DEVELOPMENT OF A MULTIROBOT MULTITASK SCENARIO FOR AUTOMATED QUALITY ASSURED PATCH PREFORMING

Christoph Frommel, Alfons Schuster, Andreas Buchheim, Clemens Schmidt-Eisenlohr, Mona Eckardt, Dorothea Nieberl, Monika Mayer, Patrick Kaufmann, Michael Kupke
German Aerospace Center (DLR e.V.)
86159 Augsburg, Germany

ABSTRACT

Reduction of weight in components for aerospace applications is one of the driving factors in industrial research in the field of aviation. Less weight of structural components results in a lower fuel consumption during flight. As a result, more cargo or passengers can be transported. An approach to achieve this, is to use materials with lower weight but comparable mechanical properties. One of those materials are carbon fiber reinforced plastics (CFRP). The production of CFRP components with less challenging properties like low gradients in thickness or curvature is at least partly automated and state of the art. However, automated layup of complex structural parts in great variation of geometries combined with small production numbers is still a technological challenge. A possible solution is the application of a highly flexible, multi-robot scenario which can both handle the sensitive materials and apply in-line quality assurance measures. One robot is equipped with the end effector and a highly accurate optical system. This optical system is used to detect individual cut-pieces on a material carrier. When the correct cut-piece is detected industrial robots grip the cut-piece and place them on top of each other. Another robot equipped with quality assurance sensor is measuring the fiber orientation. To handle all the process data, including part and process specific data as well as the acquired in-line quality assurance data, an in-house developed data management system is used. The high grade of automation supported by database supported in-line quality assurance could enable the certification of an automated patch preforming process for aviation applications.

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Corresponding author: Christoph Frommel

1. INTRODUCTION

The aviation industry is facing the challenge of reducing CO_2 emissions in order to meet global climate targets. One step towards achieving these goals is reducing fuel consumption by a weight-optimized design of structural components. In this regard, the engine deck of a helicopter offers great potential, since it has to meet a wide range of requirements due to its role as interface between engines and airframe. The engine deck builds the part of the airframe located above the passenger cabin and below the engines. So far it has been predominantly constructed from metal due to its function of supporting the weight of the helicopter's engines and to provide heat shielding in the event of engine overheating or fire. In a newly developed design concept, the elements of the engine deck will now be realized using carbon fiber reinforced plastics (CFRP). The CFRP engine deck is designed as a skeleton framework to which the engines are mounted. It consists of four longitudinal beams (longerons), which are attached to two main spars of the airframe. The longerons are connected with five crossbeams. All beams have a uniform C-profile shape and are connected via L-shaped clips and gusset plates. These overlap the joints between the beams on the underside of the deck. Rivets are used to connect the framework elements. On top of the framework a sandwich stiffened skin panel is bonded, which connects to the outer helicopter side skins on both sides. Although the C-beams have the same profile shape, they differ in length and have a ply layup adapted to their specific loads. These similar but not identical elements are thus an ideal use case for developing a flexible automated manufacturing process that enables the economical use of automation for small quantities, such as in helicopter production.

In this paper a C-beam of the newly developed helicopter engine deck is the sample application to demonstrate a flexible automated preforming process. The C-beam preform consists of a stacking of several dry carbon fiber textile cut-pieces. Two different materials are used: A 2/2 twill weave (285 g/sqm) with 6K rovings and a fabric with 6K unidirectional oriented fibers (270 g/sqm). The textiles are impregnated with binder on both sides. The calculated and designed fiber orientations of the cut-pieces differ from 0°, 45° and 90°. For increasing the C-beam stiffness a lightweight foam core is positioned between the layers. The shapes of the cut-pieces are approximately rectangles but draping over the foam core leads to slight, local offsets of the outer contours. As preparation for preforming fabrics are cut, placed in a movable storage and transported to the robot cell. Following, the developed pick and place process is used to produce a patch preform. This system detects, grips and transports the cut-pieces to the designated position on a preforming unit. The preforming unit consists of pivoting diaphragm and a heatable tooling which has the inner contour of the C-beam and is surrounded by a lowerable platform. After positioning the cut-pieces on top of this platform the diaphragm (clamped in a frame) is placed over the stack of plies and is sealed. Next, the platform is lowered and a vacuum pump generates a partial vacuum under the diaphragm. During this process step the textiles are draped around the tooling to conform to the shape of the C-beam. After draping the binder is activated by an external heat source and the heated tooling, so that the plies are consolidated and retain the shape of the C-beam. These process steps are repeated several times to build up the C-beam preform. The finished preform is then infused with resin and cured using the aerospace approved vacuum assisted process (VAP).

The focus of this paper is the development of a flexible quality assured preform process that combines an adaptive cut-piece detection, automated handling and in-line quality assurance as well as data storage by an in-house developed data management system. The database handles process data, including part and process specific data as well as the acquired in-line quality assurance data.

2. PROCESS DEVELOPMENT

Since the produced parts are used in aerospace applications there are several requirements for the patch preforming process. During handling of the textiles, it must be ensured that no defects are caused and changes in the fiber angle are avoided. Absolute positional accuracy and repeatability must be met for each part. Also, the multiple parts with different cut-piece shapes, sizes, materials and fiber angles need to be covered. To ensure the quality of the process, quality assurance methods need to be implemented. The variety of parts, low batch sizes and investment cost of implementing such a system in production make it mandatory to be flexible and precise with low maintenance and downtime.

2.1 Autonomous preforming system

To handle these specific process requirements for the patch preforming, an in house developed autonomous pick and place system was used as a basis [1]. It was initially designed to patch preform with a single robot or to use two robots for cooperating transport of large textile cut-pieces. The enhanced system is using a manufacturing execution system (MES), computer vision algorithms, industrial camera, grippers that are used to pick up the plies, the robot cell containing industrial robots and material carriers. The camera is mounted on the grippers to detect the plies and calculate the coordinates of them on the material carrier. The use case of manufacturing the C-beam requires the usage of two robots for material handling and another robot for quality assurance. Therefore, the MES and the robot controls were enhanced to include more robots as well as the functionality to use a fiber angle measurement sensor within the system.

The preforming software is written in C++ and has several interfaces for different process systems. It consists of three main components, MES, robot execution and cut-piece detection. The cut-piece detection algorithms did not need to be changed for the use case. The robot execution is realized by using a parametrized robot program running on each robot configured in roboteam. KUKA Ethernet-KRL [2] is used to send coordinates, tools, bases and gripper/sensor actions to the robots. This part only needed the integration of the third robot and configuration of the robot team synchronized movements. The biggest improvements were done in the MES and corresponding process description to depict and execute the more complex process scenario.

The process description is generated as a so-called job definition file (JDF). The JDF contains three parts:

- Ply information for cut-piece detection including contour and reference point derived from the OpenCV minAreaRect() function [3].
- Robot and task specific actions listed in form of grip point (GP) and drop point (DP) actions.
- Process sequence to establish the correct layup regarding the ply book.

So far, the GP definition included how to grip the cut-piece with predefined robot positions. This needed to be enhanced to let each robot do an individual task or movement in the respective coordinate system of the material carrier from where the gripping is done. The solution was the introduction of a new key word “BASE” in the JDF description which allows movements in the material carrier coordinate system. In this way flexible robot movements and tasks during the gripping state of the system are enabled which is needed for safe movement of the robots. The manually defined process description can now be done in such a manner that each robot moves out of the way before performing a specific task. Since this description includes downtime of individual robots, keywords to exclude the robots performing any action were introduced to shorten the task description definition. With these changes it is now possible to handle any number of robots individually during the gripping state. This also includes quality assurance or preparation tasks on the material carrier.

The system's DP definition already included more advanced robot and task handling to meet the needs of cooperative ply transport. Therefore, no further development was required. However, the logic in controlling gripper actions (e.g. activation of suction units or spot welding) was modified to handle other actions like sensor activation. This was needed to trigger the quality assurance measurements after the placement of the ply.

2.2 Fiber angle measurement and database

The fiber angle measurement is done by an optical sensor system called F-Scan [4]. In previous experiments the sensor was used with a prototype interface for automation that utilizes TCP/IP for sensor communication and KUKA Ethernet KRL to communicate with robot control. This solution had to be reworked for the new process scenario. Therefore, a Python based solution was chosen to be more flexible for further improvements in future projects. The new solution also uses TCP/IP to communicate with the sensor interface which allows connecting to the sensor, starting a measurement, saving the raw measurement data and evaluation directly from the sensor software in form of two found fiber angle peaks. To correctly trigger the measurements during the preforming process the KUKA Ethernet KRL interface was used to receive trigger signals from the robot after he reached the detection position for the measurement. This solution allows fully automated fiber angle measurements and evaluation on the fly during production. Finally, the interface for the storage in the database needed to be established. The database is a centralized data management solution called storage for heterogeneous product and research data (shepard). This storage solution helps to easily collect data across process chains and large projects. Concerning the fiber angle measurements, the raw data and a json summary containing robot positions as well as fiber angle peaks of each measurement is uploaded to shepard.

The data in shepard is organized into collections. Collections serve to group subordinate data elements and therefore contain so-called DataObjects. DataObjects represent the actual data and can be hierarchically and logically structured. Each DataObject can have exactly one parent object and multiple predecessors, successors, and child objects. Using the parent and child objects, hierarchical structures can be represented, while the predecessors and successors are used to model temporal or causal dependencies. These referenced objects must also be DataObjects. User data is organized into containers. There is one type of container for each data type. A container can contain multiple user data objects. The connection between DataObjects and user data occurs through References. References always belong to one DataObject and point to one or more user data objects in exactly one container. The data model is exemplified in Figure 1 [5].

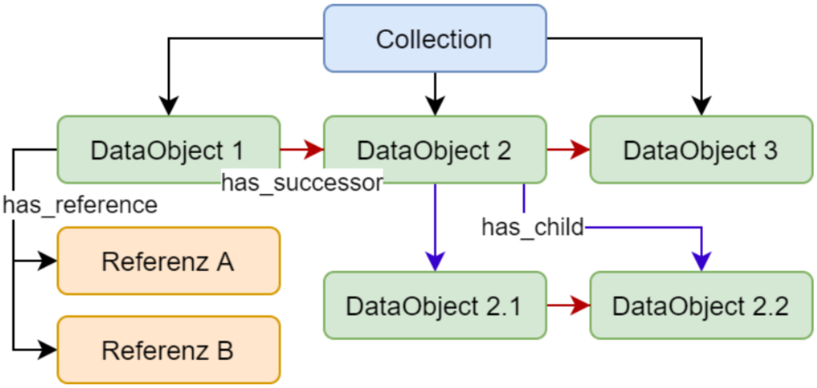

Figure 1. Shepard data model.

Shepard has several interfaces to handle all kinds of systems providing data to the database. Since the new developed fiber angle measurement software was written in Python, the Python interface for shepard was implemented to communicate with the database. To handle the data correctly the fiber angle software needs the respective Collection-, DataObject- and Container-IDs of the current measurement to correctly save the data. This was realized by modifying the robot programs that are used during the preform process to handle the gripper actions like described in chapter 2.1. At each measurement point a specific gripper action is called that triggers the measurement of the sensor and provides the respective IDs. The individual gripper actions are defined in the JDF drop point definition. With this solution the fiber angle sensor can act like an independent service within the production process since it gets fed with all necessary shepard context from the MES. This enables easy integration into other process scenarios.

3. EXPERIMENTATION

To test the developed preforming system an altered version of the C-beam layup was used. This layup has seven plies which cover the spectrum of shape sizes and fiber orientations (0°, ±45° and 0°/90°) used in the layup of the final C-beam. The order in which the different plies are picked up and positioned is determined to alternate between the two preforming robots. This includes process specific gripping orders to ensure collision free paths and optimized usage of robot workspace.

For preforming an industrial robot cell with ceiling mounted robots as seen in Figure 2 was used.

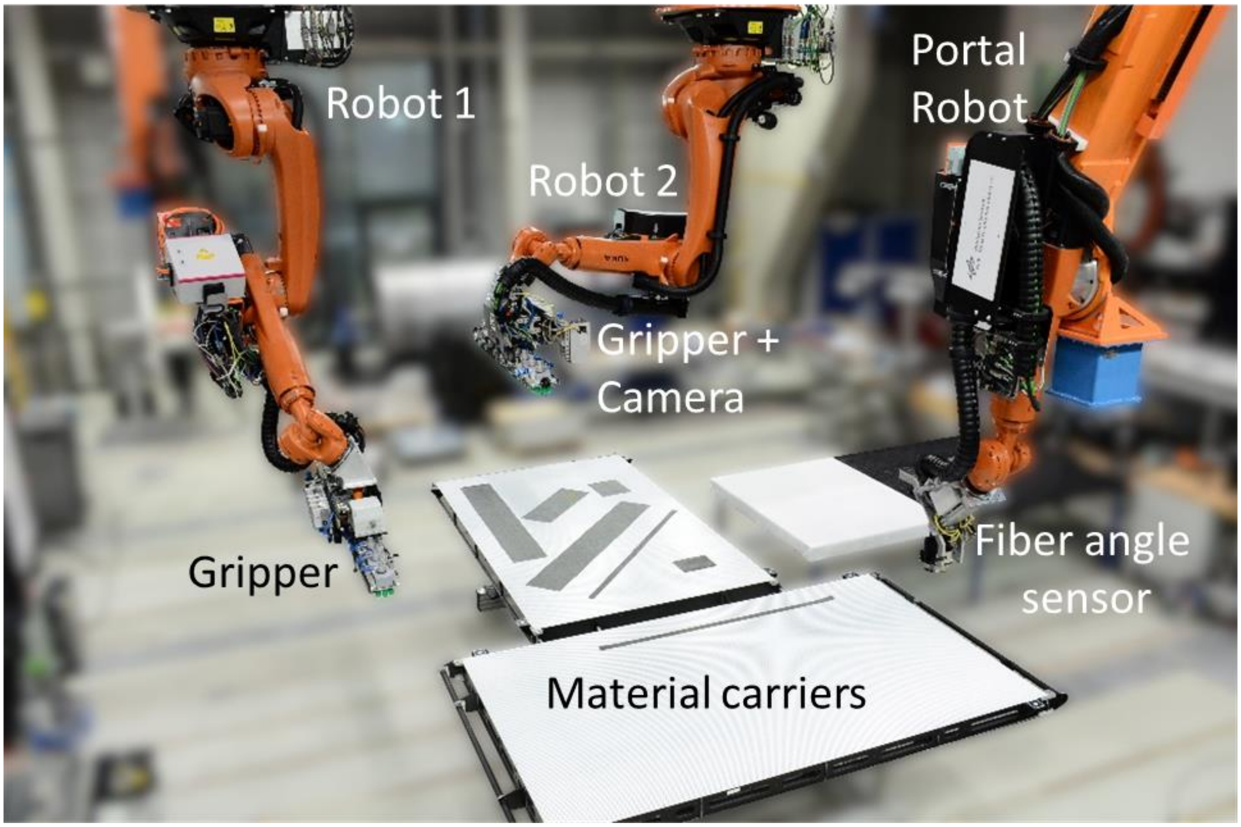

Figure 2. Experiment setup with robots, grippers, fiber angle sensor, material carriers, cut-pieces and deposition table.

The robots are two standard six axis industrial robots (KUKA QUANTEC KR210 3100 Ultra) on a shared linear axis and a specialized portal robot with axis 1-3 as portal units and 4-6 as standard robot axis. The rarity in this portal robot is that axis 3 is angled and not perpendicular to axis 1 and 2 which makes offline programming more difficult since no standard inverse kinematics can be used. This setup was chosen to demonstrate the flexibility of the system to handle multiple different robot types in one system. Figure 2 shows the final setup of the robot cell with the three robots mounted with grippers, camera and quality assurance sensors.

Two material carriers with the seven cut-pieces as well as a table as substitute for the diaphragm preforming unit are located inside the cell. Both the table and the material carrier are calibrated to each robot and the camera. The left robot is equipped with a gripper, the middle robot with a gripper and camera system and the right portal robot has the fiber angle measurement sensor mounted.

To start the process all robots are moved in a starting position with a following movement of the camera mounted robot to a detection position above the material carrier. As described in 2.1 the camera is used to calculate the position on the material carrier, to grip the cut-pieces correctly and to ensure to grip the correct cut-piece. Figure 3 shows the detection of the system for the first cut-piece in the layup order.

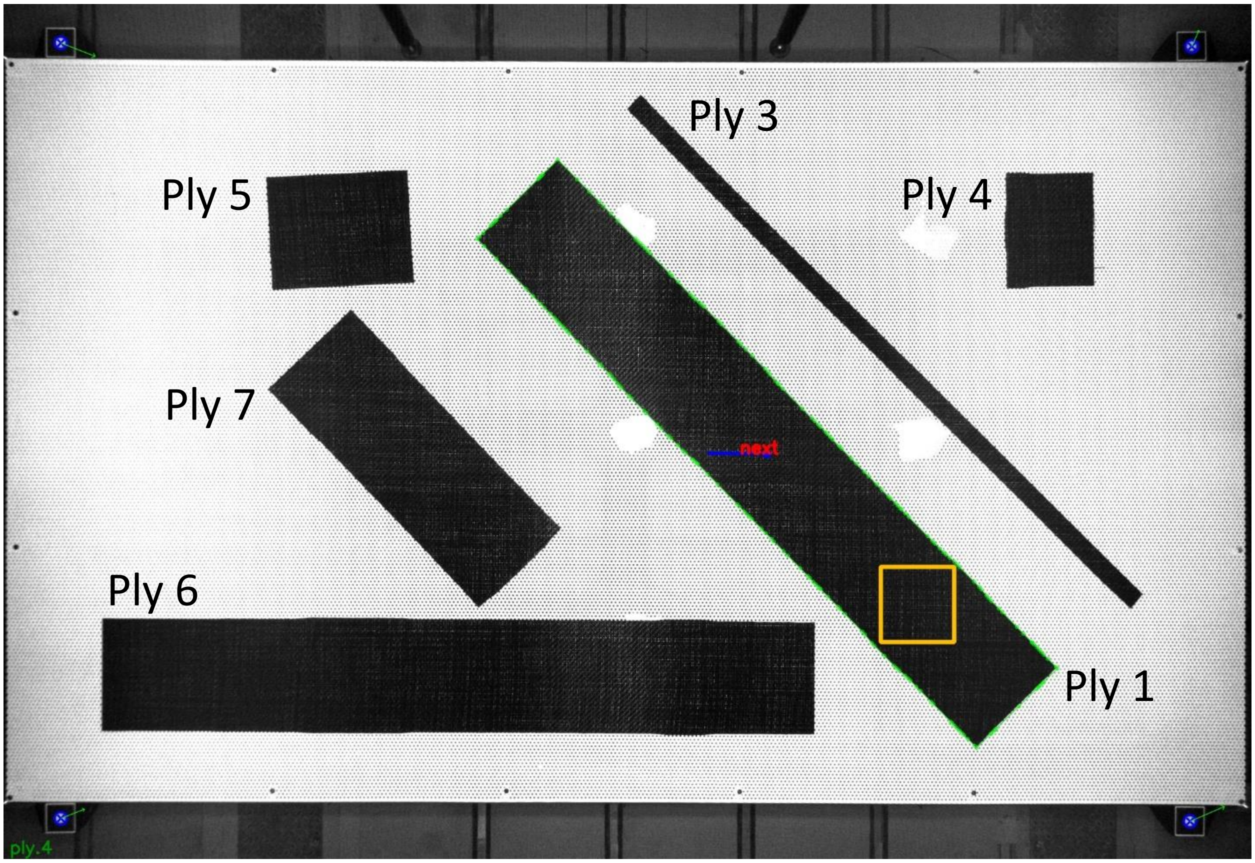

Figure 3. Detection of cut-piece on material carrier with weave fabrics numbered in layup order with ply 2 on the other material carrier for unidirectional fabrics.

The plies in Figure 3 were cut in one step and transferred to the material carrier with a transfer gripper all at once. The resulting position of the cut-pieces in the robot cell show slight movement due to forces induced during transfer of the carrier to the cell. Cut-piece detection is mandatory to ensure repeatable accurate gripping of the plies. Next to correct gripping, it also checks if the cut-piece that is requested from the MES is present on the material carrier or missing. It would stop the preforming process if the cut-piece would be faulty cut, misplaced on the carrier or is out of shape. After detection the calculated coordinates are send as a KUKA Frame via Ethernet KRL to the robot control and robot movement is executed.

The gripped ply is transferred to the table and placed on the position that is defined in the DP section of the JDF. Afterwards the robot moves out of the way and the portal robot moves to the desired measurement position. The python software that controls the sensor is triggered from the MES with the corresponding DataObjectID to store the result in the database for the respective ply. The initial data structure with the collection, DataObjects and data container is set up manually using the Shepard frontend. After the measurement the fiber angle raw data is stored as a .mat file in a file container and the evaluated fiber angles as wells as robot positions during measurement in a structured data container. After the storage the references are automatically generated within the database to link the DataObjects to the data containers. Figure 4 shows the sensor during a measurement after placement of ply 5 with the characteristic illumination from different angles.

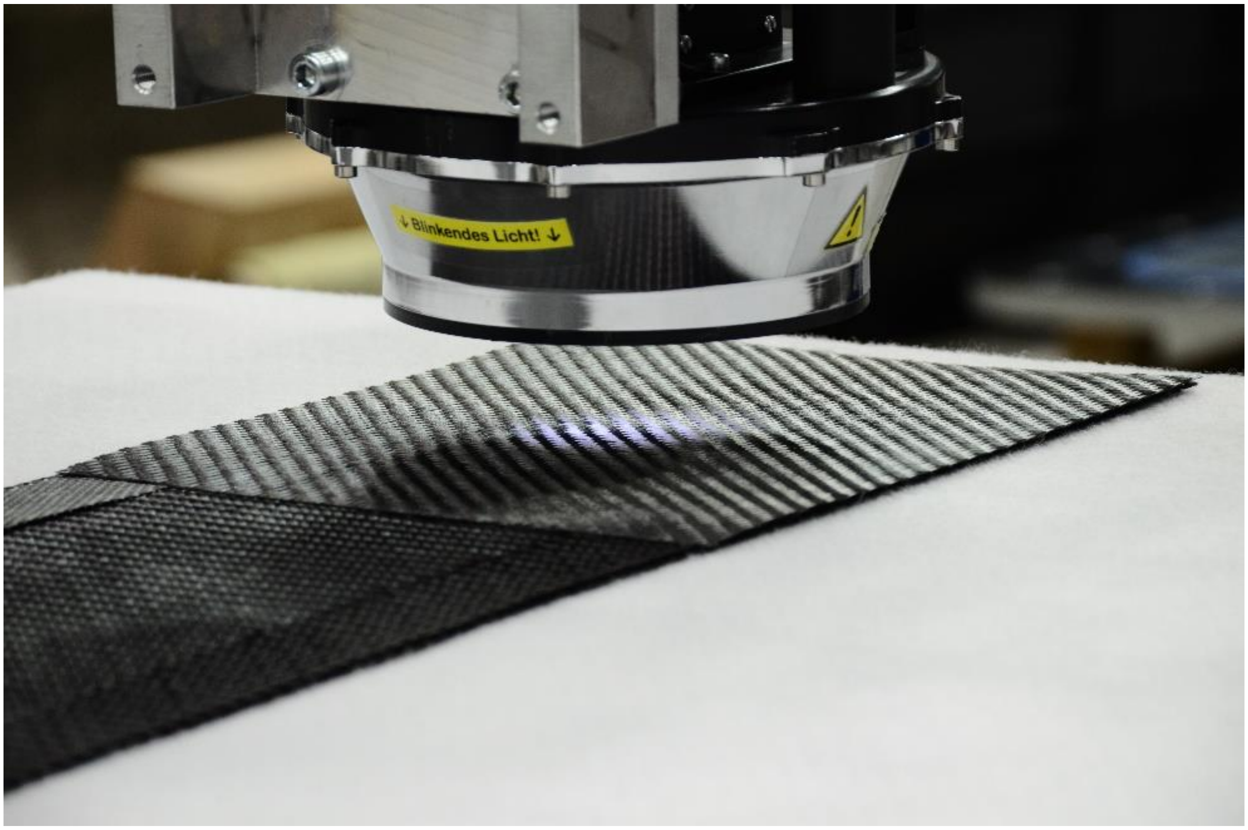

Figure 4. F-Scan sensor during measurement of ply 5.

After finishing the measurement and storing the data the portal robot moves to its starting position and one cycle of preforming is finished. This is repeated for all plies until the preform is established. The process flowchart is shown in Figure 5.

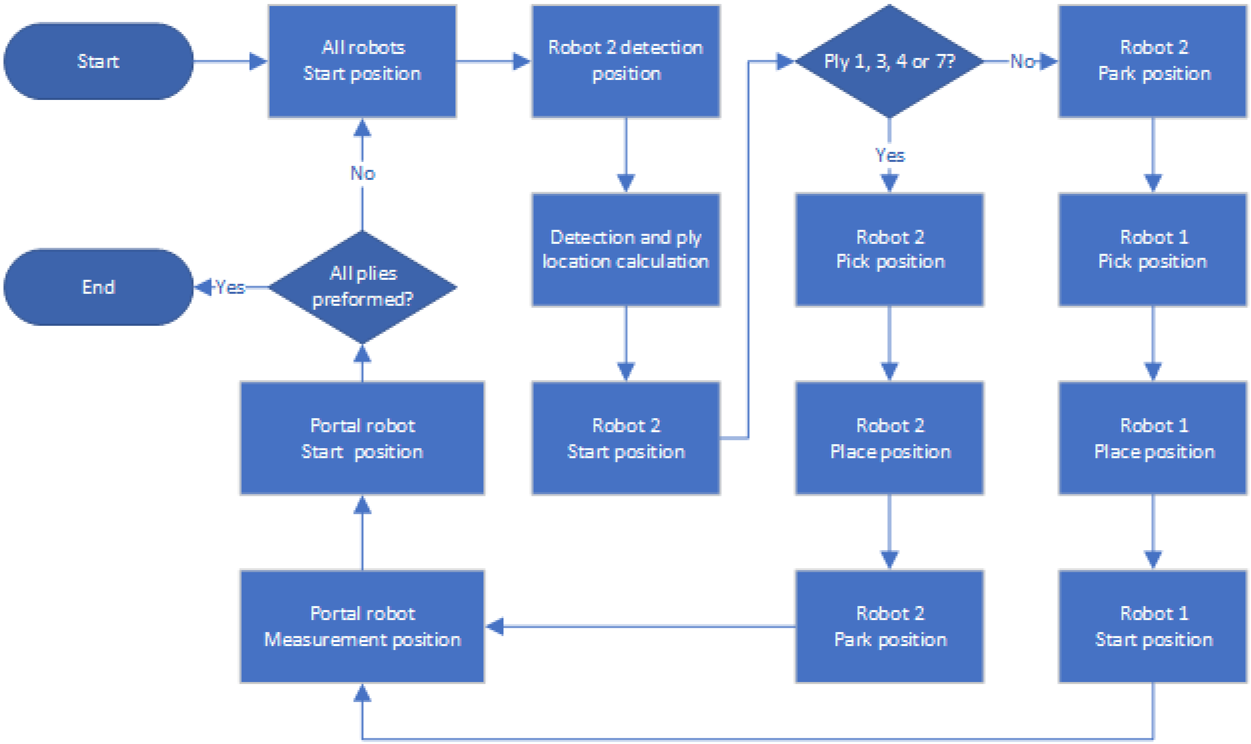

Figure 5. Flowchart of the C-beam preforming process.

As seen in Figure 5 this process behavior includes all the necessary process steps of robot movements, detection, pick and place as well as the quality assurance measurement in such a way that collision of the robots is impossible.

4. RESULTS AND DISCUSSION

4.1 Preforming

During preforming the only manual step was to change the material carrier for the different fabrics. Otherwise, every process step was fully automated and in total no manual influence on the material was necessary. Cutting, transfer on material carrier, gripping and placing was done by devices in a fiber friendly way. This ensures that no defects are caused as well as a reproducibility of the achieved accuracy. Figure 6 shows the finished preform on the deposition table.

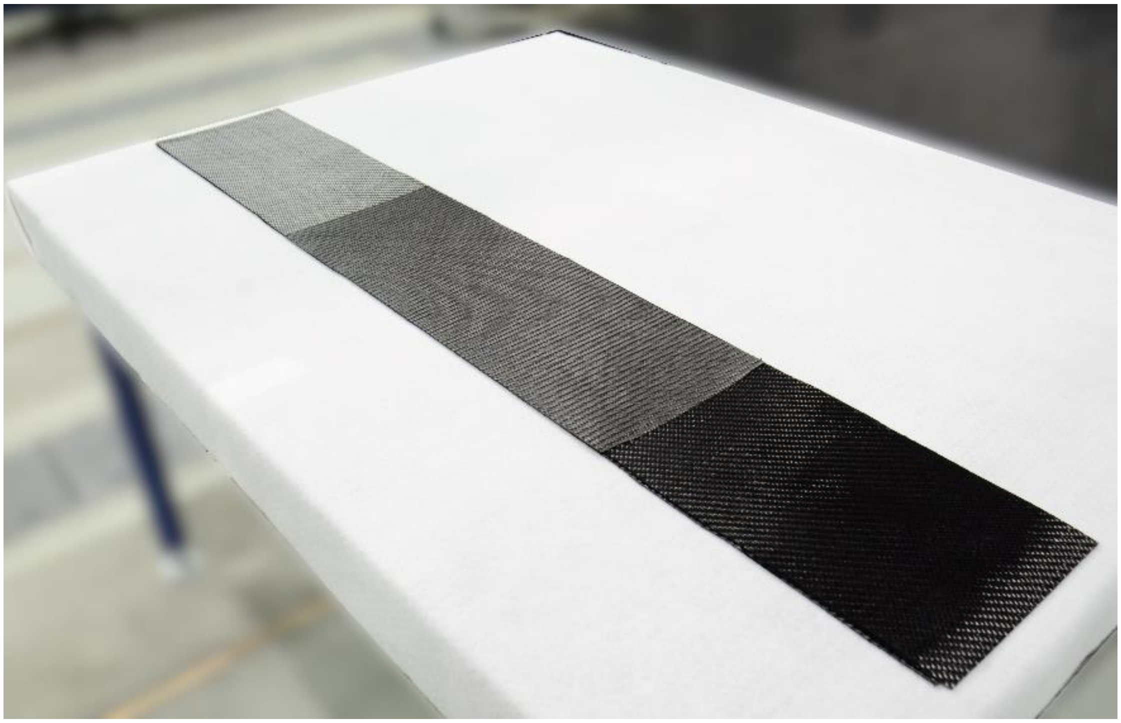

Figure 6. Finished preform of C-beam ready for diaphragm preforming.

The placement accuracy was evaluated by visual inspection. It could be seen that the absolute position accuracy varied up to approximately 3 mm between some plies. Comparing the individual robots used for preforming it could be seen that the plies preformed by robot 2 were placed better than robot 1 and had only slight translational errors under 1 mm. Robot 1 preformed plies had a slight tilt which results in higher translational errors of long cut-pieces due to higher pointing errors. Figure 7 highlights these observations.

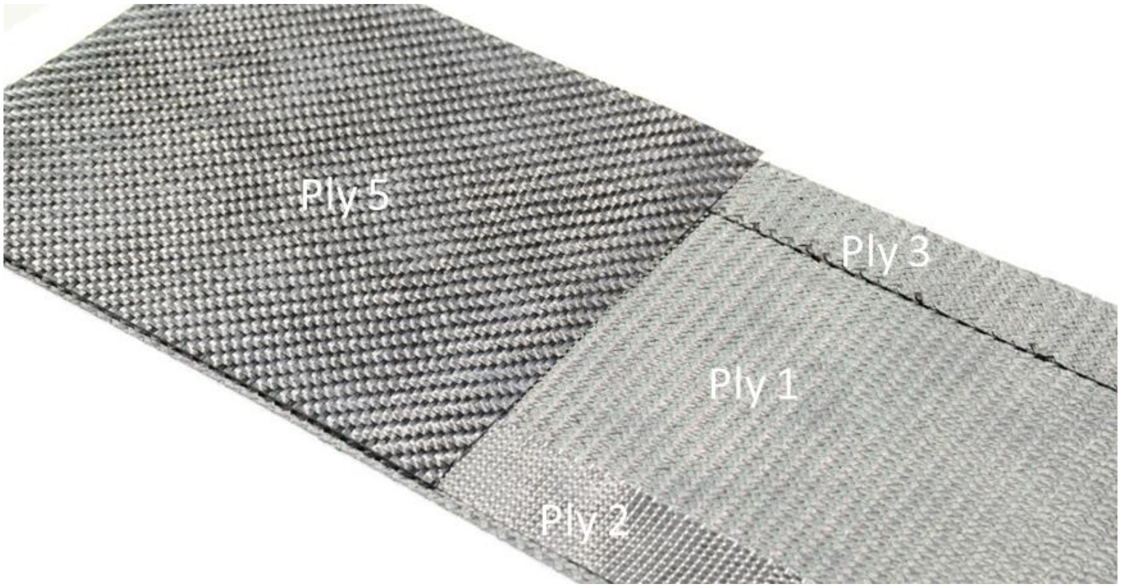

Figure 7. Close-up of plies 1, 2, 3 and 5 for accuracy inspection.

Plies 2 and 5 (robot 1) have up to 3 mm border to ply 1 (robot 2). Furthermore, ply 3 (robot 2), which is the counterpart of ply 2 on the other side, has the desired distance to ply 1.

Table 1 shows the matching factors the cut-piece detection algorithm achieved. The small long cut-pieces with approximately 0.92 % cross correlation have the lowest accuracy, with approximately 0.95 % for the other plies. This value derives from the OpenCV template matching algorithm [3] which calculates the cross correlation between the input template and the found contour in the picture. A higher value means that the contour of the template matches the contour of the found ply better.

Table 1. Matching factor for each ply.

Matching factor in %							
	Ply 1	Ply 2	Ply 3	Ply 4	Ply 5	Ply 6	Ply 7
Matching factor	0.947	0.918	0.924	0.966	0.969	0.961	0.950

4.2 Quality assurance

With the new fiber angle measurement software, a fully automated QA service could be provided for the preforming process. After starting the python code on the respective PC, the fiber angle measurement was done fully automated during the preforming process. Every measurement was triggered by the MES with the respective DataObjectID to store the measurement data. Figure 8 shows the measurement of ply 2 on the left and ply 3 on the right in its raw format.

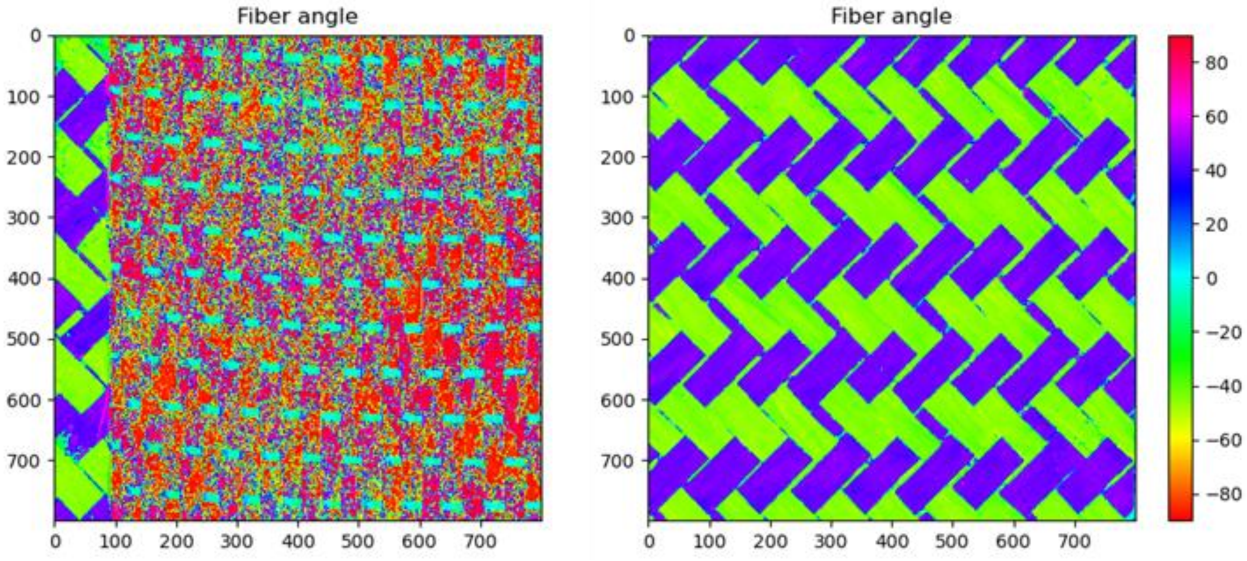

Figure 8. Fiber angle measurement raw data of ply 2 (left) and ply 3 (right).

Table 2 shows the evaluated fiber angles as peaks for each desired fiber orientation. The evaluation was done directly with the python code after each measurement.

Table 2. Measured fiber angle peaks for each ply.

Measured fiber angles in degrees							
	Ply 1	Ply 2	Ply 3	Ply 4	Ply 5	Ply 6	Ply 7
Peak 1	-45.12	-89.68	45.61	1.83	1.67	-89.72	-44.9
Peak 2	46.11	-	-44.8	89.86	-89.9	-0.86	46.4

Figure 9 shows the achieved data structure in the shepard database with the individual DataObjects connected to the data containers by references as well as successors and predecessors that reflect process behavior (see chapter 2.2). This ensures traceable process data management that could be addressed in future for possible failures, maintenance, repair or certification requirements.

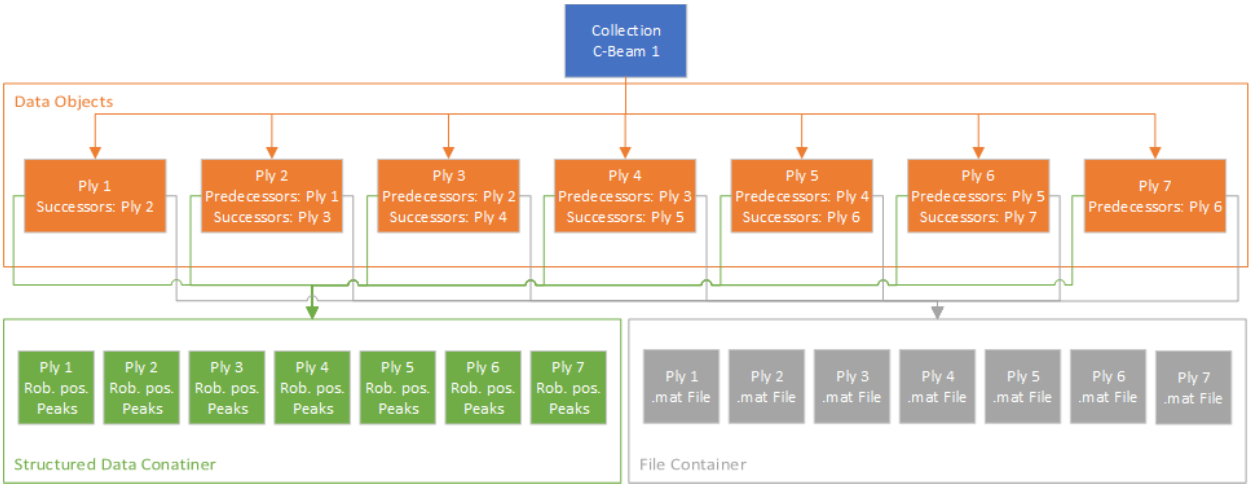

Figure 9. Shepard data structure of stored quality assurance data.

4.3 Discussion

The achieved results in this experiment highlight the high grade of automation of the preforming process with the material carrier handling being the only manual process. No errors or stops occurred during the preforming or QA process which highlights the robustness of the system.

Placement accuracy showed deviations from the expected result. High matching factors of the detected cut-pieces ensure that the cutting was done correct and the cut-piece detection system was calibrated accordingly. Since the matching factor is influenced by holes in the table it even further excludes the cut-piece calibration from the achieved position accuracy. Based on the results from the visual inspection (see chapter 4.1) the calibration of the robots in terms of tool center points (TCP) as well as base calibrations of the material carrier and table are most likely the reason for the achieved position accuracy. Since the deviation of the plies preformed by robot 2 were under

1 mm the TCP should be fine. However, robot 1 preformed plies showed systematic errors since all plies are slightly tilted. Longer plies have shown higher errors which is hinting on errors in TCP calibration. Therefore, the absolute accuracy can be optimized by better calibration of the TCPs as well as bases. This can be achieved by TCP correction procedures like used in [1] and raising the table and material carrier to be in better working areas of the robot. Since the ceiling mounted robots have to reach to the edges of their working room the accuracy decreases [6] during calibration of the bases.

These deviations in placing accuracy can also be seen in the fiber angle measurements shown in Figure 8. Ply 3 covers the complete measurement window whereas ply 2 is slightly displaced to the right. The figures also highlight the different reflection behavior of the textiles. Both materials are binder impregnated which leads to the unidirectional fabric reflecting very diffuse whereas the weave has slim to none diffuse reflections. The measured fiber angle peaks sway around the expected fiber angles and also the raw format pictures show correctly aligned fiber angles. However, since absolute position accuracy and the tilt of the plies influence fiber angles the variation are within the standard deviation of the fibers within the fabrics itself.

On basis of visual inspection, matching factors of cut-piece detection as well as the fiber angles and respective raw format pictures the overall accuracy in its current state of the system is already acceptable. Since systematic calibration errors lead to the deviations the accuracy can easily be increased with higher calibration efforts.

5. CONCLUSION

With further development of the preforming system a fully automated multi robot multi task scenario for patch preforming could be achieved. The functionality of the system was shown by automated patch preforming and quality assurance of a C-beam structure for an aerospace application. The modularization of the software and generalization of the process description enabled the individual robot tasks and behaviors in the C-beam use case. This also enabled the fully automated integration of the fiber angle measurement during the preforming process. To store the achieved measurements the shepard database was integrated in the fiber angle sensor software.

The process integrated quality assurance could be used to analyze placement accuracy and the cause of slight deviations from the determined position. The evaluated errors can be improved with better calibrations of the system but are already within the tolerances.

The achieved development state of the system generated further ideas of improvement. The cut-piece detection, MES and robot handling should also store process data directly into shepard during production. This would be enabled by a C++ library implemented in the existing software. The process description for the MES was done mainly by hand due to the new features. This could be automated to even further optimize the virtual commissioning. The database structure in shepard was done manually. Since there is already a complete process description necessary for the MES this could be used as input for an automatic shepard structure generation. Also, previous and following process steps like cutting, diaphragm preforming and curing should be added to the database structure and process data included. All of these improvements lead to a fully quality assured and documented manufacturing process which could enable a certification of the process in the aviation industry.

Retrospectively, the achieved state of the process allows to preform all of the different C-beam structures of the engine deck. The dimensions of the skin panel require the usage of cooperating robots. Therefore, a path planning software called CoCo [7] needs to be implemented to handle the complex task of generating cooperating synchronized robot movements. These paths guarantee correct handling of the large fabrics without dropping them. The addition of CoCo would also allow the generation of optimized robot paths for picking and placing of single plies during preforming. With this setup the automated preforming for all components of the engine deck can be realized.

6. ACKNOWLEDGMENT

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