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Robot preformed CFRP rear pressure bulkhead as an example for highly automated manufacturing of large carbon fibre aircraft parts

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Abstract

We present our approach to an automated solution for high quantity manufacturing of a Rear Pressure Bulkhead from carbon fibre reinforced plastics in one overall process using several robots in a single robotic cell. The process contains sub-processes such as cutting and delivering material, preforming cut-pieces and in-situ non-destructive testing. The focus is set on the sub-process of preforming, where many different plies (structure and reinforcing) are identified, picked-up, draped, transferred and laid-up into the mould. Online sensors as well as subsequent measurements of fibre angles and the exact position of the placed plies provide data for process monitoring and quality assurance documentation. The paper presents the design of the overall process and its possible implementation in factory environment as well as the latest stand of the development. We also discuss the comparison between our solution and the current manual manufacturing process.

Keywords: automation; carbon fibre reinforced plastics; aircraft structure part; manufacturing process; robot; draping; pick&place; vacuum bagging; industry 4.0; cutting; nesting; gripping

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Nomenclature

CFRP	Carbon Fiber Reinforced Polymer
RPBH	Rear Pressure Bulkhead
VAP	Vacuum Assisted Infusion Process
MFZ	Multifunktionelle Zelle (Multifunctional Robotic Cell)
DCS	Distributed Control System
AGV	Automated Guided Vehicle

1. Introduction

The technological benefits of using CFRP materials are often impaired by high manufacturing costs, especially in small series production driven industries like the aerospace industry. This is particularly true for large parts or components with complicated and/or double curved geometry where the handling of flexible dry textile materials is mandatory. Due to lack of proper handling tools almost the entire manufacturing process is usually done in manual labour. This affects the manufacturing costs, the production cycle and the manufacturing quality to a high degree. The increasing utilisation of CFRP parts in modern aircrafts result in a higher demand for highly automated manufacturing solutions from aerospace industry.

2. State of the art

The rear pressure bulkhead (RPBH), shown in Fig. 1 (a), was one of the first large aircraft structures made of CFRP materials and is utilised widely in a variety of modern aircraft types among aircraft manufactures. The manufacturing process in this paper is based on the process performed at Premium Aerotec GmbH in Augsburg for the A3X0-aircraft family. In our research we try to be as close as possible to the original process using the same tooling geometry, materials and tolerances for generic plies.
The original process contains many single process steps which are mostly done in manual labour. Fig. 1 (b) shows the process divided into major steps described in Table 1.

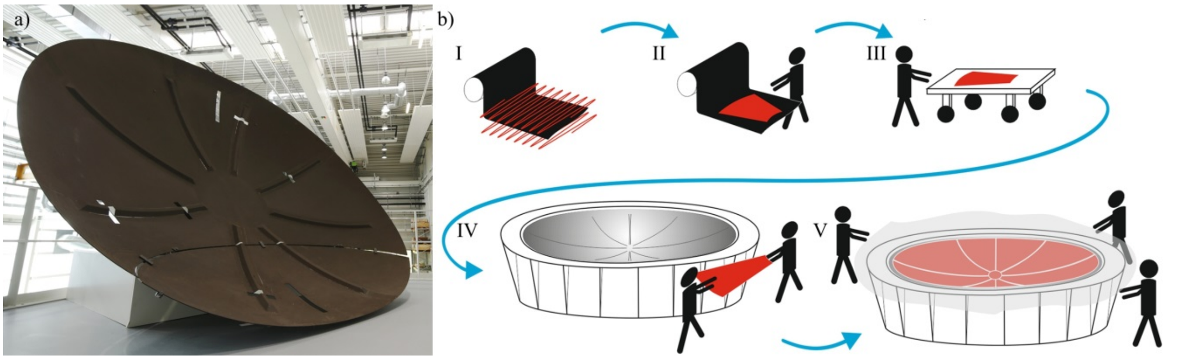

Fig. 1 (a) RPBH manufactured manually in Project AZIMUT, (b) scheme of original manual process (infusion and finishing are not depicted)

Table 1. Manual process from Fig.1 (b).

#	Sub-process	Action
I	material preparation	the material is heated up to increase material stiffness due to melted thermoplastic fibre woven into the fabric
II	material cutting	the plies are cut by programmed 2D cutter and then transferred manually on a tray
III	material transport	the trays are moved by workers to the tool station
IV	material applying (preforming)	the material is picked up and draped by one or more workers into the mould. The target position is shown by laser projection on the mould surface
V	vacuum bagging	auxiliary materials are applied in manual labour by one or more workers

The subsequent Vacuum Assisted Infusion Process (VAP) and the finishing complete the manufacturing but are not part of the considered process in this paper. The challenges of the process lie in the double curved shape of the RPBH, high diversity of size and shape of the used plies (full-width and 5 meters long structure plies and complex-shaped, polygonal plies up to 2 meters as reinforcing plies), the easy drapeable and thus rather unstable material and the amount of the material.
The current manufacturing almost throughout the whole process is done in manual labour. This results in high

costs, low scalability and worker dependent quality. Therefore, demand for automation is very high and with the RPBH as a life-size generic CFRP part of an aircraft structure the solutions achieved in this project can be transferred to other components made of dry textile materials. So far, most automation approaches dealt with the picking & placing of the plies. Our research should present a well-coordinated solution for the process as a whole with greater emphasis on material logistics.

3. Automated Approach – continuous process

The aim is to develop a manufacturing process for large complex aircraft structures in CFRP design. We use the Multifunctional Robotic Cell (Multifunktionelle Zelle, MFZ) at the Center for Lightweight Production Technology (ZLP) as the heart of the auto mated manufacturing process (Krebs et al. (2013). The MFZ is 30 meters long, 15 meters wide and 7 meters high. The center beam of the gentry-like system contains three 6-axis robots (KUKA KR210), the side beams three 5-axis portals. The MFZ is shown in Fig. 2(a). This highly flexible and modular robotic cell can be divided into single work areas where the robots can act simultaneously as a team or independently. The layout for the automated process – resulting from the given layout of the facility – is shown in Fig. 2(b). The area of the multifunctional robotic cell is divided into two zones: zone A is occupied by other project where zone B is available for the RPBH manufacturing. C is the cutter station, D the mould for the RPBH. E stands for two 6-axis robots and one 5-axis portal. H (light grey coloured area) stands for the paths for the material (red for reinforcing plies, blue for the structure plies). The plies are provided at transfer stations F and G. While the delivery at the station F can be achieved without interrupting the automatic mode of the MFZ, due to the limited resources for necessary modifications of the robotic cell the delivery at stops the automatic mode for safety reasons. Concepts for safety-sufficient delivery of structure plies are currently in discussion. The developed process aims to cover all the necessary steps from the manual process in Fig. 1 (b) with the highest possible order of automation. The desired process workflow is shown in Fig. 3 (a) were the single steps are listed in Table 2.

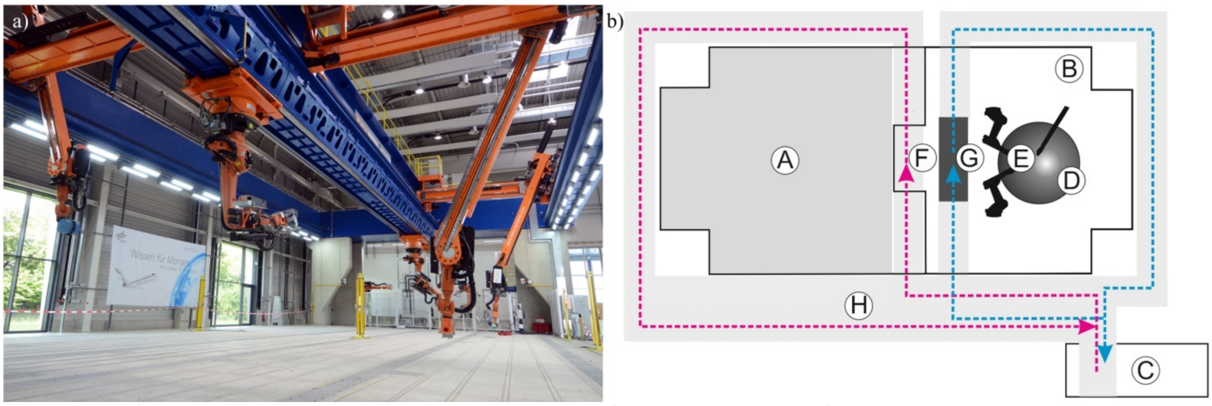

Fig. 2 (a) Multifunctional Robotic Cell at ZLP in Augsburg, (b) layout for the material logistics for the automated process

Table 2. Automated process from Fig. 3 (a).

#	Sub-process	Action
I	material cutting	each ply is automatically nested, picked up and transferred to the transporter
II	material transport	one or more plies are transported autonomously to the robotic cell (MFZ)
III	material applying (preforming)	the material is picked up, draped and laid into the mould with one robot tool. The applied ply is measured by the means of its position and drape quality with second robot
IV, V	vacuum bagging	auxiliary materials, membrane and vacuum foil are semi-automatically applied on top of the preform

The process is orchestrated and monitored by a distributed control system (DCS), whose architecture is shown in Fig. 3 (b). The DCS is based on the OPC UA standard and contains interface nodes (representing hardware) and virtual nodes (as connection point for digital services, for example to orchestrator and database). The DCS is highly modular and allows connection of further nodes in the future and services outside the DCS.

3.1 Process chain

The developed process chain contains sub-processes, which were researched during a different project as isolated applications (Nieberl (2015)). The challenge in this project was to reach sufficient level of maturity of each sub-process and to link them into one continuous process where the material and data is exchanged between the sub-processes without any interactions from the outside of the running process. This allows integration the process into any kind of *smart-factory*-based manufacturing layout. While the material is provided and guided very linearly from one sub-process to another, data and information is managed by the control system and distributed to each process or stored in the database. The sequence of the process steps is pre-determined for each process but it is also conceivable to act autonomously with a more sophisticated algorithm. This would allow to react to disruptions within the process and act properly or to manage the production according to the given boundaries such as customer demands, available resources and economic guidelines. In the following each sub-process will be described in greater level of detail showing the key features of our solution.

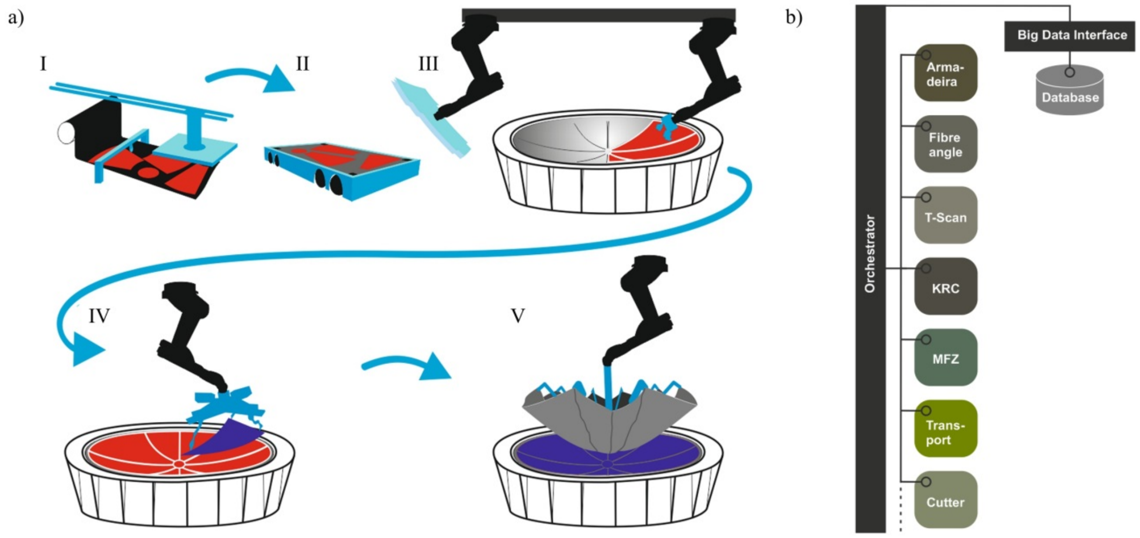

Fig. 3 (a) scheme of the automated process with no manual interferences, (b) concept for the architecture of the distributed control system

4. Sub-processes

4.1 *Material cutting*

The material used in the process is PRIFORM fabric from Cytec delivered in 1.27 m width on roll in approx. 60 m length. The material is no longer required to be stiffened by melting the binder fabric (compare to manual process in chapter 2.) because it is not supposed to be handled manually within the entire process. The cutting approach depends on the length of the plies. The RPBH is composed of the full-width and 5 meters long structure plies and complex-shaped, polygonal up to 2 meters long reinforcing plies. The former are cut to desired length and shape of the ends, then rolled on a roll synchronised to the cutter's conveyor belt to minimise the distortion of the ply. The later are automatically nested (according to specified criteria), picked up and placed on the tray. The criteria can follow rules as for least possible material waste, placing order, process time and others with weighted mixture of all the mentioned. Fig. 4 shows typical nesting and the automatic calculated position of the gripper for picking up the cut reinforcing plies.

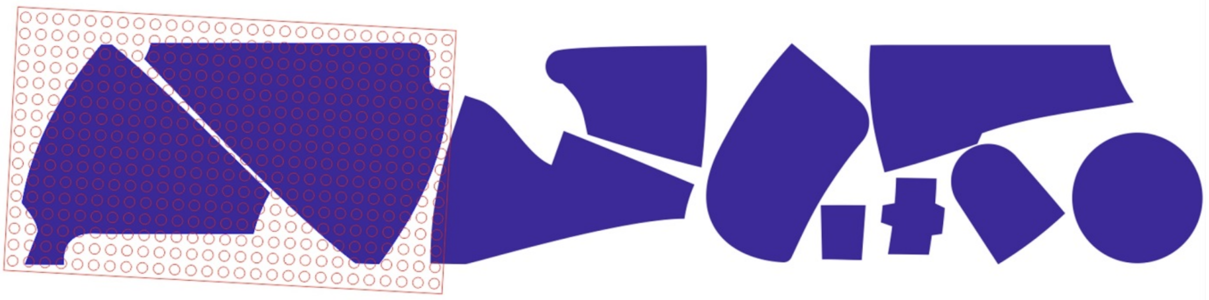

Fig. 4 Nesting of the generic plies (blue shapes) and calculated optimal position of the gripper (red) for the reinforcing plies. Figure shows the screenshot of the nesting and gripping software tool in plain view on the conveyor belt.

4.2 Transport

The plies are transferred to the MFZ via mobile tray or rack mounted roll with rolled-up long structure ply. Both can be replaced by automated guided vehicle (AGV) carrying the tray or the roll. In this project due to the limited resources the logistic behind the delivery of the material could only be researched with hand-operated frames for tray and racks for the rolls. Nevertheless, the process sequence (including the communication with the DSC) remains unchanged, therefore conclusions regarding to the scalability and the performance can be estimated within a confiding range.

The tray was designed to carry the largest of the reinforcing plies and is approx. 1.5x2 m as shown in Fig. 5. It is built from perforated metal plate on the top and glass fibre plate on the downside with stiffening ribs in between. In every corner there is a centring socket for the rack or another plate. One of the most important requirements was the ability to be carried by two workers, so it is done from lightweight materials and has handles on each short side. The other requirements were plain surface (without any interfering contour on the plane top side), high stiffness, and the possibility to be stacked and/or mounted on a movable rack or AGV. The top side is equipped with QR-codes and/or RFID-tags for identification and variable targets for precise position determination within the MFZ.

The rack is moved into the pick-up position, where the robot equipped with the modular gripper can reach the delivered ply. The long, rolled- up structure plies are delivered manually due to the limited available space in the robotic cell and unrolled onto long table ready to be picked up. For more details on the delivery paths see Fig. 2 (b).

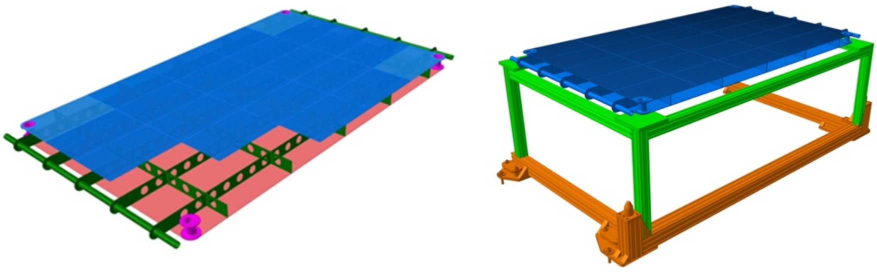

Fig. 5 Tray for reinforcing plies and rack for the transport of the tray

4.3 Autonomous Picking-Up

After the delivery of the ply the position of the tray/table is known. However, the position of the ply itself is only roughly estimated because the position where the ply has been placed bear some inaccuracy; also the ply can slip during the transport. It is planned that this sub-process uses an optical system containing a camera with lightning gear to determine the delivered ply and its position and orientation. The former minimalizes the risk of swapping plies during the layup, the later provides the exact position of the ply. This information is needed to provide exact gripping points for the modular gripper to ensure the correct position of the ply on the gripper surface. This technology – with some modifications to the optic – can be used for the long structure plies on the long pick-up tables as well. Fig. 6 (a) shows the developed tool for ply recognition and detection during technology validation with thermoplastic cut pieces (Kuehnel et al. (2017)).

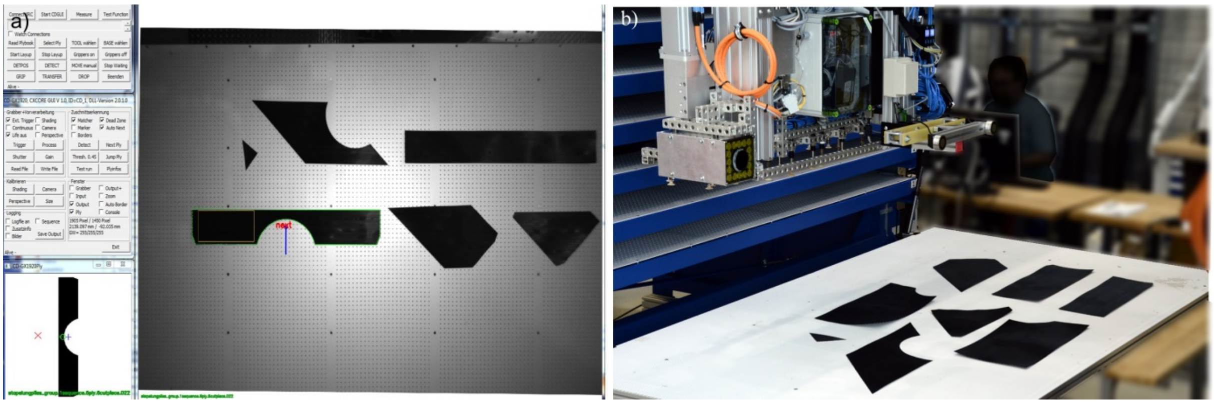

Fig. 6 (a) Tool for autonomous ply recognition and detection, (b) experimental setup for thermoplastic plies

The technology has been already used for stacking smaller thermoplastic plies out of a drawer magazine with tailored pick&place gripper and provided adequate performance and accuracy. The transfer to the modular gripper and integration in to the DSC is currently under development. Fig. 6 (b) shows the experimental setup validated for the thermoplastic plies.

4.4 Preforming

The preform of the RPBH consist of several layers of structure plies which are up to 5 m long and have the full width of the material roll. Placed next to each other they are covering the entire surface within one single layer. In between are the reinforcing plies in many different polygonal shapes and dimensions up to 1.5x2 m are placed to strengthen the structure where some lead-through openings in the RPBH are intended. During the manufacturing of the RPBH very different plies in size and shape have to be picked up and placed into the mould. While the manual manufacturing can deal with this plurality pretty well, in automated process for each group of plies a different strategy has to be developed. Additionally for the first layer the problem of sufficient adhesion on surface covered with release agent has to be solved. There are some concepts for the automated solution to generate some additional grip between the ply and the mould surface which can also be used for fixation between the layers. The ideas range from applying some sticky media (binder material or even resin used for infusion) and adhesive tapes at the edge of the plies. In fact this problem occurs only within our experimental setup, because the mould is made of CFRP and not from steel like in the manufacturing process. The fixation of the plies on metal mould can be easily solved applying and removing magnets on the very top of every layer via a robotic tool.

4.4.1 Structure Plies

The plies are delivered rolled-up on a rack. The ply is then spread on a table. The rotation of the roll on the table must be synchronised with the movement of the rack over the table in order to avoid any forces effecting the material. This will be achieved by a toothed rack mechanism connecting the roll and the table. Then the delivered ply can be processed by the recognition and positioning module of the autonomous picking-up sub-process (Chapter 4.3).

The structure plies are used for eight layers in total. They all have different lengths and differently shaped endings due to non-symmetrical geometry of the RPBH. For the pick-up and placement we developed grippers covering the width of the roll. The grippers are based on five modules in a row connected with ball-and-socked-joints and vacuum grippers on each module. This allows reproducing a spline for every section of the 3D-mould of the RPBH. The ply is gripped on each end by one of the grippers rolling from the very edge module of the gripper to the adjacent module. Every module grips perpendicular to the 2D-ply while the geometry of the gripper as a whole represents the surface where the ply edge has to be placed. We use two grippers, with one 6-axis robot each which can act cooperative and simultaneously. The picked-up-ply relaxes in funicular shape between the two grippers during the transport into the mould. The ply is then laid onto the mould surface and released (Brandt et al (2017)). Fig.7 shows the sub-process during the development where the (a) shows the transport shortly after the picking-up and (b) the applied ply in the mould.

Because the RPBH doesn't have radial symmetry the setup of the gripper modules for each ply is different. Therefore in an automated process this setup also has to be adjusted automatically. We are developing an automated adjusting station for the grippers which uses fixed position of one module and adjusts the rest of the gripper with the help of the robot it is mounted on.

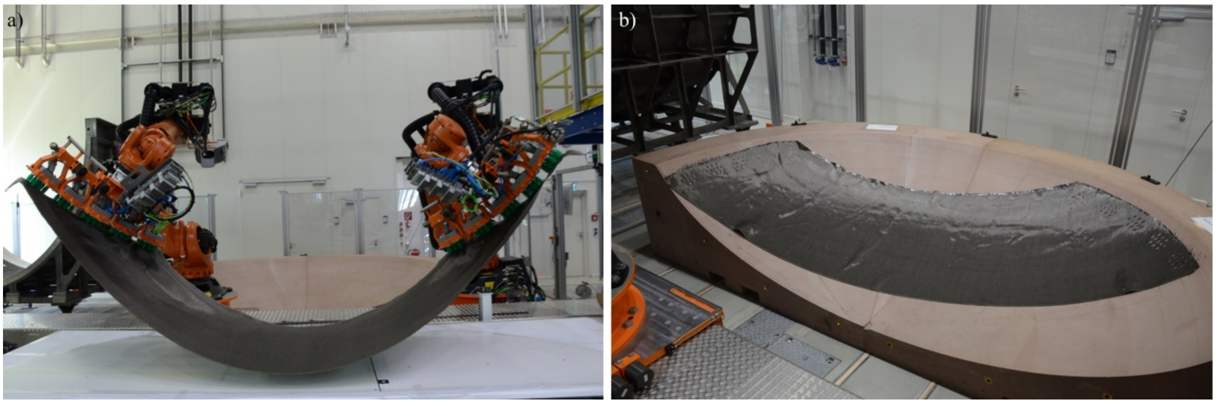

Fig. 7 (a) Applying Structure Plies with two cooperative robots, (b) automatically applied ply

4.4.2 Reinforcing Plies

The reinforcing plies (more than twenty) are all in different shapes and geometries up to 2 meters. They are delivered on a tray – depending on the used nesting algorithm and ply size – separately or as a group. The autonomous picking-up sub-process recognises the ply on the table and its position and orientation. The DCS determines the next ply to be applied. Using the position/orientation data the grip points for the picking up can be calculated as well as the robot trajectory for the robot. For the application of the reinforcing plies the modular gripper (Nieberl (2015)) is used. It contains 127 palm sized modules with coanda-effect based grippers which are connected linewise (ribs) by joints. The ribs are attached to spine made of glass fibre rods which can be deformed by tree linear actuators. This construction allows the modules to build a continuous surface which ca be transformed into double curved surface similar to the RPBH mould. The construction of the modular gripper is shown in Fig. 8 (a) where the ribs are marked with red and the spine with blue lines. For the picking-up step, the surface of the gripper is plane and the gripper makes contact to the flat ply. The gripper modules whose suction force can be regulated separately for each module are switched on and the flat ply is held by the gripper. During the movement into the mould the gripper surface is transferred from 2D in 3D and the ply is draped into the target 3D geometry (Fig. 8 (b)). The draping movement is monitored with optical sensors which are distributed within the modules along the gripper surface. This movement is necessary for the draping and can be calculated prior the process for each ply in order to achieve the desired draping. The obtained data indicates the quality of the draping and can be used to regulate suction force of the grippers for the optimal draping (Körber et al (2017)).

Fig. 9 shows the integrated sensors (a) and the data achieved during the first experiments (b). The optical sensor occupies the centre of the module and is surrounded by holes for the air suction. In Fig. 9 (b) the material movement calculated from the data recorded by the 10 sensors during draping is displayed. The red lines show the movement vectors, however they are yet not scaled to any length unit (yet).

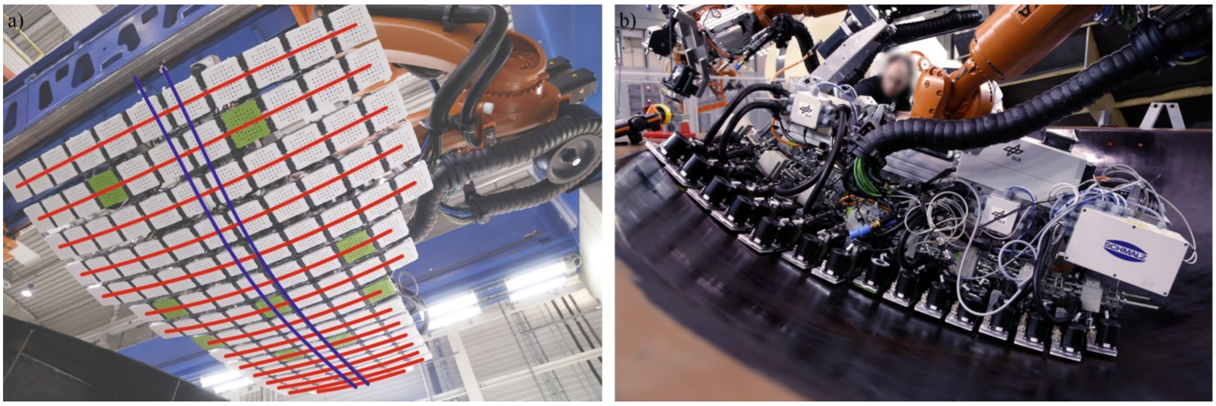

Fig. 8 (a) modular gripper – the ribs (red) and spine (blue) form the 3D geometry with the 127 coanda-modules, (b) the modular gripper adapting to the RPBH-mould

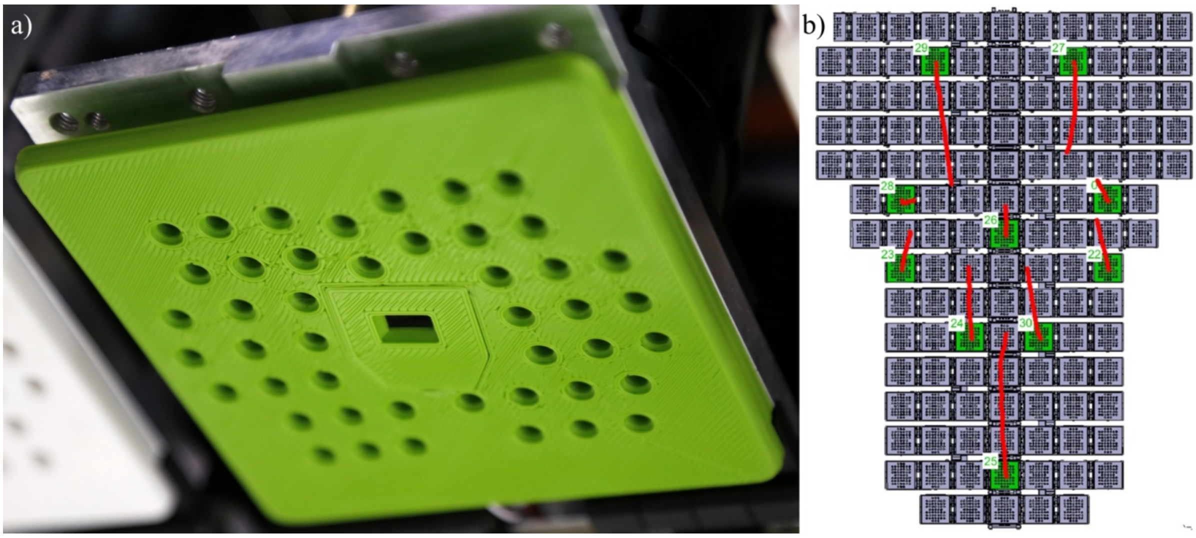

Fig. 9 (a) one of ten modules enhanced by the optical sensors, (b) the position of the optical sensors and detected movement vectors during the draping

After the draping process the gripper with the attached ply is moved into the mould, maintaining slight contact with the mould surface and releasing the ply into the target position. The first experiments with one generic ply show high reproducibility, good quality regarding draping and position. However, there are still many tweaking options left for the improvement of the process.

4.4.3 Quality assurance

After placing a ply a second robot is used to determine the quality of the lay-up. A camera for measurement of fibre angles and a laser scanner are mounted on a single robot tool and thus both can be used for scanning the laid-up ply. Full-surface measurement of the fibre angles gives information about the deviation from the simulation and thus the quality of the draping process. The laser scanner moves alongside the edge of the ply and determines the position and geometry. Fig. 10 shows both methods: (a) the measurement of the fibre angles and (b) the position of the ply.

4.4.4 Stringer integration

After the preforming is finished, eight stiffeners (stringer), all with slightly different geometries, are integrated. This task can be achieved with the multi kinematic gripping system with three 6-DOF-robotic manipulators, which is currently under development for the application of the auxiliary materials in vacuum bagging (4.5).

4.5 Vacuum bagging

When the preform is finished it has to be vacuum bagged for the Vacuum Assisted Infusion Process (VAP). The vacuum bagging is one of the most complex processes in manufacturing of CFRP parts and thus it is done almost entirely in manual labour so far. In our project we focus on three complementary solutions for high-grade automation process. The first approach deals with the sophisticated design of the auxiliary materials developed for the best possible drapeability of every cut-piece of the used material. The auxiliary materials are consolidated into material packages which can be applied as a whole on a defined section of the preform. This kind of materials can be consolidated and delivered by a supplier simplifying and shortening the vacuum bagging process. To develop the shape and the compound of the materials extended basic research on draping mechanism was done.

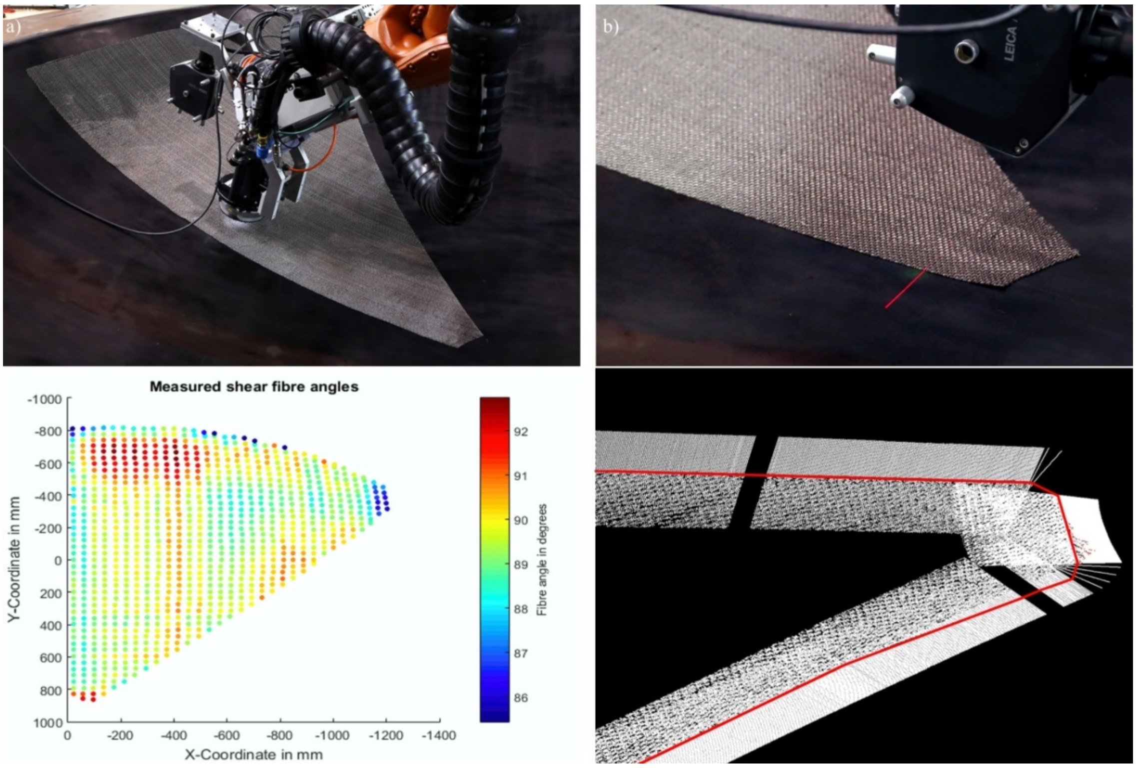

Fig. 10 (a) measurement of the fibre angles (top – experimental setup, down acquired data), (b) measuring the position of the ply with T-Scan (top) and data with calculated edge (down)

The second approach allows us to bring in the developed auxiliary material packages into the mould. The robot tool used for this task consists of three 6-DOF robots on a standard industrial robot and is shown in Fig. 11 (a) in the first design stage during initial experiments (Schmidt-Eisenlohr (2017)).

The third approach is the applying of large pieces auxiliary materials such as membrane or vacuum bag. This step can be achieved with an umbrella-like gripper, where the materials are pre-tailored and suspended onto the gripper (Nieberl (2015)). The last step of the applying process of membrane into mould during the concept development is shown in Fig. 11 (b).

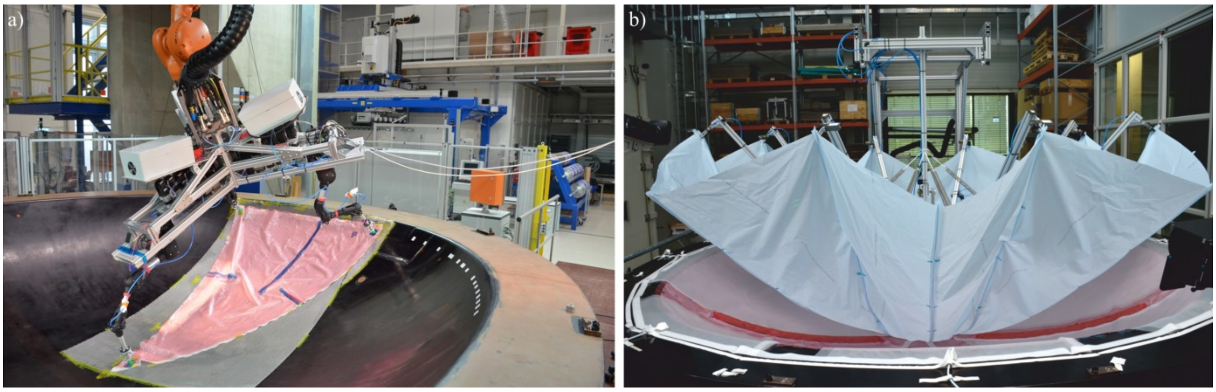

Fig. 11 (a) multi kinematic gripper applying auxiliary materials package, (b) umbrella-gripper applying membrane into the mould

5. Economic and technologic comparison between manual and automated process

Comparing the current manufacturing process to our (intended) fully automated process there are many areas whereas the automated process shows significant improvements. We would like to focus on three areas which are particularly important within the aerospace industry.

The first are the costs for manufacturing of one exemplar of RPBH. The quantifying comparison is however difficult thus the exact costs and times for the current process are considered secret and therefore unknown. Leaving the necessary investments aside and considering the automated process working as planned (without the quality assurance measurements) we hope to reduce the manufacturing time to approximately one-third. The demand for manual labour should drop from at least one to three workers for the whole process to one single worker for short time periods.

The second area is the quality. Manual deployed plies will vary in quality (i.e position and draping) throughout the whole process. In contrast, the automated process where the plies are handled by deterministic robotic tools should be highly reproducible and result in constant and robust results within very narrow production tolerances. Our solution has adjustable build-in quality assurance such as sample testing of the ply position and fibre angles, the automatic detection of the plies (leaving no room for mix-up), monitoring the draping process of reinforcing plies, etc. This leads to reduction of deficient parts and costs. Narrower tolerances can be used to re-design the manufactured parts with less material; which in turn would make them cheaper but also lighter and thus more attractive for the customers. High grade of automation allows the process to be included in the industry 4.0 environment of the future manufacturing systems.

The third area is the scalability and modularity of the automated process. Highly flexible and modular robotic cells like the MFZ allow a highly integrated distributed control system to efficiently use the facilities and resources for one or more products at the same time. This manufacturing environment due to its highly modular nature can be scaled up if the production scheduling demands higher output rates even for short periods of time.

More detailed comparison will follow after the validation of the entire process chain and is planned for second half of 2018 in future publications.

6. Conclusion

We showed the current stand in development of the automated manufacturing process of large, double curved CFRP parts of modern aircraft using the example of Rear Pressure Bulkhead. We have presented the technologies tackling all sub-processes derived from the state-of-the-art manual process and their connections to one continuous process. The technologies discussed in this paper are still under development and their validation is planned for the year 2018. After this a full cycle of almost entirely automated process is scheduled for the second half of 2018 where a full-size demonstrator RPBH will be built using original materials and parameters. With our solution we are hoping to achieve the next level of automation of CFRP production for large and complex lightweight structures towards the implementation of Industry 4.0 standards in the previously manually based manufacturing processes. This development will have strong impact on costs, quality and manufacturing cycle and make the CFRP production more accessible and affordable.

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