TAILORED THERMOPLASTIC PREFORMING WITH CONTINUOUSLY AUTOMATED CUTTING AND ROBOTIC PICK AND PLACE PROCESSES OF VARIOUS SEMI-FINISHED GOODS

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Keywords: carbon fiber, thermoplastics, tailored preforming, draping simulation, forming simulation, near net shape, nesting, cutting, robotics, pick and place, ultrasonic welding, automation

Abstract

Today’s automated production lines for parts of carbon fiber reinforced thermoplastics (CFRTP) are mostly designed for one special part or application. Changing part geometry or material would lead to a complete re-design of the whole process chain. Here comes the flexible and highly automated the DLR process into game: A continuously automated production line “from fabric delivery to the machined and quality inspected part – ready for shipment”.

The paper and presentation focus on the first half of this process chain: “from fabric delivery to the tailored preform – ready for consolidation”. The utilized fabrics can be rolled goods like unidirectional (UD) tapes, non-crimp fabrics (NCF), wovens, fleeces and foils or even sheet goods like consolidated organo sheets. The rolled goods are automatically stored, fed and cut on the DLR’s cutting center (see picture 1). After cutting the cut-pieces are automatically picked and stored in a mobile drawer storage system, from where they are automatically supplied to a robot cell. A robotic pick and place process with a cut-piece detection camera, material friendly vacuum gripping and ultrasonic fixation units then detects, grips, stacks and fixates the cut-pieces to point-welded stacks ready for consolidation with e.g. thermoforming or vacuum consolidation.

With the paper and presentation, the authors like to contribute to the industry’s increasing needs of continuously automated but highly flexible process chains for variable high volume CFRP parts.

1 Introduction

In modern helicopter industry production rates for one model typically vary from 50 to rarely 100 helicopters per year. Considering such low production rates it is mostly not possible to justify an extensive invest in automated production lines. The degree of capacity utilization of such lines, being specialized on the production of one single part, hardly can be shown. [1]

The same applies for aircraft manufacturers with a high part variety, such as e.g. the so called A350 clips, where more than 2500 different clip designs among 5000 clips exist. These designs can differ e.g. in the outer contour, laminate thickness, stacking sequence matrix material, folding angles or foot radii. [2]

In contrast to existing, costly production lines and with respect to the above mentioned industry’s needs DLR invented a highly flexible and continuously automated process chain “from fabric delivery to the tailored preform” with comparably low invest.

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2 Engineering of tailored cut-pieces/preforms

To achieve the flexibility of the process chain, the authors started at the beginning of it – at the part and manufacturing engineering. Tailored preforms were realized with material efficient near net shapes and laminate stack-ups, which were optimized for part processing and part performance.

2.1 Near-net-shaped and performance optimized cut-piece geometries for draping and forming simulations

In order to get a near-net part shape the single cut-pieces making up its laminate have to comply with this near net shape. As the cut-pieces usually are cut out of flat (e.g. rolled out) fabrics, the manufacturing engineering has to consider the draping of the cut-pieces from two to three dimensions. Therefor the authors used draping simulations in *Dassault's CATIA R23 Composites Part Design* (CPD) with a kinematic approach in case of low deformation degrees, which cause only low stresses during draping (comparable to a manual draping process). Hereby the flexibility of the later described lay down process allowed the engineering to optimize the part by its performance and not restricting it for a better producibility (demonstrator part for draping by gripper and vacuum bag with performance optimized ply endings see Figure 1). The near-net shape was generated by using the flattening and geometry transfer functions, which consider the internal kinematic mesh used for draping.

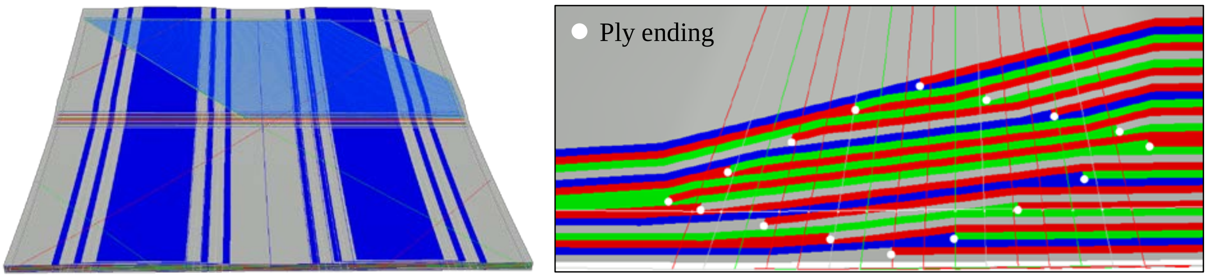

Figure 1: Left: Draping simulation of a 45° cut-piece of a fuselage skin part preform (A350 curvature radius) out of CF/PES UD tape. Tooling surface (green) reconstructed out of laser measurement. Right: Diamond shaped ply endings from thicker to thinner laminate region.

When expecting comparably high deformation degrees the authors used forming simulations in *ESI's Pam-Form 2015* based on finite element analysis, and therefore considering high stresses in the preform, as e.g. occurring in a forced forming process applied by two moulds in a press (demonstrator part for forming in a press see Figure 2).

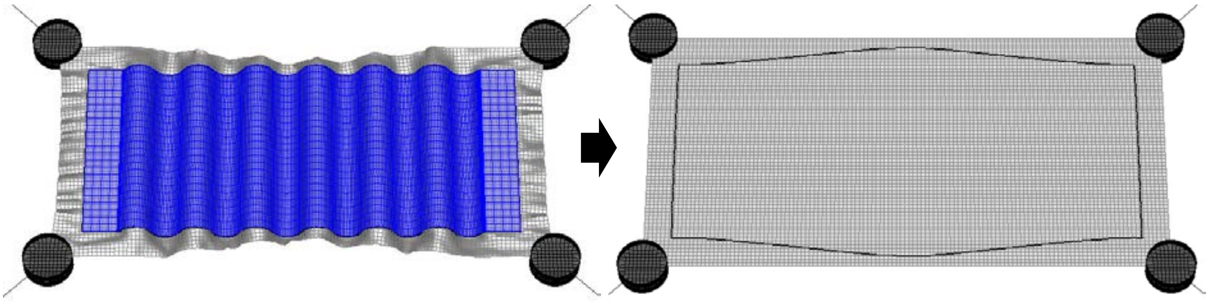

Figure 2: Deformed preform (wave beam web) with tooling (blue) in forming simulation (*Pam-Form*, left) and recalculated net shape (black) of the part or tooling edge on the flat preform prior to the forming process (right).

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Here the near net shape was generated by projecting the near-net part shape on the formed organo sheet and then recalculating its undeformed shape. Afterwards butt straps were added in *CATIA Generative Shape Design* (GSD) and the new geometry was again formed and iteratively recalculated. Tests showed that after three iterative steps a satisfying near-net shape can be generated. [3]

2.2 Material efficient nestings

The thus generated near-net-shaped cut-pieces were then imported into the cutting software *GTK Cut* where they were nested with the nesting algorithm *AutoNesterT* from *Fraunhofer SCAI*. This nesting algorithm originally was developed for furniture and clothing industries. [3] Tests showed that it is possible to increase the material efficiency by 10% and more when choosing a fiber-angle-suited cut-piece shape (fragmentation) and nesting and cutting several preforms at once (see Figure 4f). Considering this, material utilization degrees of up to 95% could be shown.

Figure 3: Nesting for a skin part preform out of sliced UD layers, material utilization degree ≈ 95%.

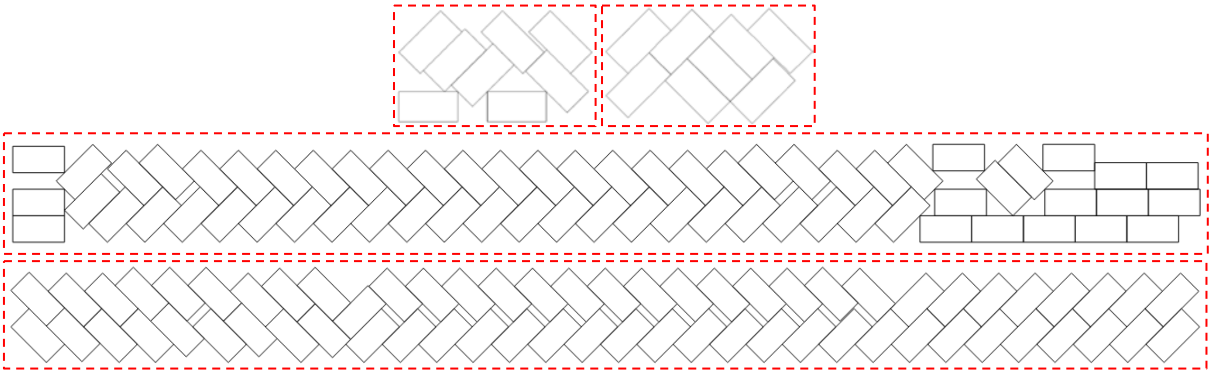

Figure 4: Top: Nestings for one web preform with (left) and without (right) 0/90° layers.
Middle: Nesting for eight web preforms with 0/90° layers.
Bottom: Nesting for eight web preforms without 0/90° layers.

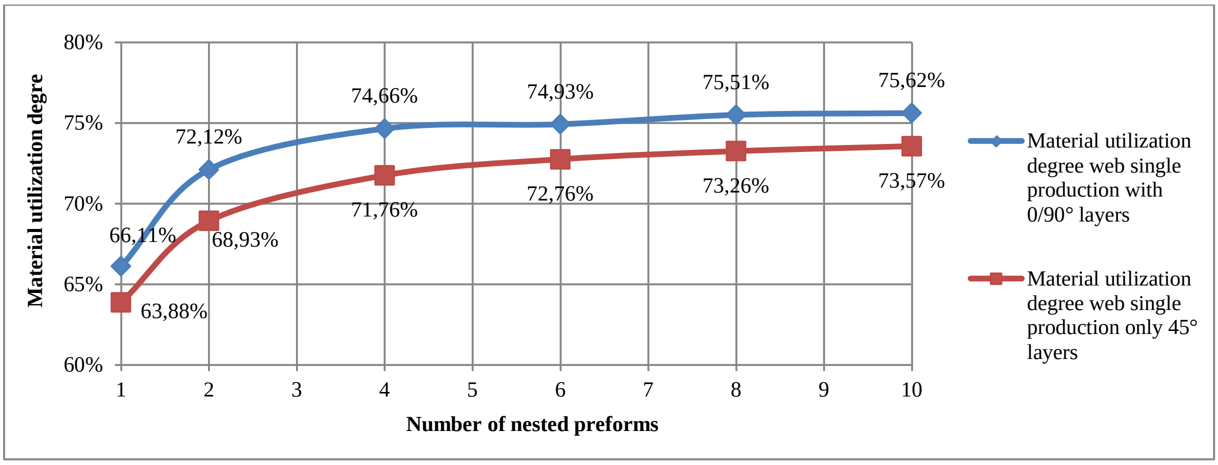

Figure 5: Material utilization degrees of different nestings for one to ten preforms with (blue) and without (red) 0/90° layers.

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3 Production of tailored cut-pieces – automated cutting process

After the Engineering of the tailored preforms comes their production. Once a material efficient nesting is generated it can be cut out of the considered material.

3.1 Storage, automated supply and cutting of various semi-finished goods

At DLR Augsburg cut-pieces can be generated on a cutting center consisting of a fabric roll storage tower, from which the fabrics automatically are brought to a feeder unit, which supplies a digital cutter, where the nestings are cut out, a gripping unit, which picks the cut-pieces from the cutter table and lays them down in a drawer storage, in which the cut-pieces are brought to a robot cell (see Figure 6):

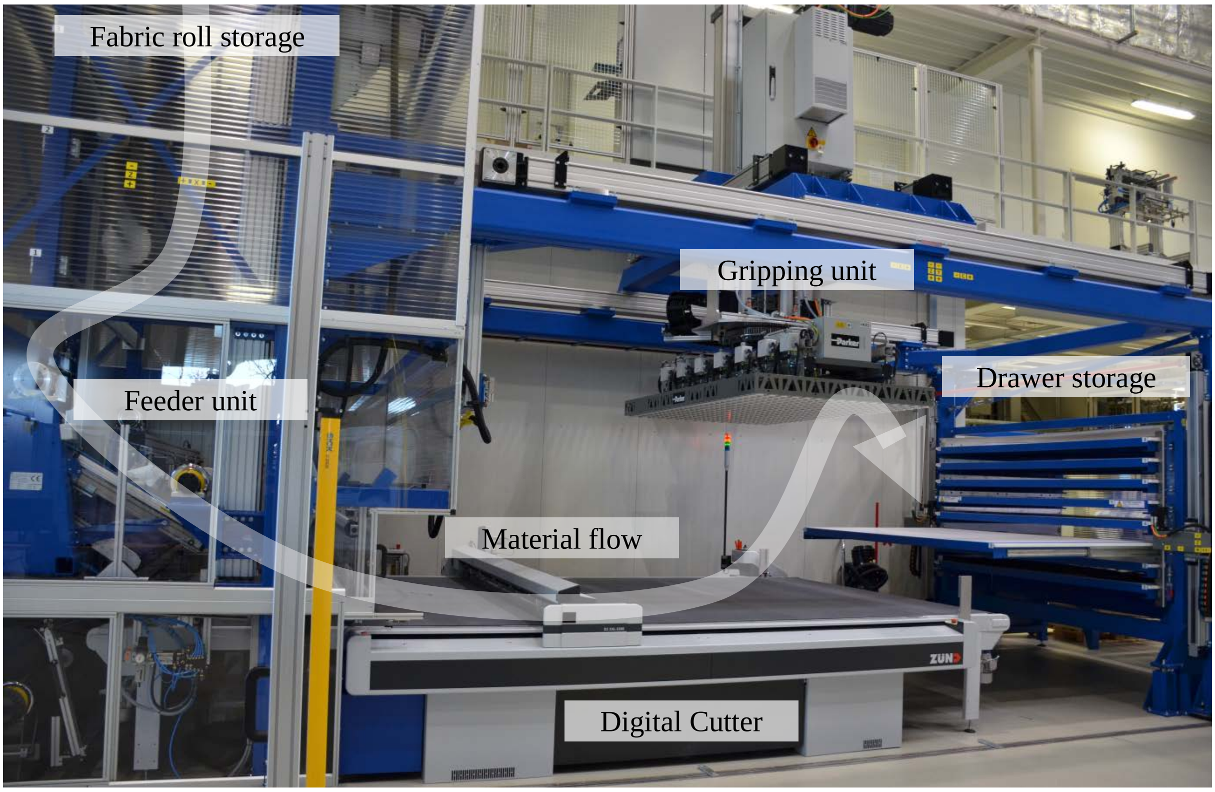
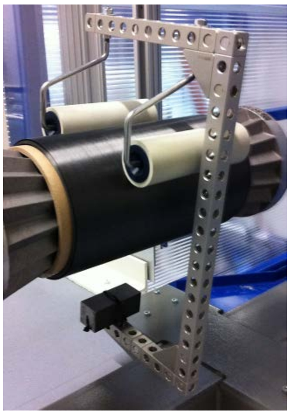


Figure 6: DLR’s cutting center with movable drawer storage system.



The cutting center as well as the later described pick and place process are designed to handle various semi-finished goods like uni-directional (UD) tapes, non-crimp fabrics (NCF), wovens but also foils, paper or even sheet goods like thin consolidated organo sheets. To achieve this special add-ons or adjustments have to be undertaken depending on special material characteristics or behavior. For example if there is the need to process transparent thin foil, then the beginning of the roll has to be stiffened out a little bit and made opaque so that the laser-sensor can register it. Or if there is the need to process bending resistant rolled goods e.g. thermoplastic impregnated fabrics with a high impregnation degree like UD tape, then the residual stress in the material makes it necessary to avoid de-spiraling of the roll e.g. with a clamping mechanism as shown in Figure 7

Figure 7: Example of a clamping mechanism to hold down bending resistant rolled goods like UD tape while being fed to the cutter.

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3.2 Automated handling of cut-pieces on cutter table and lay-down in drawer storage

Because the surface of the cutter is limited, cut pieces have to be physically removed from the cutting table at certain times in order to allow ongoing processing. To automate the cut-piece handling a 4 degrees of Freedom (DOF) axes portal kinematic with a gripping unit is installed above the cutter table. The manipulator is equipped with 432 electrically powered vacuum grippers which can be controlled independently. Cut-pieces are removed from the cutter surface by lowering the gripping unit on the cut-pieces. Only the vacuum grippers covering the surfaces of the desired cut-pieces get switched on, applying adhesive forces between grippers and cut-pieces. By lifting the gripping unit the cut-pieces get separated from the remaining waste and can be placed in a drawer storage for further processing. Once all cut-pieces are removed, the waste gets disposed into a recycling box placed in front of the cutter by moving the cutters conveyor belt forward. The described process can start over with section 3.1.

To fulfill todays requirements of a fully automated, flexible and reliable production process, a software solution had to be developed that generates optimal control commands for both the described cutting and handling process. By solving complex and interrelated optimisation problems [5] it enables an efficient production with minimal waste and without time-consuming physical reconfiguration of hardware or manual changes to the executable machine program.

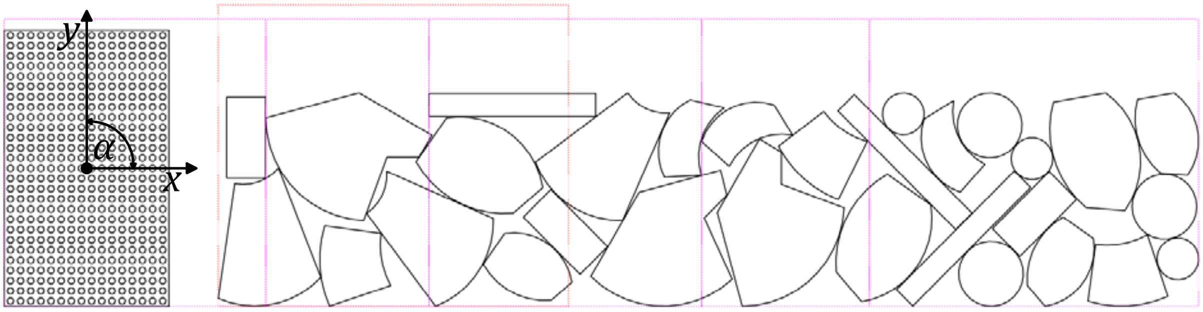

Figure 8: Handling of cut-pieces in 3 DOFs (2 translations, 1 rotation) under constraints.

3.3 Automated supply of cut-pieces to a robot cell

As soon as the drawer storage device mentioned in 3.2 is completely filled with cut-pieces, it can be driven to a receiving robot cell with a mobile logistic unit. The mobile logistic unit can be either an automated guided vehicle (AGV) or a manual controlled platform (Figure 9). By using multiple drawer storage devices a continuous flow of cut-pieces can be provided to one or more robot cells.

Figure 9: Drawer storage with cut-pieces on its way to a robot cell.

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4 Production of of tailored preforms – robotic pick and place process

In the robot cell the supplied cut-pieces are then processed by a robot based end-effector, which detects and grips the cut-pieces, lays them down in a tooling (which can also be weakly curved, like a part of an aircraft fuselage, see Figure 10) and fixates them with ultrasonic welding. Both the gripping with vaccum and fixation with ultrasonics enables a fast and material-friendly processing of various materials.

Figure 10: Robotic pick and place end-effector in robot cell (top left: on board view).

4.1 Automated cut-piece detection system

One major advantage achieved by the use of tailored preforms is the enhanced degree of freedom in part design. This comes with additional requirements for automation, because now there is a multitude of individual cut-pieces that causes conventional automation concepts, like aligning the cut-pieces by stoppers, to fail. A good concept is to store position and orientation of the cut-pieces after cutting (compare section 3.2). A better concept, that also compensates mechanical deviations due to machine imperfections or uncontrolled movement of cut-pieces e. g. during transport, is to equip the production system with computer vision capabilities.

In our use case we mounted an industrial GigE vision camera together with a powerful flash illumination to the robot’s gripper. Software for identifying cut-pieces and determining their positions was developed and thoroughly tested in combination with the industrial robot. The preferred method concerning robustness and accuracy was rotational template matching in combination with border following [11]. The 2D-shapes of the cut-pieces are used for generation of rotated, correctly sized bitmaps which are matched to the camera image, what yields good true positive detection rates but has difficulties in distinguishing similar cut-pieces, what can be compensated by a subsequent border following step. Robustness of the detection is very important due material undulations we experienced in our samples. After transformation to the robot’s coordinate system the cut-pieces can be processed autonomously. Concerning overall accuracy a standard deviation in the range of 0.2 mm may be obtained for pick and place of “flat” materials, for an undulated material accuracy is reduced to the range of approx. 1-2 mm.

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4.2 Process automation

Autonomous processing requires a system architecture that is capable of generating the required actions from a generic description. A good part of this description is found in the plybook, but there is still the need for some further meta information, namely points and orientations where to grip and where to drop the cut-pieces [11], which vacuum cups to activate for gripping, where to weld the cut-pieces and the correct layup order. The plybook plus the meta information is passed to a manufacturing execution system (MES) that carries out all necessary steps (Figure 11).

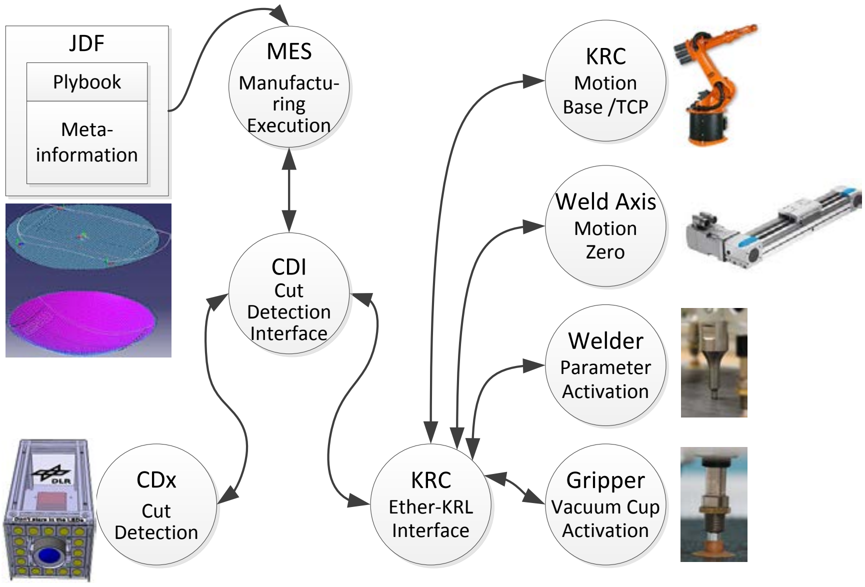

Figure 11: Robot system layout.

The MES converts the generic description of a job definition file (JDF) to robot events like robot movements, base or tool change and I/O switching, which are passed by a cut detection specific interface layer to the robot interface, in our case a KUKA technology package for Ethernet-communication with a KUKA KRC 4 control. The subsystems are subsequently controlled by the KRC 4, what gives the user a well-known and easy to change environment. The events generated by the MES trigger parametrized robot modules by sending command messages to the Ethernet-KRL interface's main command loop.

5 Conclusions and Outlook

With this paper the authors tried to show different technologies and approaches for a continuous automation of the process chain from fabric delivery to a tailored preform – ready for consolidation. The next research steps focus on an automated and reproducible supply of cut-pieces to the robot cell with an intelligent cell interface, including different opening and closing techniques for the drawers. In addition the whole process chain will be evaluated and optimized by its main cost drivers like process time, energy consumption or invest.

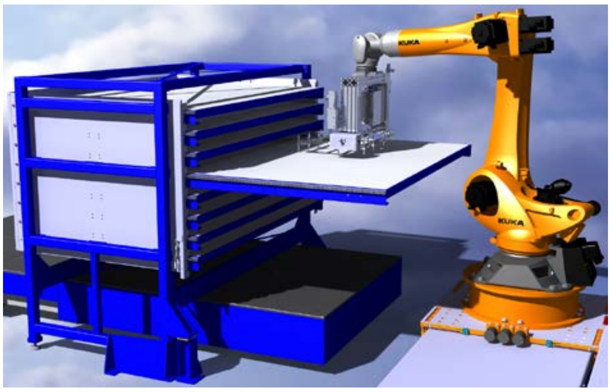

Figure 12: Automated supply of cut-pieces to a robot cell with drawer storage.

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References

[1] S. Gubernatis, R. Freitas: “Lösungsansätze für eine vernetzte Produktion von Hubschrauberstrukturen mit geringen Stückzahlen – Forschungsprojekt iPro” conference contribution to German Aerospace 2015, Rostock, Document-ID 370209, http://www.dglr.de/publikationen/2015/370209.pdf

[2] A. Deterts, A. Miaris, G. Soehner: “Serial Production of Thermoplastic CFRP Parts for the Airbus A350 XWB”, ITHEC 2012, Bremen

[3] F. Oxenbauer, M. Kuehnel: „Erforschung von FEM-Simulationsstrategien und Einspannkonzepten mittels PAM-Form zur Umformsimulation endlosfaserverstärkter Thermoplaste“, DLR internal report DLR-IB 435-2015/22, March 2015

[4] Fraunhofer SCAI data sheet about *AutoNester-T*: http://www.scai.fraunhofer.de/content/dam/scai/de/documents/Mediathek/Produktblaetter/OPT_Autonester_T_DE.pdf

[5] R. Glück, “A Heuristic Denesting Algorithm,” in EuroCG 2016, Lugano, Switzerland, March 30–April 1, 2016.

[6] M. Kuehnel, A. Schuster, A. Buchheim, T. Gergross and M. Kupke, „Automated near net-shape Preforming of Carbon Fiber Reinforced Thermoplastics (CFRTP)”, Paper for the ICS of the JEC Europe 2014, Paris, March 11-13, S. 2f, elib.dlr.de/86585/1/2013-11-18%20Paper%20JEC%20Europe%202014.pdf (28.12.2014)

[7] M. Kuehnel, A. Schuster, A. Buchheim, M. Kießig, T. Gerngross, M. Kupke, „Automatisiertes endkonturnahes Preforming carbonfaserverstärkter Thermoplaste mittels robotischer Halbzeugablage", conference contribution to German Aerospace Congress 2014, Augsburg Document-ID 340052, www.dglr.de/publikationen/2015/340052.pdf (21.04.2015)

[8] Schuermann, H.: “Konstruieren mit Faser-Kunststoff-Verbunden” (2. Ausg.), S. 640, Berlin, Springer-Verlag, 2009.

[9] A. Schuster, „Computer Vision für die CFK-Produktion - Autonomes Greifen von individuellen Preforms”, contribution to the working group “automisation” of Carbon Composites e. V., 27.03.2014

[10] A. Schuster, T. Schmidt, „Computer Vision für die CFK-Produktion: Autonomes Greifen von individuellen Preforms”, Kongressbeitrag Deutscher Luft- und Raumfahrtkongress 2014, Document-ID 340022, www.dglr.de/publikationen/2014/340022.pdf (27.12.2014)

[11] A. Schuster, „Autonomes System zur Herstellung von Organoblechen und Preforms“, Dissertation, University of Augsburg, https://opus.bibliothek.uni-augsburg.de/opus4/files/3410/Dissertation_Alfons_Schuster.pdf (04.12.2015)

Excerpt from ISBN 978-3-00-053387-7