WORKSHOP

Industrieroboter als Bearbeitungsmaschinen


Fortgeschrittene Regelungsverfahren für die Bearbeitung mit den Industrierobotern

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Motivation

Requirements of machining industry (both large and SME’s)

• Flexibility
• Surface quality
• Accuracy
• Low volume - High precision – Large Variety
• Cost/Time efficiency

Potential benefits of industrial robots

• Flexibility
• Large working space
• Low costs (1/10 vs. CNC machines)

Hurdles / challenges

• Low stiffness (1/100 vs CNC machines)
• Critical precision
• Low bandwidth (1/10 vs CNC machines)
Robotic Machining Overview


### Robotic Machining Applications Overview

<table>
<thead>
<tr>
<th>Material</th>
<th>Titanium</th>
<th>Glass</th>
<th>Annealed Steel</th>
<th>Cast Iron</th>
<th>Aluminum</th>
<th>Copper/Brass</th>
<th>Plastic</th>
<th>Wood</th>
<th>Foam</th>
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<tbody>
<tr>
<td>Hardness</td>
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<td>Prototyping/Molds</td>
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<td>Component/Sub-assembly</td>
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<td>Final Product</td>
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**Production Stage**

**Present vs. Future Materials:**

**Current (non-metallic/metallic):**
- Thermoformed or molded plastics
- Foam
- Wood
- Stone
- Graphite
- Fiberglass
- Aluminum
- Cast steel

**Future:**
- Titanium
- High density steel
- Annealed steel
- High density alloys
- Tool steel
- Glass
- Ceramics
Industrial robots for machining development trends
Preliminary studies - ROBINSTONE project

- 3D-scanners (ViALUX)
- CAM G-code generation in UGNX.
- Robot Program Generation in Easy-Rob
- Realization (Comau C4GOpen)
Robotic machining – position and role

Better understanding – essential for industrial applications
FP7 COMET Project

Plug-and-produce Components and Methods for adaptive control of industrial robots enabling cost effective, high precision manufacturing factories of the future.
EU initiatives – robotic machining

**COMET**
- “right first time machining”
- High-end milling
- Precision and quality through positioning
- High-tech (costs) sensory techniques
- Full automation
- Proprietary technology
- Mass production

Some common points in planning and programming – background for established cooperation

**HEPHESTOS**
- Multi-steps iterative methodology
- Combination of processes (milling, grinding, polishing, drilling, tapping etc.)
- Precision and quality through force-feed control
- Affordable sensing technology
- Human-in-loop
- Open frameworks
- Low-batch high-variants manufacturing
HEPHESTOS - Architectures
Robot signature - planning
2.2 Function DLL’s
Integration Comau ORL - Interpolation

- ORL is running in Linux (VM)
- Communication via TCP/IP Socket
3 Use Case I
NC-Import, Pre-Planning, Simulation, Program Export
3.1 Use Case I
NC-Import, Pre-Planning, Simulation, Program Export
4. Sensor Interface

API

Function DLL
Export fct_01()
Export fct_02()
...

Human Path

Pre-Planning + Simulation

PDL Program export
Planning – Path Correction
Data streaming to the robot control - ROBOMOVE
Manual programming
Industrial Robot Control Systems – Machining Operations (SOTA)

- Not a development goal (position and trajectory tracking control primarily, niche developments)
- Compensation control (payload, feed-forward dynamic control)
- Interaction control (extra package – additional force control, general purpose, impedance control KUKA LWR)
- Trends for machining (CNC robot control, HEPHESTOS-Workshop 2013 – Round table discussion: “If automotive companies apply robots for machining, we will do something”)

Specific control improvements are for machining applications are urgently needed
Improved Robot Control – Machining Operations - I

Position Control Improvements

- Ripple suppression
- Trajectory shaping
- **Joint elasticity** control and compensation (gears!)
- Compensation control (cutting forces)
- Compensation for joint change of direction (backlash, friction)
- Override control (real time adaptation)
- Increased stiffness of the controller
Improved Robot Control – Machining Operations -II

Contact-task, force- and impedance based Control

- Position based impedance and force control
- Impedance control (milling – robot configuration and direction compensation)
- Orthogonal force-feed control (grinding, polishing)
- Collinear force-feed control (milling)
- Feedback robot dynamic and cutting force disturbances compensation (“computed torque”, “resolved acceleration”, “non-linear decoupling”…. - based interaction control)
- Human-robot interaction control (manual guidance, admittance-display, adaptive contact transition control)
Integration Environment C4GOpen

Preliminary developments (FP6 ARFLEX, ECHORD RODIN), running activities (FP7 X-Act, FP7 IP ROBO-PARTNER), COMAU developments (C5GOpen)
Position control – initial experiments – I (TRC)
Position control – path governor (backlash, friction compensation)
Position based force/impedance control – 25 years after

Design, parameterization for various processes
HEPHESTOS – Exploitable Result

In-Spindle build F/T Sensor (5 DOF) – ME Messtechnik GmbH

Patent pending
Hard metal – Robotic Grinding – Initial experiments

Very good removal rates (new tools)

Feasible Feed-force control (further investigations)

High frequent oscillations
Force/impedance control – initial experiments – polishing
Force/impedance control – initial experiments – polishing

Good achieved performance:

Feed tracking: 5, 10, 20 mm/s
Force control: 1.5, 3, 5 N
Easy Programming, Reproducibility

Force tracking: 1.5 N

Relatively good surface quality (Ra < 0.4 μm)
(precise motion in robot “dark motion zone”)
Co-directional feed/force and force/impedance control algorithms
Hard metal – Robotic End Milling – Initial experiments

Feasible metal removal rates

Critical chattering – errors higher than registered robot control errors

Relatively low forces (high frequent oscillations)
Hard metal (inconel) and novel tools (ceramic-based, PCD)

- New ceramic tools
- High speed (> 30000 rpm, 0.15 m/s) - power
- High temperatures (1500°C)
- Chip formation

Figure 1.4 (a) Model of chip formation suggested by Nakayama et al., and (b) its experimental verification by König et al. [11]
Ceramic tools experiments—Inconel
Robot-Machining Process Simulation
Instead of Conclusion

Advanced robot control for machining - Perspectives

- Good potential to cope with robot machining problems and achieve goals
- Combination of milling (material removal), grinding and polishing (quality) operation needed to make final products
- Relevance of further development of tools and adaptation of control techniques
- Extensive use of modeling and model based control
- Experimental investigations (understanding of robot and control performance) and benchmarking are quite important
- Good perspectives also for “robotic hard” materials
Safe/Stable pHRI with industrial robots?

- Principally possible (smaller light-weight robots)
- Backdriveability essential (not ensured)
- Performance can not be guaranteed (IMPACT)
- Additional advanced safety sensors highly recommended
- Acceptance critical (heavy robots)
- Distance to robot (process) – critical
- Design of new intrinsically safe robot - quite favorable and motivated!

Echord RODIN (2013)
Human Robot (Cobot) Cooperative Machining - Vision