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Towards a fully automated process chain for the lay-up of large carbon dry-fibre cut pieces using cooperating robots

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Abstract

At the Center for Lightweight Production Technology (ZLP) a pick and place process using cooperating robots for the draping and handling of large textiles in the production of a rear pressure bulkhead from carbon fibre reinforced plastics (CFRP) has been developed and presented in the past [1]. This work has primarily shown the feasibility of draping and handling large cut-pieces with passively adjustable end-effectors that can reproduce spherical geometries. The process chain developed recently is mirroring a complete industrialized production and incorporates different technologies developed at our facility. Sub-processes include the planning of grip- and drop-points based on the ideal tool geometry, preprocessing of the data, automated adjustment of the grippers, cut piece detection and finally a collision-free path planning system [2,3] for the robots. The process chain was used for several plies within the production of a full scale demonstrator of a rear pressure bulkhead. This work depicts the current state of the development and shows the results of the full scale application of the process. Opportunities and limitations of the setup for an industrial environment are discussed.

1 Introduction

In recent years the demand for new aircrafts has increased. Current production is not fit for higher quantities and a higher degree of automation is crucial for a ramp up of production rates. Further, the automation needs to be flexible towards changes in production unlike typical automation, which is designed for high volume parts. In the past different approaches for the automated preforming of large CFRP components have been investigated by the ZLP which were recently used to build a demonstrator of an A350 rear pressure bulkhead in an automated and industrialized way[4]. One production method used is 'pick and place' of large dry fibers using cooperating robots. Together with different key technologies for a fully automated production like ply detection and automated path planning, the cooperating 'pick and place' method has been matured into a fully automated process chain that includes the generation of production data, adjustment of the grippers, pick-up and lay-down strategies, ply detection and path planning. In earlier studies the technology modules for the ply detection and path planning have been successfully working together but were limited to the demonstrated process parameters and cell layout [2]. The manufacturing of the rear pressure bulkhead made further development necessary that enables these technologies to be applied for general 'pick and place' tasks in automation. The flow diagram of the process is depicted in Fig. 1. The purple steps were partly manual whereas the green steps were fully automated.

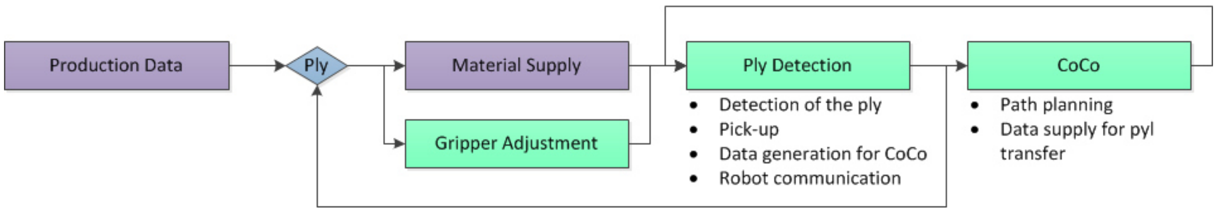

Fig. 1: Flow diagram of the process

2 State of the Art

The technologies used for the manufacturing of the demonstrator have been developed in different projects at the ZLP. In the following a brief summary of the status of development before the technologies were combined is given.

2.1 Cooperative Handling of large Cut-Pieces

There are many approaches to the handling of large cut pieces. Passively adjustable endeffectors that are built as a kinematic chain of volume-flow suction modules are sufficient for the task of handling and pre-draping large carbon fibre plies for spherical female mould geometries. This has been shown in previous researches at the ZLP, in which the adjustment of the grippers, as well as the generation of the process data was done manually [1]. The main problems caused by intensive manual workshare of the cooperative handling are the angular deviation of the gripper setup and the teaching of the robots. The angular deviations of the adjusted grippers prevent an accurate pick-up motion and prone the process for collisions with the surface on which the plies are supplied. This ultimately compromises the quality of the lay-up. Originally the grippers were designed with an associated measuring system consisting of two laser sensors that can measure the actual geometric state of the gripper and a clamping station that holds each suction module during the passive adjustment. However, the station was fixed in a small experimental cell and there was no robotic routine for the adjustment. The second problem is the time consuming path planning for cooperating robots, if the robots are not geometrically coupled. However, this is not possible for the given process because each robot has to move individually during the pick-up motion in order to preshape and drape the large cut-pieces into a 3D geometry. Further, path planning becomes increasingly difficult if robots interact due to the risk of self-collision. This depends on the layout of the robotic cell, the size of the ply and the pick-up position relative to the ply.

2.2 Ply Detection

In previous researches at the DLR a system for autonomous manufacturing of composite parts with a multi-robot system was established. The system contains of two industrial

KUKA Quantec KR210 R3100 robots standing on a linear axis. Both are equipped with a vacuum gripper endeffector. One of the endeffectors is equipped with a computer-vision system for cut-piece detection. This setup was used to detect cut pieces of approximately 1.6 m by 1 m, grip them from the material carrier and transport and deposit it into the manufacturing mold of a fuselage demonstrator[2].

2.3 Automated Path Planning

In recent years, the CoCo system which automatically generates collision-free paths for cooperating industrial robots [3,5] has been developed. So far the system has been used for path planning of floor mounted cooperating robots on a common linear axis. The system is implemented in C#, uses Helix Toolkit [6] for 3D visualization and BEPUphysics [7] for collision detection of the simulated objects. For path planning sampling-based as well as evolutionary algorithms (EA) are used. For sampling-based algorithms Open Motion Planning Library (OMPL) [8] has been integrated into CoCo which includes many state-of-the art sampling-based motion planning algorithms like PRM, Rapidly Exploring Random Trees (RRT), RRT-connect. A detailed description of the implementation and a benchmark of the EA can be found in [5].

3 Experimental Setup and refined Process Chain

The goal of this research is to show the feasibility of the fully automated process chain. This was done by using the automated process as part of the manufacturing of a rear pressure bulk head with Airbus A350 geometry [4].The following gives an overview of the hardware used and the changes made to existing sub-processes.

3.1 Experimental Setup

The demonstrator was built on the multifunctional cell (MFZ) at the ZLP in Augsburg [9]. The cooperative handling was done with two ceiling mounted KUKA Quantec KR210 R2700 robots on a common gantry. Both robots face in the same direction. The material carrier was positioned centrally under the gantry with a height of 998 mm in order to ensure reachability. The edge of the mold was 1682 mm high and its center is shifted [mm] mm from the axis of the gantry. The position was chosen as a trade-off between reachability of the robots and collision prevention. In this setup however, it was difficult to find valid paths that can reach over the edge of the mould right underneath the gantry, due to the robots axis limits and self-collision. There were two different ply geometries that can be distinguished and are seen in Fig. 2.

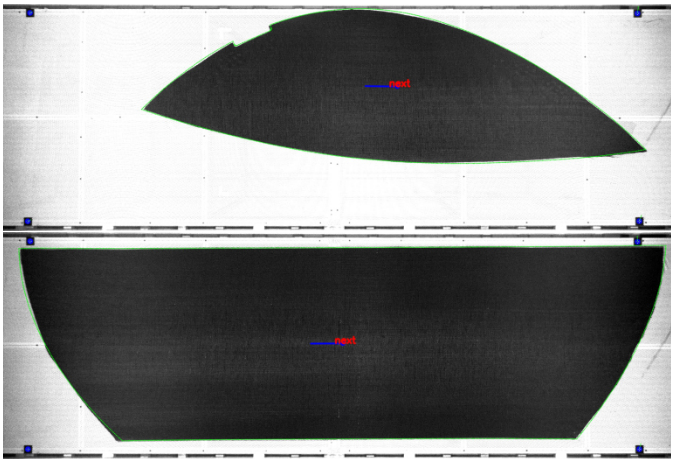

Fig. 2: Plies as detected by the camera – edge ply (upper) and center ply (lower)

The two pictures were taken by the ply detection camera and show the plies before pick-up on the material carrier. The first cut piece was the edge ply (upper picture) with a length of 3700 mm. The second cut piece was a center ply which was 4300 mm long and 1315 mm wide.

3.2 Production Data

The production data is derived from a 3D CAD plybook. It consists of information about the shape of the flat ply including pick-frames relative to its center (2D), the drop-frames in the mould (3D), as well as corresponding angle settings for the grippers. The 3D information is directly derived from the CAD plybook via macro. This data is used to calculate the corresponding 2D pick-frames in the plane. For this purpose, first a mesh of 2D points was generated. Subsequently, using the geometry transfer functionality of CATIA, for each of these points the corresponding 3D point in the mould was computed. Now the gripper position in the mould was expressed in a local coordinate system consisting of the nearest three generated 3D points. The corresponding 2D points were used to obtain the orientation of the local coordinate system in the plane which corresponds to the 3D coordinates relative to the ply and thus the pick frames. This strategy is inverse from the one described in [2] where the 3D positions were computed from given 2D positions. However, the calculated pick-frames have to be further manipulated to fit the process. Due to the rolling pick-up motion in combination with the spherical geometry the modules diverge from each other during the process. However, the modules are placed normal to the plane and a simple rotation around the z-axis was used to solve this problem. Specifically, the current gripping frames were rotated around the z-axis in such a way that the two preceding modules - which already left the gripping plane – stayed equidistant compared to their respective gripping frames during pick-up. Mathematically this was done by a numerical approximation due to the heavy involvement of trigonometric functions.

3.3 Automated passive Adjustment of the Grippers

The measuring and clamping unit that is part of the gripper system was redesigned in the past in order to work independently of the layout of the robotic cell. The adjustment station with the gripper during its routine is depicted in Fig. 3.

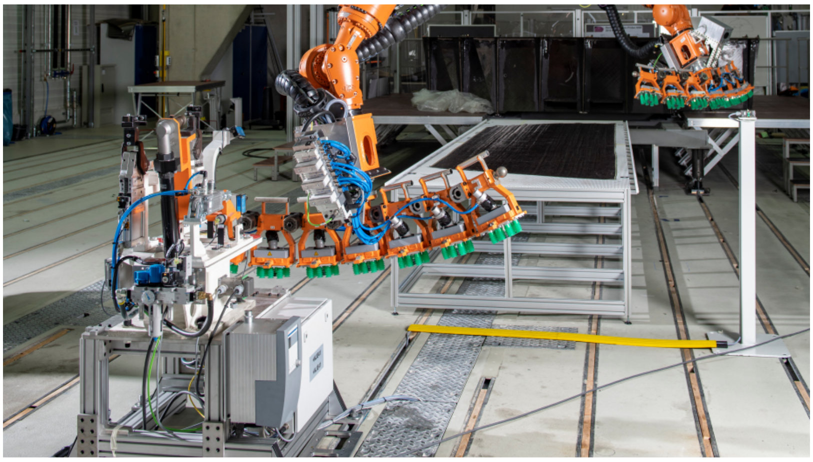

Fig. 3: Robot with gripper during the adjustment at the station

A robotic routine for the adjustment was developed. The program measures each module of the gripper twice with two photoelectric sensors. Two measurements are needed to calculate the orientation about one of the axis of a local coordinate system which is subsequently oriented parallel to the clamping unit (Fig. 3). After measuring the actual geometric setting of the gripper the robot moves the measured module in the clamping unit and performs a rotation about the ball joint of the module to the desired geometry. This is repeated starting from the center to the outer modules until the gripper reaches its nominal geometry. Subsequently, the actual geometry is measured and stored in the program as basis for the following modules in order to prevent consequential errors in the kinematic chain.

3.4 Ply Detection

The hardware for the computer-vision system for cut-piece detection was added to the robotic cell. First an industrial PC was set up in the cell and connected to the robot gigabit network. The PC was installed with a manufacturing execution system (MES) with integrated cut-piece detection software (CDI). The MES coordinates the preforming processes of detection, robot movements and path planning. In order to detect the cut-pieces an industrial camera was mounted to one robot (R10) and connected to the network. Regarding to the increase in cut-piece length from approximately 1.8 m up to more than 4 m several improvements of the existing system were necessary. First, the camera needs to be approximately two times higher above the material carrier to see the entire cut-piece. According to the higher distance the camera focus was adjusted to generate sharp pictures. Also the gain of the flash lamps was increased to produce high contrast pictures. Most changes concern the robot movements. There are two defined poses for the robots during detection and pick-up. First a starting position (SP) which is the default position. From the SP the robot moves to a detection-position in which the camera is above the center of the material carrier. After detection the SP is reached again to guarantee collision free movement. To handle the larger distances the movement along the linear axis was added during the transfer between these positions. Due to the complex spectrum of cut-piece geometries, one SP is not sufficient to reach all cut pieces. Therefore a third position in the grip position (GP) is added. The GP aligns the robots close to the grip points of each cut-piece to ensure reachability. For the pick-up motion several grip-frames are processed during the routine, one for each module. Since this feature was designed for picking from a plane, an add-on was needed to move into the spherical transport position for the ply. This position is the starting frame for the path planning algorithm.

3.5 Path Planning

CoCo was previously used for floor-mounted robots on a common linear axis. For the production scenario presented here, the robotic cell was modelled with ceiling mounted robots. For collision detection the individual axes of the robot, the pick-up table and the gripper are represented by convex hulls. The collision shape of the tool shape is represented by a grid structure, because when using a convex hull, the positioning of the grippers within the tool shape would always lead to a collision.

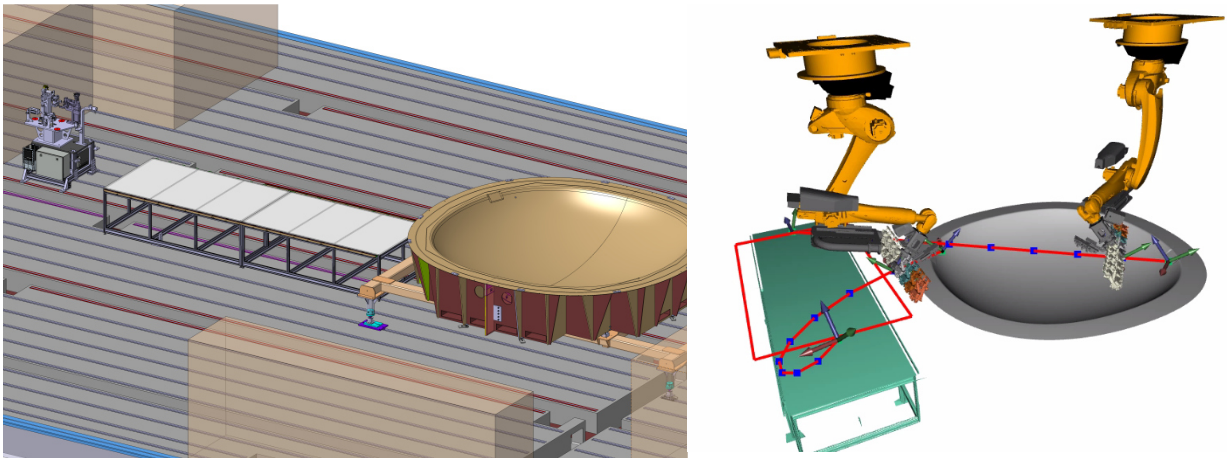

Fig. 4: Experimental setup (left) - Simulation of early ProtecNSR scenario in CoCo environment with calculated path in red (right)

The planning was executed with constraints in the cartesian SE(3) room. For this purpose, the orientation of the grippers is first reoriented to the orientation of the drop position after the 2D pick-up and then fixed during the entire planning process. RRTconnect was used as planning algorithm. The inverse kinematics of a common 6-axis robot can be determined analytically so that a maximum of eight possible solutions can be found. If an external axis is added, there are an infinite number of solutions for each position. Therefore, a heuristic was developed for the positioning of the external axis, which provides a valid position of the external axis for each TCP position. To do this, the slider of the external axis of the right robot (R30) is first positioned as far to the right as possible and the slider of the left robot (R10) as far to the left as possible. Then the external axis of R30 is moved step by step in the direction of R10 until a valid configuration has been found. In the second step, the external axis of R10 is then moved in the direction of the configuration just found for R30 until a valid configuration has also been found.

4 Results and Discussion

In general, the interplay of the three presented technologies works well with the implemented improvements. This was demonstrated for both ply geometries. However, we were not able to pick up and place all plies due to limitations regarding collision and reachability. This was caused by the setup of the robotic cell, namely the high placement of the tooling and the axis orientation of axis one of both robots. This can be seen in Fig. 5, which depicts the transport of one of the large plies. Both robots are set up facing the same direction, which limits the possible robotic paths when handling cooperatively. In the following the results for the overall process are assessed focusing on the different stages of the process: process preparation, pick-up and lay-down strategy, as well as path planning and transport.

Fig. 5: Transport of one of the center cut-pieces

4.1 Process Preparation

As a first step in the process chain the grippers were adjusted. Our tests showed that the robotic routine of measuring and resetting the endeffector works well. The control measurements indicate that the angular deviations are within a degree of the nominal value which results at most in a translation of 6.6 mm for the center of the innermost modules. Naturally the consequential errors add up which causes greater errors in the modules further out. However, the geometry matched the calculated pick-up motions, even for the border plies where both endeffectors form a continuous chain of suction modules. This poses a massive accuracy improvement compared to the manual adjustment.

Ply detection was the second process step. The added features in the MES and CDI enabled the detection of cut-pieces up to over 4 m in length. No false detections were made. The minimum correlation factor between the given CAD generated cut-piece geometries and the detected was 84 %. This is satisfying but can still be improved in different ways. For large geometries a camera with a higher resolution can be used to increase the pixel to mm ratio. Further, improvements are needed regarding the cut-piece logistics. Though the transport from the cutter to the material carrier is only semi-mechanized, deformation and sheering occur, thus reshaping the ply.

4.2 Pick-up and lay-down Strategy

The pick-up strategy for the plies is a rolling motion to the calculated grip-frames. Fig. 6 shows the grippers during pick-up of one of the center cut-pieces. Two gripper modules at the time – one for each robot – are moved simultaneously to their corresponding gripping-frame and the ejectors are switched on.

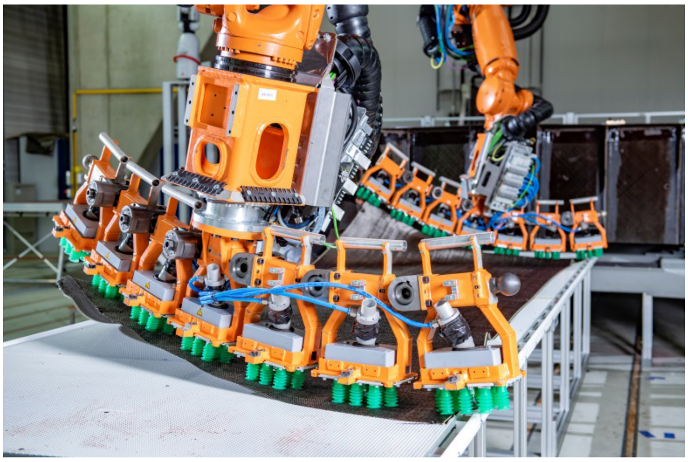

Fig. 6: Grippers during the pick-up of a center cut-piece

After all modules are attached the robots move into the pose relative to each other that is equivalent to the pose during drop-off. The positioning of the modules depends on the ply geometry. The outer suction pieces of the gripper had a distance of 80 mm from the edges. For the edge plies both grippers form a consecutive chain of modules on the long edge. The center plies are handled on opposing sides of the ply (compare Fig. 6). Unfortunately, the grippers caused problems, due to insufficient volume flow. Since a module can only be used if all its suction pieces fit on the ply, the number of modules varied with the different cut-piece geometries. In some cases the amount of material sticking out caused the ply to peel during pick-up. In order to prevent this, the volume flow rate of the ejectors must be increased. Further, the optimal width of plies should be considered during design of the plybook. The lay-down motion was a simple movement down from a position where the ply was not in contact with the mould. The idea was that the robots hold the ply in its final shape during transport in order to avoid unintended sheering of the material. This proofed to be insufficient, because the soft suction pieces of the grippers need to be pushed into the mould to ensure contact over the whole active surface. The simple motion downwards therefore pushed the material slightly. This caused waviness in the material. Additionally, excess modules not used for the given ply got in contact with the material during lay-down and caused misplacement. This happened despite excess modules were maximally adjusted to keep away from the mould. The mentioned problems can be seen in Fig. 7, which shows an automatically placed center cut-piece. On the left side an unused module pushed the material and a big crease formed. Although this did not happen on the right side, distinct waves originate from the sole downward movement. A lay-down strategy with the modules pushing the ply into the mould normal to its surface is a potential alternative but may cause different problems due to the spherical geometry and is topic to be further examined.

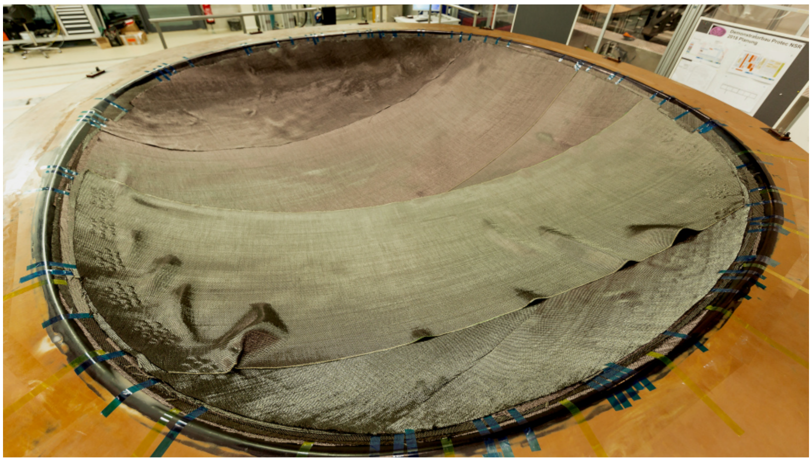

Fig. 7: Center cut-piece placed automatically in the mould

The accuracy of the position of the ply was checked with a laser projection and is satisfactory for both types of plies. This indicates that the general principle of the process is feasible.

4.3 Path Planning and Transport

The CoCo system was able to find collision-free paths for use in the scenario presented here with ceiling-mounted robots. It has been shown that the possible paths for the robots are very narrow, since self-collisions between robot and end effector can occur very quickly when lifting and transporting the blank. Only the possibility of CoCo to search the whole range of possible configurations of the external axis makes it possible to find collision-free paths. The calculation of the paths with the RRTconnect planning algorithm took an average of one minute.

During the tests it was shown that it is important to have exact models of the end effector and the attachments, especially in particularly narrow scenarios. The cable trailing should also be taken into account in the simulation, which represents a future improvement of CoCo.

There are still issues regarding the grippers during transport and placement. The volume based suction is not sufficiently strong for the given ply sizes and masses. Further, the adjustment limits between the suction modules are not large enough to prevent unused modules from interfering with the ply. This leads to a poor lay-up quality as seen in Fig. 7 and makes an assessment of the quality of the overall process difficult.

5 Conclusion

The automated process chain for the automated lay-up of large dry fibre cut-pieces using cooperating robots has been displayed for two different types of plies. The gripper system has been improved but should be redesigned in order to cope with current shortcomings. Passive adjustment is a feasible approach for adjustable grippers. Further, it has been shown that in-line path planning with CoCo saves an enormous amount of time compared to traditional OLP methods. Together with the ply detection the process becomes flexible for different production environments. However, the experiment proofed that the layout of the robotic cell itself has a vast influence on producibility despite the path planning algorithm. If these limitations are considered during the design of the robotic setup the displayed process chain is well suited for an industrial production.

6 Acknowledgement

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