HIGHLY AUTOMATED MANUFACTURING PROCESS CHAIN FOR LARGE DOUBLE CURVED CFRP AIRCRAFT PARTS

M. Malecha[1], C. Frommel[1], M. Köerber[1], M. Mayer[1]

[1]Institut für Bauweisen und Strukturtechnologie, Zentrum für Leichtbauproduktionstechnologie, Deutsches Zentrum für Luft- und Raumfahrt , Am Technologiezentrum 4 86159 Augsburg, Germany
Email: Marcin.Malecha@dlr.de, Web Page: http://www.DLR.de/Augsburg

Keywords: automation, manufacturing process, rear pressure bulkhead, pick&place, double curved, gripping, dry textiles

Abstract
Application of novel materials in modern aircraft often goes along with challenges regarding to the manufacturing. The state-of-the-art carbon fibre reinforcing plastics (CFRP) for aircraft parts are still manufactured mostly in manual labour and therefore there is high demand for automation. Large, double curved parts, provide additional requirements concerning logistics and processing. As an example, the rear pressure bulkhead (RPBH), is an excellent sample for such aircraft part made entirely from CFRP. Our work aims to automate the whole manufacturing process of RPBH including quality assurance and manufacturing execution system (MES) which interlinks many high complex sub-processes. We will discuss our concept for the process, the reached status with emphasis on the most advanced sub-process of pick&place of reinforcing plies and give a short outlook for the future. The recent results show expected benefits of our solution compared to manual manufacturing regarding to quality, robustness, manufacturing times and costs. For the first time, the implemented MES allows to embed the process in industry 4.0 manufacturing environment.

1. Introduction

The high demand for digitalisation of the production processes forces the manufacturers to evaluate and change their well-established processes towards the guidelines for industry 4.0 and the ideas of the so called factory of the future. The benefits are variegated ranging from better organised and automated work flow to simply lower costs. In the contrary, the high investment and necessary modifications of the processes are the negative aspects that have to be brought into account. Therefore carefully balancing of the pros and cons for each process has to be carried out. One of the aircraft parts we investigate towards automation of manufacturing is the rear pressure bulkhead (RPBH) of the Airbus A350. This exemplary part provides us with challenging features: the size is up to 5 m, the geometry is double curved, its highly complex due to the high variety of the different cut-pieces necessary for the build up, the convex construction method and the fact, that it is, as state of the art, built almost entirely in manual labour. Fig. 1 (left) shows RPBH built manually in project AZIMUT [1]. For the manual manufacturing process see Fig. 1 (right). In the beginning the material (carbon fibre fabric with atlas weave) is preheated to increase the stiffness to necessary extend for manual handling. Then plies are cut and transported to the preforming cell. With the help of two or more workers, the cut-pieces are brought into the mould and draped manually to the shape projected on moulds surface. The quality assurance is done mainly by visual inspection regarding the edge position and appearance of the sheared fibres. The preforming is completed by manual integration eight stringers. At the end, vacuum bagging is preformed. The

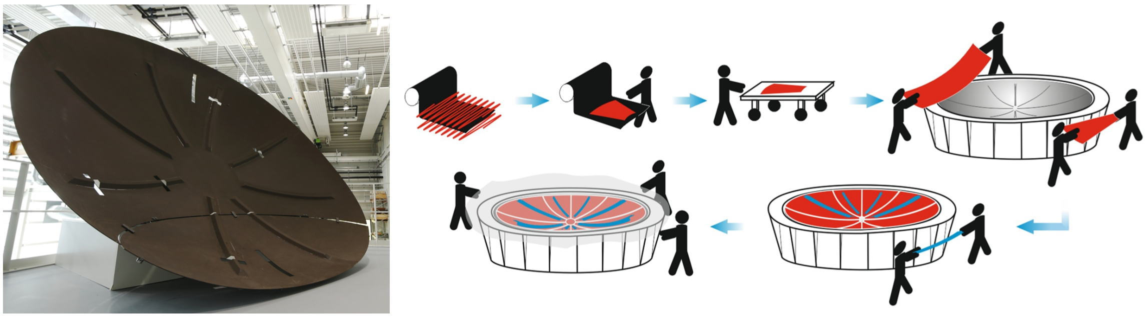

Figure 1. left: rear pressure bulkhead built in Project AZIMUT, right: current manual process for manufacturing RPBH. Single process steps are explained in text above.

main disadvantages are the high demand for manual labour, often in uncomfortable working posture, mandatory material preconditioning, lack of quantitative quality assurance, non-robust manufacturing quality due to human factor.

Addressing the flaws of manual process, we have developed an automated approach for the complete manufacturing process, including the material delivery, the preforming with included quality monitoring, integration of stringer and the vacuum bagging. The automated process is shown in Fig. 2. The process is controlled and monitored by designated manufacturing execution system (MES) based on the open source OPC UA architecture. The MES is highly modular and flexible and can be easily adopted to changed or extended process. The MES is the integrating tool for the sub processes, it orchestrates the integrated members in the process chain, distributes and collects information to and from the process participants. It also manages the acquired data from the quality assurance measurements.

In the following, the single process steps will be presented regarding their desired functions and acquired readiness so far.

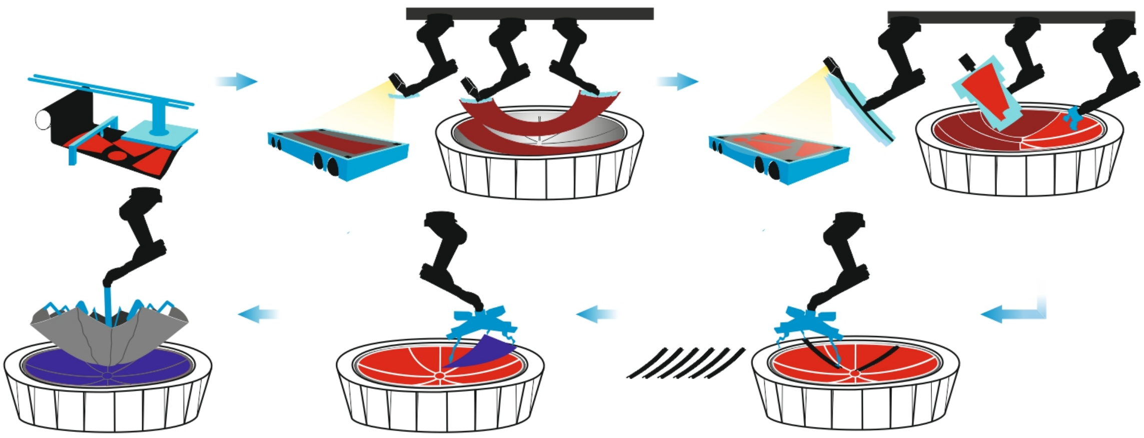

Figure 2. Scheme for automated manufacturing process. For explanation please see sections 2 and 3.

2. Automated approach

2.1. Cutting and transporting cut-pieces

The material used for all cut-pieces requires no longer pre-conditioning and can be used right from the roll. The automated cutting machine (cutter) uses deliberated algorithms for nesting cut-pieces (focusing on waste reduction or build-up sequence) and uses automated seven level drawer to store or buffer the cut-pieces. From there (or cutting space) reinforcing cut-pieces are picked up and transferred onto transport system via automated pick&place manipulator within the cutter. The transport system, in our case a palette (1.5 m x 1.5 m), is large enough to receive the largest reinforcing cut-piece or few smaller ones and due to its little weight can be moved by one person while mounted on movable rack or small autonomous guided vehicle. The transport system delivers the cut-piece to the pick-up zone within robotic cell.
For long structural plies, transport is different and the cut-pieces are cut strict in the sequence order. After cutting, the cut-piece is rolled on large diameter tubes and fixated. The tube is then transported to the robotic cell, where the cut-piece is unrolled on long pick-up tables.

2.2. Preforming

The preforming of the RPBH is done in three steps: the first four layer of structural plies, several layers of reinforcing plies with large variety of shapes and sizes and the second four layer of structural plies. In summary, there are almost 60 different cut-pieces that have to be applied into the near to 5 m diameter large concave mould. For each, structural and reinforcing cut-pieces, two different technologies have been developed. First, we show the approach for the long cut-pieces making the bulk structure and then in greater detail, the approach for large diversity of reinforcing plies section 3).

2.2.1. Structural plies

The starting point of this sub-process is cut-piece lying on pick-up table. For the pick&place two robots on linear axis and equipped with line-grippers are used in co-working mode. Each gripper is build from seven identical modules with nine bellows suction cups and which are connected in row via ball joint. Therefore the modules can be twisted and rotated regarding to their direct neighbours and reproduce every spline on the surface of the RPBH mould. Because of the non-symmetry of the RPBH, for each cut piece both of the grippers have to be adjusted to the target geometry. This is accomplished by the adjusting station where the position of every module of the gripper is measured and the adjusted to the target geometry.
Once both grippers have proper geometry for provided cut-piece, they grip the short ends preforming rolling movement from one module to the next assuring desired preforming of both ends of the cut piece (Fig 3 (left)). Simultaneously, both gripper pick up the cut-piece, which now has the shape of a catenary curve, and transfer the cut-piece into the mould. To deploy the cut-piece, both grippers descend into the mould for their target positions (Fig. 3 (right)).
The current development deals with autonomous detecting and gripping of cut-piece, using the same technology implemented in the reinforcing plies sub-process, see section 3. Furthermore an autonomous path generating system CoCo (Collision-free Cooperation, [2, 3]) is currently under investigation to be implemented as well. Thus will make the entire sub-process autonomous: each cut-piece is automatically detected, gripped, transferred and dropped into the mould with mostly autonomously generated robotic paths.

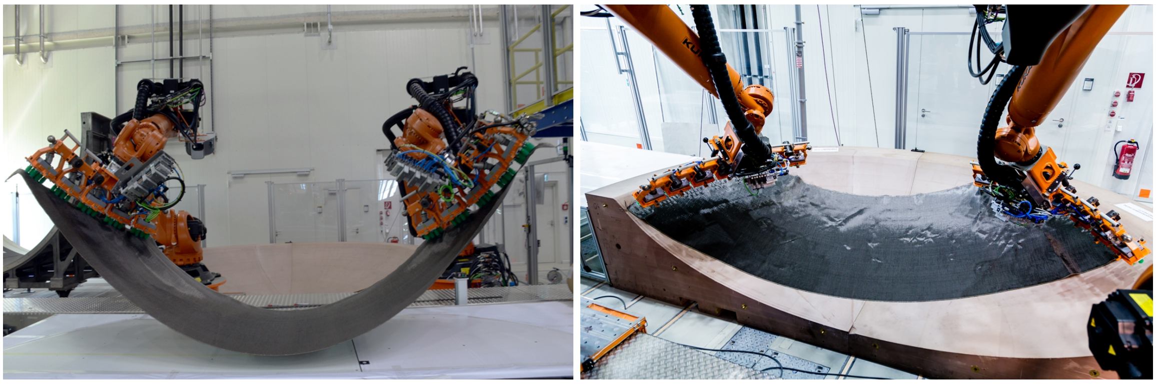

Figure 3. Preforming of long structural plies with two co-operating robots.

2.2.2. Quality assurance

To determine the quality of the preformed cut-pieces two automated methods have been developed: measurement of the fibre angles and position of the cut-piece edge. The equipment (ProFactor-Camera and Laica T-Scanner) is mounted on a robotic portal. They can be used successively to gain data for the complete cut-piece deployed or for selected areas of interest. The data can be referenced to previous calculated data or to boundaries set for given tolerances and thus build a decision criteria whether the reached quality meets the requirements. The data is stored in process data base and can be used for documentation or analysis purpose.

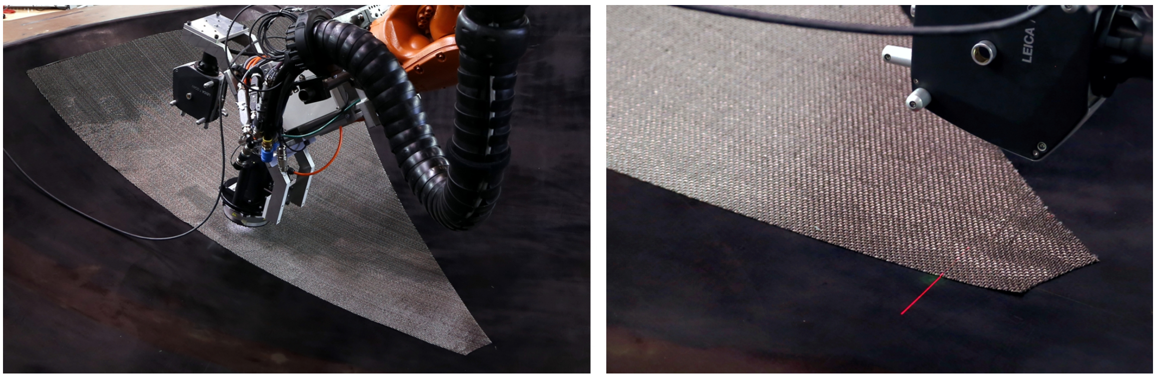

Figure 4. Implemented quality assurance methods, here for reinforcing plies: left: fibre angles, right: edge detection.

2.3. Stringer integration, vacuum bagging and infusion

For the sub-process of integration of stringer elements and the build up of vacuum bagging a developed multicinematic gripper is used. A six-axis light weight robot is mounted on an industrial robot which gives additional degrees of freedom to handle the fragile auxiliary materials. The eight stringers are picked up from a repository and deployed to their target positions in the mould. The prepared auxiliary materials are picked up, similar to reinforcing plies, and laid over the preform. Due to the large extent of the sub-process and because it is only semi-automated, it will be not further discussed in this paper.

3. Reinforcing plies

3.1. Process description

The application of reinforcing plies as an example of hight automated sub-process will be discussed in greater detail in the following. The large number and variety of the geometries and their distribution over the almost entire circumference of the mould make this sub-process the most interesting regarding to an intelligent and high-cycle manufacturing process. The draping occurs during transport movement from the pick-up position to the mould and is carried out by specialised modular gripper developed by DLR and Schmalz GmbH for the project AZIMUT ([1, 4]). The gripper contains 127 modules with Coanda-effect based gripping surfaces which are connected linewise by joints as ribs. The ribs are connected along the center symmetry line by glass fibre rods creating a spine which curvature can be adjusted by three linear actuators. The construction of the modular gripper is shown in Fig. 5 (left) where the ribs are marked with red and the spine with blue lines. This construction allows to reproduce the surface of the mould on almost every position by the modular gripper. Additionally, twenty of the 127 modules carry optical sensors which can detect and measure the movement of the material attached to the surface of the gripper, see Fig. 5 (middle). The acquired data represents the movement vectors of the material and therefore allows to study and monitor the draping process of the cut-piece (Fig. 5 (right)). Similar to the manual draping, some areas of the cut-piece have to be hold firm and show no movement at all (seed points) and others should move along calculated vectors. The holding force can be programmed for every module prior to the draping process or in-situ controlled on the basis of the sensor data. In the planned validation of the process only the first approach will be implemented. The gripper also is equipped with a camera for cut-piece recognition.

The sub-process follows strict sequence: The MES requests the next cut-piece from the cutter. The cut-pieces are nested on the basis of chosen algorithm (minimal waste, process sequence), cut and buffered or sorted out onto the transport system. The MES sets the destination for the transport system and waits till the arrival. After docking to the station in the robot cell, the transport system is hold in position and the robot with mounted modular gripper is moving into position above the cut-piece. The camera on gripper makes top-view picture of the tray and cut-piece and the algorithm tries to match the cut-piece on the tray to the shape of the next ply regarding to the draping order. If the ply is successfully identified the robot moves the gripper directly over the ply and shoots second picture of the cut-piece and reference points on the tray to determine the position of the cut-piece with greater precision. With the position of the cut-piece and the recognised ply, the systems generates path for the robot to place the gripper flat and very accurately onto the ply with the desired position of the ply regarding to the surface of the gripper. Then the Coanda-grippers are switched on and the cut-piece is sucked onto the modular grippers surface. While moving upwards, the modular gripper transforms form 2d into 3d geometry draping the cut-piece

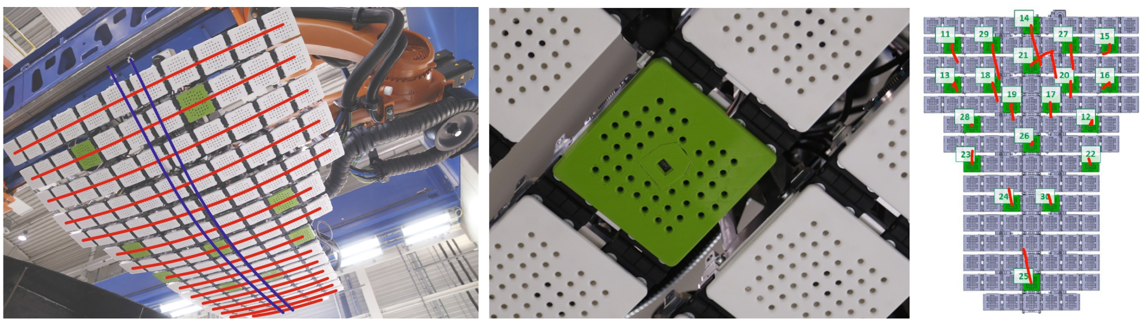

Figure 5. left: Modular gripper with market ribs (red lines) and spine (blue lines), middle: optical sensor integrated in module, right: data for material movement during preforming.

to the target geometry. The values for the actuators and the strength of the Coanda-grippers are, similar to the grip points, read from provided data base. During the transformation, the movement of the cut-piece on the grippers surface is monitored via optical sensors in modules [5]. After the draping the robot moves the gripper into the mould and above the target position and moves downwards until the contact with the mould surface. The Coanda-grippers are switched off and robot moves upwards and then into home position leaving the cut-piece in the mould. During the application of the cut-piece, the transport system is released from the docking station and moved back to the cutter. From here, all the steps are repeated for the remaining reinforcing cut-pieces. On behalf of clarity, the step for fixation of the ply is not mentioned.

After placing the cut-piece, a second robot equipped with fibre angle measuring camera and 3d laser scanning sensor are used to measure the position and the draping quality of the applied ply. While for the recognition of the plies contour the scanner has to be moved along the edge, the fibre angle measurement can cover the full surface of the ply or just single positions for quality assurance reasons.

In following the drape mechanism will be explained in greater detail. The starting point for this process step is the cut piece on the tray, ready for the pick-up. The shape and number of the ply is determined via optical recognition subsystem as well as the exact position and orientation of the ply within the tray. To create the pick-up movement the system uses a look-up-table, where the necessary parameter for the pick-up and draping are stored for each cut-piece. From there, the position of the grip points, i.e. where specific areas or modules of the gripper have to be placed on the cut-piece, are read out and transferred to the position of the tool center point (TCP) of the gripper. This set of coordinates and the current position of the robot are used to generate robot path to move the gripper into the exact position on the cut-piece. When the Coanda-grippers are switched on, the holding force of every module is set accordingly to the provided look up table for the particular ply. This allows to set the exact draping pattern where the materials can be fixed (seed point) or allowed to move (draping movement) with many configurations possible and fitting the simulation for the particular ply. During the transformation of the surface of the gripper from 2d into 3d the modules are moved apart and the material is stretched according to the set draping pattern where the material has to be hold or allowed to move. As a result, the fibres of the material (0° and 90°) are sheared and the fibre angles change. Additionally, the gained data from the optical sensors (movement vector of material over time) in the modules can give instantaneous prediction if the draping occurs as expected. This data was very valuable during the pre-tests with generic cut pieces to gain knowledge about the draping mechanics and to generate look up tables for the original cut-pieces for the RPBH. The target geometry of the grippers surface was extracted from the CAD data of the mould and by means of parametrised relationship between the position of each module and the state of actuators adjusted accordingly [6].

3.2. Process validation

During the validation experiments three different original cut-pieces were deployed into the mould. For each geometry the first ten cut-pieces were draped by using appropriate target geometry of grippers surface and systematically adjusted holding force on each module. Collected data during the draping, analogue to the previous experiments with generic plies, were used for fine-tuning of the holding force for each module for the remaining plies for this particular geometry until the best possible outcome was reached.

The validation process was highly automated: the ply recognition and path generation, as well as the draping, deploying and post-process measurement of the fibre angles and contour was done without or with minimal manual intervention. Only placing the ply on the pick-up table and providing double sided adhesive tape to the draped cut-piece on the gripper was done manually. Therefore almost any influence of the manual handling can be neglected for the discussion of the results.

Regarding to the quality, the draping of the cut-piece is highly repeatable and thus the process can be

considered as stable, the draping movement is continuous and so is the strain in material steady and even, in contrary to the manual draping where the strain is applied rather non-uniform, according to the fibre angles measurements after the dropping of the cut-piece. Unfortunately, although the vast majority of the cut-piece lies almost exact along the target contour, there are small deviations from the optimum. Considering the data of the optical sensors, the deviating regions are characterised by shorter movement vectors and shorter fibre lengths and therefore allow only small draping movements. This flaw can be solved by optimising the mechanical properties of the gripper and/or computing adjusted flattening for the cut-pieces. Fig. 6 shows the experimental setup and the results for one exemplary cut-piece.
Considering the process time, the automated approach allows to apply one cut-piece (start to finish from home position, estimated) in approximately one Minute, delivering draping data from the optical sensors. The manual process from material delivery to the draped cut-piece, takes at least about five times longer process time without any quantitative quality assurance applications. Therefore the automated approach for the reinforcing plies has huge potential to reduce the manufacturing cycle time.

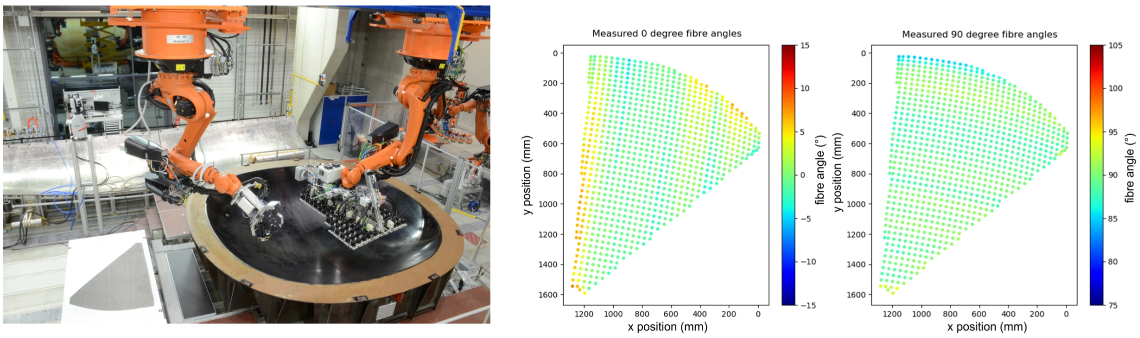

Figure 6. left: Experimental setup for for sub-process *reinforcing plies* validation, right: fibre angles data measured after cut-piece deployment.

4. Full scale validation

The validation of the entire process is planned for the fall 2018. The described sub-processes are to be brought in one throughout process and integrated via manufacturing execution system. The goal is to manufacture full-size demo part with high grade of automation and fulfill the standard requirements and conditions for aviation industry. The modular nature of the developed MES allows to easy expand or change controlled processes so depending on the maturity of each sub-process the final extent of the automation to validate will be chosen shortly before the validation and depends on the achieved progress. After the validation the achieved results, performance of each sub-process and the integrated process will be analysed comparing to manual process regarding to process times, quality and costs. Furthermore recommendations for further improvement will be finalised.

5. Conclusion

We are confident, that the presented automated solution will have major positive impact on manufacturing of large aircraft components in dry fibre process. The change of manufacturing process of this particular example, the rear pressure bulkhead, from entirely manual to high-level automation should vastly decrease manufacturing costs and ramp-up the process cycles alongside with higher and more stable part quality. But one of the most significant advantages is the implementation of industry 4.0 standards. This aspect is crucial for the perspective of sustainable manufacturing processes towards concepts of factory of the future and big data. Therefore a high invest, beside the economical business case, can be justified as an invest in future technologies and R&D affiliated projects. The exact analysis is however possible after the validation on full-automated and full-size demonstrator as described in section 4 and planned for the end of year 2018.

Acknowledgments

We would like to thank our colleagues at the Center for Lightweight Production Technologies for their excellent work and endurance. Our gratitude goes to our colleagues at Premium Aerotec GmbH. Were grateful for the financial support provided by Federal Government according to a decision of the German Federal Parliament, the Federal State of Bavaria, and the City of Augsburg.

References

[1] Dorothea Nieberl. Automatisierung zukunftsweisender industrieller Methoden und Technologien für CFK-Rümpfe (AZIMUT-ZLP) im Verbund AZIMUT, 2015. Abschlussbericht.

[2] Lars Larsen, Jonghwa Kim, Michael Kupke, and Alfons Schuster. Automatic path planning of industrial robots comparing sampling-based and computational intelligence methods. *Procedia Manufacturing*, 11:241–248, 2017.

[3] Alfons Schuster, Michael Kupke, and Lars Larsen. Autonomous manufacturing of composite parts by a multi-robot system. *Procedia Manufacturing*, 11:249 – 255, 2017. 27th International Conference on Flexible Automation and Intelligent Manufacturing, FAIM2017, 27-30 June 2017, Modena, Italy.

[4] Tobias Gerngroß and Dorothea Nieberl. Automated manufacturing of large three-dimensional CFRP parts from dry textiles. *EAS Aeronautical Journal*, 7, 2016.

[5] Marian Körber and Christoph Frommel. Sensor-supported gripper surfaces for optical monitoring of draping processes. November 2017. SAMPE Conference 2017.

[6] Christoph Frommel, Marian Körber, Monika Mayer, Alfons Schuster, and Marcin Malecha. Autonomous preforming system: Automated and sensor-aided handling of dry carbon fibre textiles. October 2018. IROS 2018, Madrid, Spain, submitted.