Holistic Approach to Digital Twins for Machine Tools

Connected – Virtual – Online

Robin Kleinwort
Digital Transformation is the Key Enabler for Numerous Business Cases of Future Factories

Overview

Global Production Networks

Local Production Shop Floors

Machine Tools

Machining Processes

“Hot Topics” in Digitalized Production

<table>
<thead>
<tr>
<th>Topic</th>
<th>Usage Today (2017)</th>
<th>Expecte usage in five years (2022)</th>
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<tbody>
<tr>
<td>Data-enabled resource optimisation</td>
<td>52%</td>
<td>77%</td>
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<tr>
<td>Integrated planning</td>
<td>32%</td>
<td>61%</td>
</tr>
<tr>
<td>Big data driven process and quality</td>
<td>30%</td>
<td>65%</td>
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<tr>
<td>optimisation</td>
<td></td>
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<tr>
<td>Modular production assets</td>
<td>29%</td>
<td></td>
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<tr>
<td>Connected factory</td>
<td>29%</td>
<td></td>
</tr>
<tr>
<td>Predictive maintenance</td>
<td>28%</td>
<td>66%</td>
</tr>
<tr>
<td>Process visualisation/automation</td>
<td>28%</td>
<td>62%</td>
</tr>
<tr>
<td>Digital twin of the product</td>
<td>23%</td>
<td>43%</td>
</tr>
<tr>
<td>Digital twin of the factory</td>
<td>19%</td>
<td>44%</td>
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<tr>
<td>Digital twin of the production asset</td>
<td>18%</td>
<td>39%</td>
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<tr>
<td>Flexible production methods</td>
<td>18%</td>
<td>34%</td>
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<tr>
<td>Autonomous intra-plant logistics</td>
<td>17%</td>
<td>35%</td>
</tr>
<tr>
<td>Transfer of production parameters</td>
<td>16%</td>
<td>32%</td>
</tr>
<tr>
<td>Fully autonomous digital factory</td>
<td>5%</td>
<td>11%</td>
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Source: Statista/PwC
Digital Transformation is the Key Enabler for Numerous Business Cases of Future Factories

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The Machine Tool of the Future

connected

Digital Shadow

Sufficiently accurate image of the relevant data with the purpose of creating a real-time-capable evaluation basis.

optimized

Digital Twin

Digital representation of a material or immaterial object from the real world with the ability to predict new conditions. The digital twin can exist before its physical representation.

up-to-date
Digital Transformation of Machine Tools and the Application of Artificial Intelligence will unleash a New Level of Automation

Overview
Application of Digital Twins during the Life Cycle of Machine Tools and Workpieces

Overview

<table>
<thead>
<tr>
<th>Phase</th>
<th>Machine Tool</th>
<th>Digital Twin</th>
<th>Workpiece</th>
<th>Valorization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Development Phase</td>
<td>Development Phase, Production-Ready Design</td>
<td>Model Generation</td>
<td>Workpiece Design</td>
<td>Simulation-driven Design of Machine Tools and Workpieces</td>
</tr>
<tr>
<td>Production-Ready Design</td>
<td>Machine Design</td>
<td>Preceding Model Usage</td>
<td>Process Simulation</td>
<td>Simulation-driven Planning of Machining Operations</td>
</tr>
<tr>
<td>Optimization and Quality Prediction</td>
<td>Realtime Process Parallel Simulations</td>
<td>Posterior Model Usage &amp; Update</td>
<td>Quality Control</td>
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<td>Development Feedback for Design Changes</td>
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<td></td>
</tr>
</tbody>
</table>

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Model Generation

Phase
- Development Phase, Production-Ready Design

Machine Tool
- Machine Design
  - Machine Simulation
- Preceding Model Usage
  - Process Monitoring
- Online Model Usage
  - Health Monitoring
- Posterior Model Usage & Update
  - Machine Optimization

Digital Twin
- Model Generation
  - Process Simulation
- Process Monitoring
- Quality Control
- Process Optimization

Workpiece
- Workpiece Design
  - Simulation-driven Design of Machine Tools and Workpieces
  - Simulation-driven Planning of Machining Operations

Valorization
- Virtual Process Optimization and Quality Prediction
- Realtime Process Parallel Simulations
- Non-Realtime Process Parallel Simulations
- Development Feedback for Design Changes

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Structural Dynamics Simulation as the Backbone of the Digital Twin

Virtual Machine Tool Structure

Possibilities

- virtual prototypes for early testing
- targeted optimization of new machine generations
- visualization of machine behavior

Benefits

- reduce time to market
- reduce costs for prototypes
- increase machine performance

Digital Twin architecture of machine tool
Flexible Multibody Models allow fast and precise simulation of Structural Dynamics in arbitrary Axis Positions

Virtual Machine Tool Structure

- Measured data
- Simulated with linear damping models
- Simulated with local damping models
- Simulated with measured damping parameters

High accuracy by using local linear and nonlinear damping and stiffness models.

Reduced calculation times by using model order reduced flexible multibody models.

FRF calculation time for a single axis position:

- Traditional FE-models: ~ 1-10 h
- Model order reduced flexible multibody models: < 1 min
Process Automation to achieve Machining as a Service

Workpiece Design and CAD/CAM Automation

Costumer → Machine models library

2,5 D Feature Detection → CAM-planning and process simulation → Scheduling → Machine 1 → Machine 2 → Digital Twins

Model Generation → Preceding Model Usage → Online Model Usage → Posterior Model Usage → Model Update
Preceding Model Usage

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- Data-driven Machine and Production Process Optimization

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The Digital Twin can be used to Improve the Accuracy and Stability of Machine Tools

Process Simulation with Quality Prediction

**Possibilities**

- Simulation of the coupled machining process
- Prediction of the static deflection and dynamic stability
- Optimization of the accuracy and process stability

**Simulation of Machined Feature**

- Dimension of the outline is too small
- Large deviation at the workpiece exit
- Large deviation during changing feed directions
- Large deviation at the workpiece entrance

**Deflection in mm: -1 0 1**
The Digital Twin can be used to Improve the Accuracy and Stability of Machine Tools

Process Simulation with Quality Prediction

Possibilities

- simulation of the coupled machining process
- prediction of the static deflection and dynamic stability
- optimization of the accuracy and process stability

With Deflection Compensation

- accurate outline
- reduction of the error at the workpiece exit
- high accuracy while changing feed directions
- reduction of the error at the workpiece entrance

Deflection in mm: -1 0 1

Online Model Usage

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Closed-loop Manufacturing using Edge and Cloud Infrastructure

Process Monitoring and Control

Machine Data Interface

Process Data Acquisition and Process Control
- Spindle speed
- Motor current
- Accelerometers (spindle, machine table, ...)
- Tool position
- ...

Real manufacturing process

Smart Box

Sensor and CNC data

Inner Control Loop:
- Chatter detection and avoidance
- Tool monitoring
- Collision avoidance

Cloud/Server

Outer Control Loop:
Machine learning approaches in the field of…:
- Output-Only-Modal-Analysis for modeling the position- and tool-dependent frequency response (Receptance Coupling)
- NC path planning and optimization

Model Generation → Proceeding Model Usage → Online Model Usage → Posterior Model Usage → Model Update
Inner Control Loop stabilizes the Process

Process Monitoring and Control

**Chatter Detection**

Efficient and intelligent algorithms for chatter detection monitor the stability of the process.

**Chatter Avoidance**

Chatter avoidance strategies within the edge-based control loop change process parameters to stabilize the process.

**Knowledge Generation**

Learn from instable machining conditions for future machining processes.

**Machine Load, Tool Wear and Surface Quality**

The occurrence of chatter results in a reduction of the machine components and tool lifetime. Chatter marks lead to poor surface quality.
Cutting Force Identification using internal Signals

Process Monitoring and Control

**Sensorless Process Monitoring**
Modern control and machine tool generations have a large number of **internal sensors** that can be accessed via various **IoT interfaces**. This enables detailed process monitoring without additional external sensors.

**Machining Forces**
By previously determining the **transfer characteristics** between motor and TCP, it is possible to **determine the process forces with motor current measurements** during machining.

**Data resolution**
The selected process parameters such as the feed rate and the spindle speed influence the **variation of the process forces**. Therefore, **high frequency data acquisition** and **resolution** is essential.
Comparing Simulation Results with CNC signals on an Edge-Device unleashes a new Level of Process Monitoring

Process Monitoring and Control

**Tool wear monitoring**

The tool wear monitoring technique will be used for high-strength metal alloys and carbon fiber reinforced polymers.

**Machine Learning**

Application of machine learning algorithm (random forest) for tool wear monitoring using cutting force and vibration data.

**Surface Quality**

Quantitative relationship between tool wear progression and machined surface integrity will be developed.

**Tool breakage detection**

In addition to monitoring tool wear, sudden tool breakage during machining should also be detected immediately to prevent damage to machine and tool.
Posterior Model Usage & Update

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Self-Monitored Fault Identification using Digital Twins

Machine Health Monitoring

- **Online Simulation**
- **System Identification**
- **Degradation**

**Model Generation** → **Proceding Model Usage** → **Online Model Usage** → **Posterior Model Usage** → **Model Update**

- Normalized linear guide stiffness $k_{L,G,i}$
- Time $\rightarrow$

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Updating the Digital Twin via IoT gateway

Machine Health Monitoring
The Digital Twin can be used to detect and even locate Wear

Machine Health Monitoring

- Ball screw
- Linear guide

Amplitude in m/N

Frequency in Hz

100% Stiffness
40% Stiffness

Stiffness

Model Generation
Preceding Model Usage
Online Model Usage
Posterior Model Usage
Model Update
Bayesian Machine Learning enables the Estimation of Remaining Useful Life

Machine Health Monitoring

- Regular condition monitoring test cycles between manufacturing periods
- Probability of class membership from Gauss Process Classification model can be tracked over time and extrapolated in order to predict the remaining useful life (RUL)
Determination of Current Machining Accuracy by continuously Updating Machine Models

Health Monitoring with Quality Prediction

**Possibilities**
- condition monitoring by observing manufacturing accuracies
- prediction of component quality depending on machine tool wear
- detect when maintenance is necessary to ensure quality standards can be met

**Benefits**
- prediction of contouring errors through updated structural dynamics models
- no failure data necessary for predictive maintenance
- schedule maintenance tasks depending on decreasing production quality

**Real manufacturing process**
- Data acquisition via IoT interfaces (OPC UA, MQTT,...)
- Receptance measurement using internal and virtual sensors

**Virtual Representation**
- Update machine tool simulation model with acquired machine data
- Simulation machining process and determine resulting workpiece quality

**Data analysis**
- Determination of machining accuracy with updated machine model
- Predicted component quality enables health monitoring of machine tools

Posterior Model Usage & Update

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**Development Feedback for Design Changes**
- Machine Optimization
- Data-driven Model Update
- Process Optimization
- Data-driven Machine and Production Process Optimization
Data-driven Model Updates can Improve the Prediction Accuracy of Digital Twins

Self-adaptive Digital Twin of a Milling Machines

Data-driven approaches of artificial intelligence can identify and compensate hidden, unknown or unmodeled physical effects of the machining process.

Data Acquisition
- Object data
- Simulation data
- Experimental data

Training
- Function approximation with machine learning
- Physics Informed Machine Learning

Prediction
- Process simulation and usage of the trained models
- Chatter affinity
- Surface quality
- Efficient milling strategy

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Learn from the Machines in the Field to Optimize Future Machine Designs

Machine Tool Optimization

Process data analysis provides valuable information for machine tool manufacturers and users

- Detailed shop floor usage data
- Agglomeration of multiple machines in the field enable in-depth comparative analyses
- Modern big data algorithms support manufacturers in finding actions for improvements
Data Privacy must be Guaranteed during the Usage of the Connected Digital Twin

Digitization, Edge and Cloud Computing and Data Security

Open challenges are

- When and where should we encrypt the data?
- What kind of encryption is suitable?
- How can we anonymize industrial data?
- How can we quantify the accompanying loss of information?
- What are the requirements for the cloud-service provider?
Application of Digital Twins during the Life Cycle of Machine Tools and Workpieces

Summary
iwb expert seminar „Digital Twin for Machine Tools”

Key topics:
- What are the benefits of the Digital Twin for users, machine tool and control manufacturers?
- What are the advantages of the Digital Twin in the various phases of a product or production?
- Which challenges and questions arise during the digitization of the machine tool and the machining process?
- How much effort will my company face during the introduction and use of digital twins?

Speakers and guests:
- Keynote: „Digital twin for machining“ - Prof. Dr. Y. Altintas (UBC, MAL Inc.)
- Presentations from industry and research:

<table>
<thead>
<tr>
<th>Partner</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMW Group</td>
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<td>c-Com</td>
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<td>Siemens</td>
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<td>University of Waterloo</td>
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</table>
Holistic Approach to Digital Twins for Machine Tools

Connected – Virtual – Online

Robin Kleinwort
Outer Control Loop learns from Machines in the field

Process Monitoring and Control

**Monitoring of Machine Load Limits**

The operating range of a machine tool is limited by dynamic stability, feed drive, and spindle torque limits. These limits must be maintained to ensure a long service life of the drive components and the tool.

**Contouring Accuracy**

High process forces have also a negative influence on the workpiece quality. The quasi-static stiffness of the tool and the spindle components have a decisive influence on the form error that occurs during machining.

**Feed Drive Optimization**

Machine load limits, stability limits, and the contouring error needs to be monitored and tracked during machining. On the basis of these data feed drive optimization can be carried out.

**Information Gathering and Preservation**

The automated optimization process chain ensures that the results flow back into the CAD/CAM chain.
CLM 4.0 - Collision Avoidance System

**Machine Kinematics**

The tool path will be checked for collision in respect to the actual machine kinematic and machine components.

**CNC Integration**

The ModuleWorks real-time Collision Avoidance System (CAS) is integrated directly onto the CNC controller to avoid collisions in real-time during the machining process.

**Support of different tools**

All milling operations, drill blocks, cutting with saws, optimization for large panel parts, tools with concave shapes.

**CNC modes**

Supports AUTO, MDI and JOG operation modes. Collision avoidance based on interpolated axes positions as calculated by CNC; no G-Code parsing required. Look-ahead, forecasted position data are used for collision avoidance.
Online Determination of Cutting Forces

For the Operational Modal Analysis, the process forces occurring during machining have to be determined to identify the excitation of the machine tool structure.

Frequency Response Function

The general receptance of the machine tool structure can be determined using FRF-estimators. This requires both the excitation and displacement of the structure resulting from the machining process.

Position and tool dependent FRF

The receptance of the machine tool depends on the current position in the working area as well as on the tool/tool holder combination which is mounted to the spindle.
CLM 4.0 - Multi Input Multi Output (MIMO) Drive Model

**Generalized MIMO drive model**
A requirement for Industry 4.0 manufacturing is the ability to identify, update, and utilize mathematical models of machine tools and processes, in a non-intrusive and effective manner.

**Key Parameters from In-process Data**
MIMO models can be used to simulate and optimize multi-axis manufacturing trajectories, so that quality and cycle time reduction objectives can be met.

**True Response and Prediction**
A good correlation between experimentally measured and online calculated transfer functions could be demonstrated at the University of Waterloo.
Energy Flexibility based on Digital Twins Enables Competitive and Independent Production Schedules

Energy Flexibility

Possibilities
- react to changing energy supply
- fill the company internal energy buffers, when energy is available and low-priced
- demand-driven energy consumption

... Benefits
- optimize production to use the energy you produce
- save energy and money to become competitive
- production without dependence on volatile energy market
...