - Camera view
  - Profile

- Scheme:
  - Part 1
  - Digit 1
  - Digit 2
  - Digit 3
  - Digit 4
  - Direction

- Binary image:
  - 6 mm
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

Additional Axis
Marking Laser
Intrinsic part scale

Measuring station

Profile positioning

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

- 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

Setup

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:
$\Delta xy = \pm 0.15\text{mm}$  $\Delta xz = \pm 0.25\text{mm}$

positioning accuracy over 6 segments
($\Delta l = 1502.05\text{mm}$):
absolute: - 0.04mm
standard deviation: $\sigma_x = 6\mu\text{m}$
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

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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

**Approach:**
Improvement of mechanical stiffness through adaptronics

Parallel kinematic machine tool with three degrees of freedom
Adaptronical Strut

Approach

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

Prototypical adaptronical strut
- The structure consist of an upper and a lower part
  - Coaxially piezoelectric transducer
  - Vibration string
Adaptronical Strut
Results and Summary

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

![Diagram showing cutting edge displacement and compensation](image)
Contactless energy transfer runs a piezo actuator to tilt the flexible, lower part. The solid-state joint enables the tilt of the chuck to direct the tool center point to its nominal point. A feasible maximum of 10-15 μm correction is possible.
Detection of tumbling cutting edges with a Blum-laser. Alternating shading of the laser triggers compensation.
nominal size: 240µm

compensation enables manufacturability of tolerable deviations from the nominal size.
Mechatronic Clamping System

Validation and results

- 50 test runs uncompensated

- 50 test runs compensated
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- Increase of machine tool accuracy is possible by scientific approaches using measuring systems
Thank you!

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