Automated Production of Large CFRP Preforms: Challenges and Solutions along the Process Chain
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Outline

- Introduction

- Automation along the Process Chain
  1. Process Preparation
  2. Preforming with Cooperation Robots
  3. Chain of Errors & Inline Quality Assessment
  4. Enhancing Accuracy on a Flexible Robotics Platform

- Summary and Outlook
Introduction
DLR Center for Lightweight Production Technology

ZLP Site Stade

ZLP Site Augsburg
Introduction
Providing Technology Readiness for Industrialization

TODAY from material to prototype

Material  Design Structures  Manufacturing Demonstrators

TRL3  TRL4 …………………………TRL6

FUTURE from materials to automated production

Robotic, Mechatronics

DLR ZLP
Automated Production
Introduction
Production of Large Aerospace Structures

Challenges for an automated composite production:
- High layup rates
- Many manual processes involved
- Potential issues
  - Material damages
  - Repeatability
  - Quality assurance
- Robotic gripper weight for large cut pieces
Automation along the Process Chain
Focus in this presentation

1. Input, process preparation:
   - Draping Results
   - Pick-up/Lay-up Positions
   - Path planning

2. Hard-/software for preforming:
   - Cutting
   - Cut piece logistics
   - Gripper components
   - Gripper system and program
   - Robotic cell
   - External guidance

3. Hard-/software for online QA:
   - Measuring cut piece position/boundary
   - Measuring fiber orientation
   - Online Assessment

4. Cured Component:
   - Quality check
   - Detailed documentation
   - Concession Handling
   - Potential rework

Dry textile → Handling, Preforming → Vacuum bagging → VAP/VARI → Debagging, Demoulding → Machining, Assembly
Automation along the Process Chain

Draping simulation:
- 3D real tooling surface
- Tooling coordinates

2D Output:
- Boundary curve
- Seedpoint

Pick-up position:
- Seedpoint relating to 2D table/cutter

Lay-up position:
- Seedpoint relating to 3D tooling

QA cut piece position:
- Laser light-section path
- Path planning relating to robot TCP

Robotics program:
- Path planning relating to robotic TCPs

Input für Visual:
- Tooling surface
- Path
- Cut piece boundary

Measurement

Visual/Edge:
- Filtering
- Smoothing
- Online Evaluation

Status Quo: manual process preparation
Vision: design to manufacture
Automation along the Process Chain

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- Cutting
- Cut piece logistics
- Auxiliary materials
- Vacuum setup
- Resin pipes
- Temperature monitoring
- Infusion process parameters
- Resin monitoring

Dry textile
Handling, Preforming
Vacuum bagging
VAP/VARI
Debagging, Demoulding
Machining, Assembly
Preforming Solutions

**Gripper principles**
- Modularity
- Flexible adjustment of deformation
- Vacuum (low pressure), high volume flow
- Supply: 6 bar, 24 V, EtherCat

**Gripper details**
- Components:
  - Valve cluster by Festo
  - Bus module by Beckhoff
  - Gripper mechanics by Kuka Systems
- Bellows suction pads (optimized for choice of material)
- Activation of thermoplastic binder by heating devices on linear actuators
Preforming Solutions
Preforming with Cooperating Robots

Pick-up

- Rectangular cut pieces
  - Dry NCF, 2.0 x 1.22 m
  - Thermoplastic binder
- Resulting forces depending on gripper distance
- Gripper movements in 3 increments
- Cut piece forms catenary
Preforming with Cooperating Robots

Lay-up

Transfer on linear track and positioning
- Grippers keep their relative position and orientation

Attachment
- Grippers hold cut piece edges in position
- Activation of thermoplastic binder
- Individual gripper movements
Preforming with Cooperation Robots
Preforming with Cooperation Robots

Performance

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<th>Initial testing</th>
<th>2 m Video</th>
<th>6 m expected</th>
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<td>8</td>
<td>11</td>
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<tr>
<td>Binder [s]</td>
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<td>5</td>
<td>10</td>
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<td>Layup rate [kg/h]</td>
<td>7.53</td>
<td>90.27</td>
<td>218.31</td>
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</table>
Automation along the Process Chain

**Input, process preparation:**
- Draping Results
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**Hard-/software for preforming:**
- Gripper components
- Gripper system and program
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- External guidance

**Input, process preparation:**
- Cutting
- Cut piece logistics

**Vacuum bagging**
- Auxiliary materials
- Vacuum setup
- Resin pipes
- Temperature monitoring

**Hard-/software for online QA:**
- Measuring cut piece position/boundary
- Measuring fiber orientation
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**Cured Component:**
- Quality check
- Detailed documentation
- Concession Handling
- Potential rework

**Debagging, Demoulding**
- Infusion process parameters
- Resin monitoring

**Machining, Assembly**
Control on Process Accuracy
Chain of Errors

- Dry textile
- Handling, Preforming
- Vacuum bagging
- VAP/VARI
- Debagging, Demoulding
- Machining, Assembly

- Draping, ply book
- Cut piece prep., poses, paths
- Programs for gripper & LLS
- Pick-up, lay-up
- Measurement
- Processing, Assessment

Hardware
- 3D Tooling
- Robotics
- LLS
- 2D Table
- Gripper

Software
- Draping simulation
- Gripper program
- LLS program
- Visual
- Edge

- System of hard- and software components
- Chain of errors with many potential error sources
Control on Process Accuracy
Chain of Errors

Process
- Dry textile
- Handling, Preforming
- Vacuum bagging
- VAP/VARI
- Debagging, Demoulding
- Machining, Assembly

Hardware
- 3D Tooling
  - Base system
  - Exact surface geometry
  - Matching reality and theory
- 2D Table
  - Base system
  - Cut piece position and orientation
- Robotics
  - Null frame (base localization)
  - Robot accuracy (absolute, repeated)
  - External axis alignment
  - Calibration (loads & poses)
- LLS
  - Tool center point
  - Mechanical installation
  - LLS accuracy
- Gripper
  - 9 Tool center points
  - Adjustment of gripper modules

Software
- Draping simulation
  - Draping simulation strategy
- Gripper program
  - Load data
  - Pick-up and lay-up poses
  - Forces on material
  - Material deformation
- LLS program
  - Load data
  - LLS orientation
- Visual
  - Coordinate systems
  - Sensor parameters
- Edge
  - Signal to noise ratio
  - Detection algorithm and filters
  - Smoothing
  - Shading
  - Material Surface
Online Quality Assessment
Concept for Position Accuracy

- Laser light section sensor
- Goal: flexible tool to cover a wide range of research scenarios
- Feasibility study: Laser scanner guided by an industrial robot

Source: Micro Epsilon
Online Quality Assessment
Measurement of Position Accuracy

- Measurement along boundary curve
- Signal quality material dependent

- Signal processing:
  - Filtering & Algorithm for edge detection
  - Transformation to global robot coordinates
  - Comparison to expected boundary curve

→ Measurement system independent of geometric complexity and composite definition
Online Quality Assessment
Concept for Position Accuracy

Laser Light Section Sensor

Robot Control

Server

Client

Profile Data

Filtering

Edge Detection

Transformation into Robot Coord.

Measurement Result

VISUAL

EDGE

Profile Data

trigger signal

position data

profile data

meseasurement task

measurement result
Online Quality Assessment Processing

- Visualization of multiple geometry features, ply book definitions and measurement results
- Live evaluation of measurement vs. CAD reference (Catia CPD)
Online Quality Assessment

Video
Automation along the Process Chain

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   - Vacuum setup
   - Resin pipes
   - Temperature monitoring
   - Gripper components
   - Gripper system and program
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   - External guidance

3. **Vacuum bagging**
   - Infusion process parameters
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   - Measuring cut piece position/boundary
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   - Online Assessment

4. **VAP/VARI**

5. **Debagging, Demoulding**

6. **Machining, Assembly**

- Cured Component:
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- **Dry textile**
  - Cutting
  - Cut piece logistics
Flexible Robotics Platform

Vision

- Up to four gantry robots and two six-axis robots
- Large space for fixtures and tools
- Easily reconfigurable virtual cells

→ Maximum flexibility for research in industrial scale
Enhancing Accuracy on a Flexible Robotics Platform

Gantry deformations

**Challenge**
- Ceiling mounted robots cause deformations in gantry structure
- Dependence on load distribution (robot and gantry positions)

**Solution: external guidance**
- Monitor robot and gantry positions
- Compensate for deviations
Enhancing Accuracy on a Flexible Robotics Platform
External Guidance

- External Sensor determines actual TCP pose
- Real time controller calculates deviation
- Filter of correction values and transmission to robot controller
- Execution of correction (during motion on path)
Enhancing Accuracy on a Flexible Robotics Platform

Measurement system selection

**Laser Tracker**
- Large volume
- Very high accuracy
- Single beam source
- 6D measurement possible (tracking single point)

**Laser Tracer**
- Large volume
- Highest accuracy
- Multiple beam sources (movable)
- 6D measurement possible (tracking multiple points)

**Indoor GPS**
- Scalable volume
- High accuracy
- Multiple beam sources (static)
- 6D possible measurement (tracking multiple points)

**Camera CMM**
- Limited volume
- High accuracy
- Multiple beam sources (static)
- 6D possible measurement (tracking multiple points)

**IMU & AHRS**
- Unlimited volume
- Medium accuracy
  (integration)
- Independent of external system
- 6D measurement possible (as source)

Selection of laser tracker as reference system
(open software architecture allows integration of different sensors)

Image sources: FARO, Etalon, Nikon metrology, VectorNav
Enhancing Accuracy on a Flexible Robotics Platform

System Components

- Sensor: laser tracker Leica AT901LR with T-CAM
- Detector: multi-sided probe with Leica T-MACs
- Controller: industrial embedded PC - Beckhoff CX1030
Enhancing Accuracy on a Flexible Robotics Platform

Experimental setup

- Comparison of normal and compensated linear motions.
- No advanced filtering of compensation data, only absolute deviation between real and desired pose is used.
- Cell configuration: KR 210 R3100 ultra, KRC4, KSS 8.1.7, RSI 3.0
Enhancing Accuracy on a Flexible Robotics Platform

Preliminary results 1

Linear motion along X (300 mm/s)

- Y compensated
- Y not compensated
- Y not compensated (initial pose error corrected)

Measurements over time (12ms between measurements)
Enhancing Accuracy on a Flexible Robotics Platform

Preliminary results 2

- Initial pose error from previous motion approximately 1.11mm (complex motion patterns with initial pose correction currently under development)

- Motion (and compensation) start around time index 22, robot is pulled on path in approx. 100ms

- Non-compensated motion shows drift along positive X

- After initial correction:
  average path error 0.07mm
  \[\sigma: 0.05\]
  min: -0.224mm
  max 0.125mm

![Distribution of Measurements](image)
Summary

- **Preforming process**
  - Process preparation
  - Gripper solution
  - Preforming process with cooperating robots

- **Online quality assessment**
  - Laser light section sensor
  - Measurement of cut piece boundary
  - Online assessment of positioning accuracy

- **Enhanced accuracy in robotic cell**
  - External guidance approach
  - Setup with laser tracker
  - Successful compensation in test setup
Outlook

- **Medium term development goals**
  - Range of possible geometries → large variety of structural components
  - High process stability → possible process qualification
  - Integrated OLP tool → fast process preparation

- **Possible improvements**
  - Flexibility of gripper kinematics
  - Improved heating system for faster binder activation
  - Integration of quality control system

- **Next Steps**
  - Current gripper allows single curvature:
    Next generation gripper (for double curvature)
    in testing with KUKA Systems
  - Implementation of integrated OLP approach
Acknowledgement

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