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**Alfons Schuster, Lars Larsen, Frederic Fischer, Roland Glück, Stefan Schneyer, Michael Kühnel, Michael Kupke**

**Angaben zur Veröffentlichung / Publication details:**

Schuster, Alfons, Lars Larsen, Frederic Fischer, Roland Glück, Stefan Schneyer, Michael Kühnel, and Michael Kupke. 2018. "Smart manufacturing of thermoplastic CFRP skins." *Procedia Manufacturing* 17: 935–43. https://doi.org/10.1016/j.promfg.2018.10.147.

Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 17 (2018) 935–943

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

28th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2018), June 11-14, 2018, Columbus, OH, USA

# Smart Manufacturing of Thermoplastic CFRP Skins

Alfons Schuster*, Lars Larsen, Frederic Fischer, Roland Glück, Stefan Schneyer, Michael Kühnel, Michael Kupke

*German Aerospace Center (DLR), Institute of Structures and Design, Am Technologiezentrum 4, 86159 Augsburg, Germany*

**Abstract**

High performance aerospace structures often require a combination of innovative materials and new production technologies. Carbon fiber reinforced thermoplastics (CFRTP) have shown their potentials over the last decades especially due to their competitive production rates. Thermoplastic matrix systems allow joining by welding, which is a major advantage for assembly. Production systems for flat thermoplastic organic sheets are readily available on the market, as well as advanced fiber placement and tape laying machines (AFP/ATL). But there is a lack of systems capable of fabricating 3D-curved, near net shaped patch preforms that may serve for mass-customization of standard parts, e.g. for future aerospace panel production. With the composite prepregs being stacked within the mold the fibers will undergo less reshaping during consolidation (i.e. debulking) thus giving a better control over fiber angles. We describe an autonomous smart manufacturing system that is capable of handling unique parts by means of a complete digital workflow from part design over automated cut-piece fabrication, generation of system related meta-information, virtual planning of grip and drop up to the final layup. The system consists of a preprocessing and production planning apps, an industrial robot, a gripper with an ultrasonic welder, a storage system for cut-piece supply, a computer vision system, a collision avoidance app and a logging system for process relevant production parameters for inline quality control. The described system was successfully used for the production of four thermoplastic CFRP skin segments each consisting of 104 cut-pieces.



*Keywords:* Innovative Manufacturing Systems and Services, Robotics and Computer Integrated Manufacturing, Production Planning, Scheduling, and Control

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Peer-review under responsibility of the scientific committee of the 28th Flexible Automation and Intelligent Manufacturing (FAIM2018) Conference.
10.1016/j.promfg.2018.10.147

## 1. Introduction

Today's aerospace structures demand extreme mechanical performance, lightweight and competitive pricing [1]. During the last decades the use of carbon fiber reinforced plastics (CFRP) based on thermoset matrix systems was established for airplane production of structural parts, mostly in manual layup of semi-finished material and later resin infusion (VAP) or for higher volumes in automated tape laying (ATL) [2]. In recent years the use of high performance thermoplastic matrices, especially of CF- PEKK in the form of pre-impregnated unidirectional tapes has gained some interest for future single-aisle aircrafts, since the impact behavior can be improved and thus material and weight can be saved [3,4].

To date in-situ tape laying in which expensive slitted prepregs are placed and consolidated simultaneously in a single value adding process lacks competitive production rates and often requires final consolidation. Press-processing of pre-consolidated organo sheets, on the other hand, is limited in part size and producible shapes.

Patch preforming may thus be a viable production technology where pre-cut plies are stacked in curved molds (or placed and fixed to molded parts) [5]. Final consolidation may be achieved by vacuum or press consolidation, depending on the respective production route.

Concerning the layup of semi-finished materials in patch-preforming hundreds of cut-pieces need to be handled. Since the number of same parts in aerospace is typically low and the parts are comparably large the use of industrial robots for a flexible production is a legitimate approach, at times even considered a decisive factor for success [6]. Obviously, for flexible production, limitations caused by manual robotic path teaching are to be avoided. Commercial products in the area of robot offline programming, in turn, lack the ability of handling huge numbers of cut-pieces. In addition, handling issues of the cut-pieces that tend to warp need to be met. Integration of special sensors to allow reliable cut-piece detection within the digital thread is indispensable.

For the automation of this process a smart and flexible, however robust system linked to the CAx (computer aided technologies)-process chain has been set up which will measure and record the process' quality parameters inline. The system completely avoids teaching and takes material simulation into account, what is a major break-through in patch preforming. We validated our production system, in our integrated work-cell for thermoplastic composite production, on the use case of a thermoplastic skin demonstrator.

## 2. Part Design and Experimental Setup

### *2.1. Use Case description*

An aircraft skin segment was chosen as use case to probe the capabilities of the process for future fuselage production. The skin segment is 950 mm in length and 600 mm in width. It is part of section 16, the cylindrical fraction of an A320 single-aisle aircraft with a radius of approximately 2 m. The ply book was adapted and scaled from the all-composite A350 design. A segment atop the windows was chosen where the skin thickness increases from 11 to 28 layers (Figure 1).

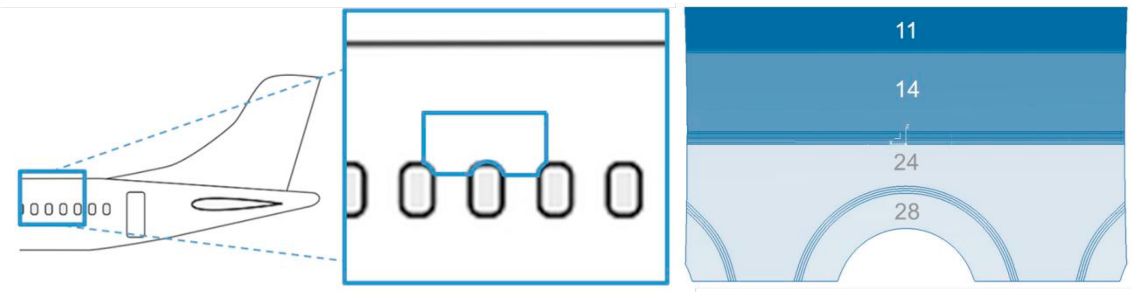


Figure 1: Fuselage skin segment with increasing laminate thickness

Especially the windows cut-outs were reinforced by circular cut-pieces which would not be producible with the benchmark technology, so-called automated fiber placement (AFP). Patch preforming was used to produce a curved laminate stack directly on a female tooling followed by oven vacuum consolidation. The ply book with its 11 to 28 layers and varying fiber orientation (0°, 45°, 90°, 135°) was designed in CATIA's Composites Part Design (CPD) V5R23. Due to the tape width of 12 inches (304.8 mm) every ply is divided into 2 to 4 cut-pieces, resulting in a total 104 cut-pieces for the entire part. To ease changes and adaptions the plybook was parametrized. It now consists of 36 plies which are spliced to a width of 275 mm. This ensures a material security excess on both sides of the tape of approximately 15 mm. This plybook, constructed on an ideal surface, was swapped onto the real mold geometry which was measured with a Leica T-Scan 5 device. The cut-pieces are subsequently supplied, gripped, transferred to the mould, dropped and fixed by ultrasonic welding by a fully autonomous robotic system equipped with a computer vision system mounted to an end-effector. The end-effector itself consists of a frame with sucker cups for the cut-piece transport and a linear axis mounted in-between the vacuum cups with the lowerable ultrasonic spot weld unit for cut-piece fixation.

### *2.2. Cut-piece Supply and Integrated Work Cell*

The net-shape cut pieces were produced from 12 inch Toho Tenax UD PEKK tape with a fully automated cutter system which uses GTK Cut software and AutoNesterT algorithm to generate the cut pieces from the ply book. The resulting nesting sequence is transmitted to the cutting unit (Zünd digital cutter). Finally, the cut pieces are automatically stored in a mobile drawer unit (Figure 2).

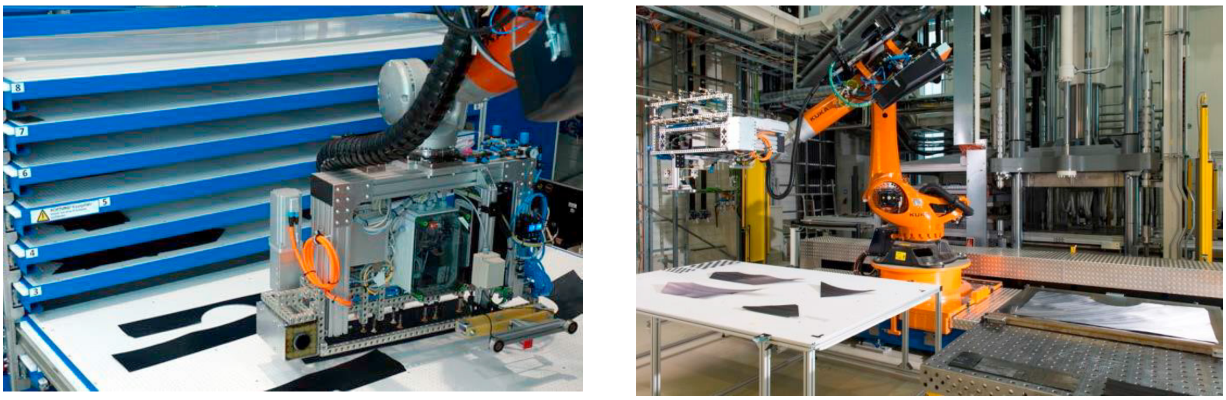

Figure 2: Mobile drawer unit for the storage of cut pieces (left), Robot in detection position above table (right)

In this intermediate quality inspection step the flat cut pieces are probed for their size and orientation with the camera detection system. Thus issues of the cutter system may be detected, and gaps in the lay-up can be minimized.

## 3. Layout of Autonomous System and Digital Process Chain

Overall goal is to allow the robot cell to run autonomously. This means that the process description is generic and contains only the information necessary for a correct part production. To avoid production induced flaws like wrinkling or warpage of the involved textiles, the information has to be derived from CAD draping simulation to ensure maximum compatibility of production and physical properties of the cut-pieces. Especially there are no conventional robot programs containing robot paths generated by teach in. The following section describes the necessary steps for a "teachless", autonomous production taking into account the material behaviour by simulation.

### 3.1. CAD Export and Mesh Generation

In order to enable further steps in the automated production, the plybook was enriched with additional meta-information concerning the relations between points on the plane cut-pieces and the draped cut-pieces. To this purpose, a grid of 2D-points with mesh size 10 mm was created on the plane cut-piece by a CATVBA script. Subsequently, pairs consisting of a 2D point on the plane cut-piece and a 3D point on the draped cut-piece with respect to the producibility of the respective cut-piece where created. This information was stored in an XML-File and used afterward for computing correspondences between arbitrary 2D and 3D points by means of interpolation.

### 3.2. Grip-Planning and Metainfo Generation

For the determination of the grip- and droppoints (i.e. the end-effector positions, where the plane cut-piece has to be gripped and the cut-piece has to be dropped into the mold) a proprietary assistant tool was developed. The user is offered a suggestion from the system how to place the gripper on the plane cut-piece. Depending on the quality of the suggestion, the skilled user can alter the position of the gripper as required. Based on the gripper position the tool calculates the vacuum cups which have to be activated, the positions where and the parameters how the cut-pieces have to be welded, and the final gripper position for the layup process. The system will place the gripper on the cut-piece such that both the number of vacuum cups on the cut piece and the number of vacuum cups near the corners of the cut-piece are maximized. In most cases the system will achieve satisfactory solutions; however, in some cases a human expert has to correct the positions by hand, mostly when the suggestion leads to a collision-prone robot pose.

The screenshot in Figure 3 gives an impression of the user interface: on the left part, the situation on 2D is shown. The orange square indicates the tool center point (TCP) of the gripper, the green circles correspond to the vacuum cups to be placed on the cut-piece depicted as a blue shape with little squares that stem from the vertices exported from CATIA. The red circles are those vacuum cups that will not cover the cut piece and hence need not be activated. Furthermore, the line segment illustrates the linear axis along which the welding unit can be moved, with the green fraction being atop the cut piece, and the red fraction lying beyond the cut-piece. Finally, the small orange squares on the linear axis show where the welding takes place. Additionally, on the right part the corresponding 3D-configuration including the entire ply within the mould is shown in an analogous representation, which gives the user a better orientation to avoid possibly unwanted robot poses.

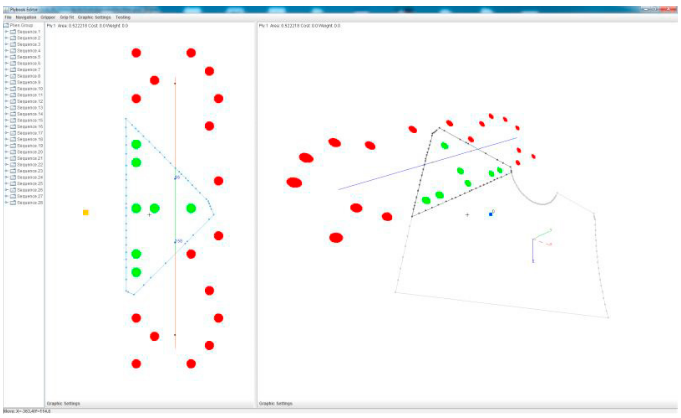

Figure 3: Screenshot from the Offline Programming Assistant

The determined grip points, drop points, TCPs, vacuum cups and weld-information are stored together with the cut-piece contours and a layup plan in a job description file (jdf).

### *3.3. MES and Metainfo Processing*

The obtained jdf now holds the necessary meta-information for autonomous production. It is passed to a manufacturing execution system (MES) which extracts the contours for the computer vision system and stores the data in a serialized action-list for the robot. Following the layup-plan the MES handles the following:

- Opening and closing of the drawers containing the next cut-piece via a magnetic gripper
- Triggering the cut-piece detection (availability, position, orientation)
- Triggering the gripping of the cut-piece at the above determined position
- Initiating the cut-piece transfer to the desired laydown coordinates
  - If available the collision control system (CoCo) is asked to render a safe transfer path which is then executed (described in detail in section 3.5).
  - Alternatively, the transfer will be a straight lift-up followed by a linear motion to a pre-drop position on the tooling surface normal through the drop point

  Of course the alternative is only feasible if the cell layout allows it. More complex transfers that fit the situation are feasible only with the collision control (section 3.5).
- Triggering the drop and the welding according to the stored meta information

A web-interface for remote operation is also provided to allow later integration in a factory-wide production management system.

### *3.4. Interaction with Computer Vision System and Robots*

One central point for autonomous production is the cut-piece detection by computer vision, since it allows more freedom in the cut-piece supply during transportation and is a safe way of avoiding missing or mixed cut-pieces. The MES interacts with the computer vision systems via a dedicated interface and both a detector and a robot HAL as described in previous work [7], thus enabling encapsulation of the software into a service oriented architecture where the future integration of other systems or the change of hardware is possible with low effort.

### *3.5. Collision Free Path Planning*

The generation of robot paths can be very time consuming and thus expensive. As already indicated in the MES section a promising solution for path generation is to generate program modules with predefined support points, which allows moving the robot from any grip position to a safe home position. In this case, the home position is defined above the drawer unit and a safe pre-position above the lay-up position. With the robot control extrapolating the paths between the predefined support points may bear the risk of configurations leading to collision. An automated generation of collision-free robot paths is far more desirable. Such a system was presented by Larsen *et al.* [8,9,10] which can automatically generate collision-free paths on the basis of a virtual representation of an(y) integrated workcell. The CoCo system is implemented in C# using HelixToolkit [11] for the visualization and BEPU physic engine [12] for collision detection. For the planning either sampling-based algorithm from the Open Motion Planning Library (OMPL) [13] of self-implemented evolutionary algorithms are used [14]. As input, the system requires the respective grip and drop position of the cut-piece and thereupon calculates a collision free path composed of a set of support points. Figure 4 shows two screenshots of results for such paths generated by the system between the lay-up table on the right (marked in green) and the drawer unit on the left (marked in grey). In the left picture the third drawer is opened and in the right one the fifth. Tests have shown that the CoCo system reliably renders collision-free paths for flexible composite production.

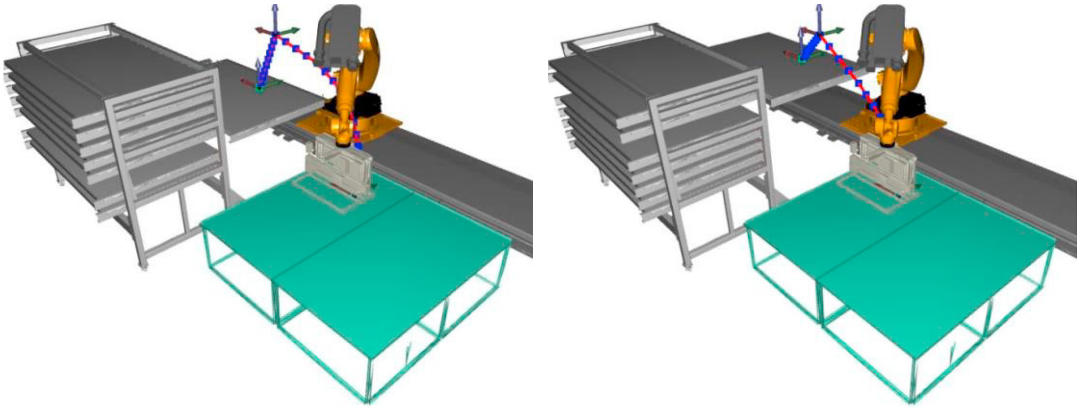

Figure 4: Planning of automatic pick and place process with CoCo system. On the left grip from drawer three and on the right from five.

### 3.6. Logging System and miscellaneous QS Methods

Another crucial point for aerospace composite production is the control of the production quality. Generally, all composite parts undergo extensive final non-destructive testing (NDT), mostly by water coupled ultrasound. In our case, data of dedicated sensors, the computer vision system, as well as from the production system (e.g. the ultrasonic weld unit) is collected and transferred to a common database and a file-storage. In the next step, these data gained effortlessly along production shall be combined with the NDT results in order to demonstrate that a final NDT can ultimately be avoided or reduced.

We successfully achieved a first step towards this far-reaching goal comprising data collection for

- Camera images with online contour control in order to control the cutting quality
- Vacuum system pressure and flow of the vacuum cups enabling the detection of cut-piece loss or vacuum cup degeneration
- Weld amplitude, power and energy via extracting the ultrasonic generator's log together with horn movement and compaction during welding mapped to the 3D CAD data
- Monitoring the robot alignment by a mini camera that detects and corrects the robot's positional drift at the its base points

Our major goal was to use low cost equipment and to test wireless data transmission for a part of the sensors mounted on the end-effector. For example, we used a 40$ Raspberry Pi Model 3b for collecting the weld generator's output and for detecting the robot's drift by the mini-USB-camera via WLAN. One Pi can handle several sensors thus allowing cheap wireless data readings.

### 3.7. Overall System Layout

The overall system layout we implemented for the tests is shown in **Error! Reference source not found.**.

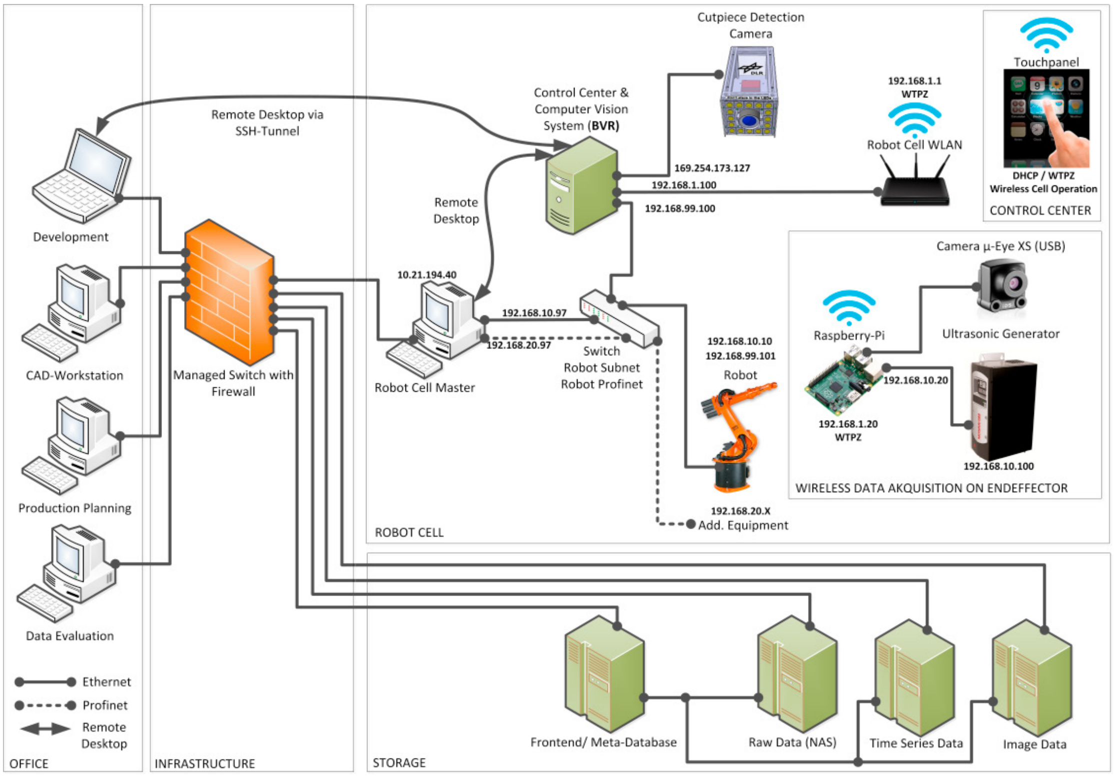


Figure 5: Factory system layout

The system is divided into five sections:

- The office part contains the workstations for development, part design, production planning and data evaluation. The production planning station hosts the apps described in 3.1and 3.2.
- The infrastructure part consists of the in-house network cabling and connects the office part to the robot cell on the shop floor and to the storage by a managed switch with firewall in order to make the shop floor part safe. Interconnections from office to shop floor and storage are restricted to absolutely necessary firewall exceptions and to ssh tunnels via a limited number of master computers which can be supervised easily.
- The robot cell consists of several subnets connected to the switch's shop floor side only through a cell master computer shielding the robot subnets and routing the necessary network traffic as desired. The subnets include PROFINET safety, TCP/IP communication to the robots and cut detection camera as well as a separate WLAN for measurement, visualization and operation purposes. Only non-function-essential and non-safety-relevant traffic is allowed here. It is thus possible to operate the robot cell from different places that can be changed on the fly or even carried along.
- The storage part contains a NAS for raw data storage, a database for time series data and image data storage.

Research will be performed on the frontend which shall comprise a meta-database governing several types of databases suited for the specific application, e.g. time series and image data bases.

## 4. Experimental Results

### 4.1. Layup Process

The system was tested on the manufacturing of three skin demonstrators with 104 cut-pieces each. Automated loading of the drawer storage is still under investigation, so for our tests the cut-pieces were stored manually in the drawer unit. The process proved to be very stable except of the problem that was introduced by manual loading: Several cut-pieces were twisted by 180° what led to a safe production hold, because the detection angle was out of the parametrized range (±15°). A few others were turned upside-down, which also led to a hold because of the non-matching geometry. Further, we encountered three cases where the cut-piece was twisted just slightly out of the a. m. angular range. This proves that further research has to be performed to overcome manual loading, which will be an intolerable obstacle for a future practical application.

Since the material warpage is considerably high the template-matcher responsible for the cut-piece detection had to work with increased tolerances and thus accepted this out-of-angle cut-pieces but with a wrong detection angle. This leads to production errors such as gaps and overlaps of the stacked laminate and thus has to be avoided.

### 4.2. Accuracy Issues

The a.m. issues were examined by detecting the very same cut-piece "as-is" with warpage and held down by magnets without warpage. Figure 6 shows the deviations for the first case where the deviations can be seen clearly.

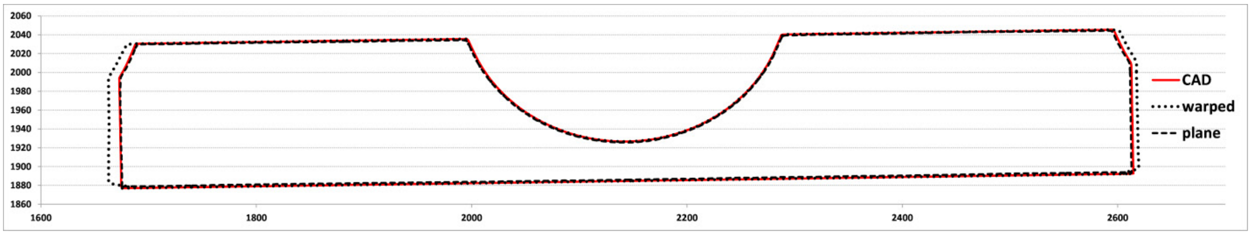


Figure 6: Material warpage leads to significant deviations from the CAD data.

When holding down the cut-piece both curves are visually identical. Resulting gaps or overlaps of adjacent cut-pieces were measured with a steel tape measure. Production with warped cut-pieces yielded laydown deviations in the range of roughly ±1 mm, exceptionally even ±1.5 mm, which is significantly higher than what was already achieved before with non-warping materials [4]. Examining the held down cut-pieces revealed another error: due to a faulty calibration the cutter added or subtracted 0.5 mm to the contour depending on the cutting direction, what may have led to those exceptionally high deviations when the effect pointed into the same direction.

In order to minimize such accuracy issues caused by ply warpage, the cut pieces may alternatively be placed on a vacuum table in an intermediate quality assurance production step.

## 5. Conclusion

Fully automated patch preforming based on a pick and place process of composite cut pieces was established and tested on three identical demonstrator parts. The cut pieces were detected by a camera system and matched against the part ply book. Plies were picked up from a mobile drawer unit and placed on their predefined position on the curved tool. Thus a total of each 104 cut pieces was stacked automatically to form a preform. The system proved its stability in a total of three productions with 312 cut pieces but showed potential for improvement concerning the desired accuracy. The encountered accuracy issues were tracked down to material warpage and a faulty cutter calibration and may be overcome by the use of an intermediate downholder table comprising vacuum or electrostatic forces, which is subject of current work, as well as a more frequent recalibration of the cutter system. The production integrated quality control proved to be reliable. Due to the localization both in the time and spatial domain the data can be correlated with the results from NDT in the future.

## References

[1] G. Berchtold, R. Schimkus, K. Schulte, Automatisierungstechnologien für große CFK-Strukturen der Luftfahrt, Lightweight Design, 4/5/2009, 72-73.

[2] F.C. Campbell, Manufacturing Processes For Advanced Composites, Elsevier Advance Technology, Oxfort, 2004

[3] M. Kühnel, A. Schuster, C. Rähtz, and M. Kupke, Eds., Near net shape thermoplastic preforming with continuously automated cutting and robotic pick and place processes. Bremen: International Conference and Exhibition on Thermoplastic Composites, 2016.

[4] A. Schuster, M. Kühnel, M. Kupke, Automated preforming of curved thermoplastic organic sheets. SAMPE Europe, 15. - 17. Sep. 2015, Amiens, France.

[5] A. Björnsson, M. Jonsson, K. Johansen, Automated material handlich in composite manufacturing using pick-and-place systems – a review, Robotics and Computer-Integrated Manufacturing 51 (2018), 222-229

[6] D. Steegmüller, M. Zürn, Wandlungsfähige Produktionssysteme für den Automobilbau der Zukunft, publised in Handbuch Industrie 4.0 Bd.1, Produktion, B. Vogel-Heuser, T. Bauernhansl, M. ten Hompe (Eds.), Springer, Berlin, Heidelberg, 2017

[7] A. Schuster, M. Kupke, L. Larsen, Autonomous Manufacturing of Composite Parts by a Multi-Robot System, Procedia Manufacturing (2017) 11, 249-255

[8] L. Larsen, J. Kim und M. Kupke, „Intelligent path panning towards collision-free cooperating robots,“ 11th International Conference on Informatics in Control, Automation and Robotics (ICINCO), Vienna, 2014.

[9] L. Larsen, V.-L. Pham, J. Kim und M. Kupke, Collision-free path planning of industrial cooperating robots for aircraft fuselage production, Seattle: IEEE International Conference on Robotics and Automation (ICRA), Seattle, 2015

[10] A. Angerer, A. Hoffmann, L. Larsen, J. Kim, M. Kupke und W. Reif, „Planning and execution of collision-free multi-robot trajectories in industrial applications,“ 47th Symposium on Robotics - International Symposium on Robotics (ISR), Munich, 2016.

[11] Helix Toolkit, 08 02 2017. [Online], Available: https://github.com/helix-toolkit

[12] BEPUphysics, 07 02 2017. [Online]. Available: http://www.bepuphysics.com/

[13] I. A. Sucan, M. Moll und L. E. Kavraki, „The Open Motion Planning Library,“ IEEE Robotics & Automation Magazine, 2012.

[14] L. Larsen, Kim, J. Kim, M. Kupke, A. Schuster, "Automatic Path Planning of Industrial Robots Comparing Sampling-Based and Computational Intelligence Methods," 27th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM), Modena, 2017