Automated handling and positioning of large dry carbon fibre cut-pieces with cooperating robots in rear pressure bulkhead production

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ABSTRACT

For new generation long-haul aircrafts the rear pressure bulkhead is made of carbon fibre reinforced plastics. The production process is usually realised by a manually performed dry fibre preforming process followed by a vacuum assisted resin infusion. The preforming process is laborious, complex and for the workers non-ergonomic due to the handling of large cut-pieces with high positioning accuracy requirements. In order to fulfil the increasing production rates, this process has to be enhanced. For this reason the German Aerospace Centre in Augsburg develops an automated preforming process using a female tooling of the pressure bulkhead. This paper presents first investigations to handle large cut-pieces of the rear pressure bulkhead plybook by cooperating robots. The grippers used in this process are passive adjustable. They consist of five elements which are connected by ball-joints. Due to these ball-joints the geometry can be adapted to different shapes. The main objective is an investigation of suitable gripper movements in order to pick-up the cut-pieces from a table by draping it, transport and place it with high lay-up accuracy in the pressure bulkhead tooling. In total four different pick-up strategies are investigated to figure out which one is suitable to handle the cut-pieces without wrinkles, folds and bridging. The best strategy is optimised and used for lay-up tests where the same requirements obtain as for the pick-up movement. In conclusion the used gripper system can ensure a material handling without damage. Consequently it is possible to realise the preforming process with the passive and less complex gripper system. This may result in a more reliable and cost-effective process.

KEYWORDS Aircraft, Automated production process, Carbon fibre reinforced plastics, Cooperating robots, Rear pressure bulkhead production

1 INTRODUCTION

The increasing amount of civil air traffic results in a higher demand of aircrafts. In addition the demand for fuel efficiency and cost-effectiveness is increasing. This leads to the requirement to decrease the weight of aircrafts. An approach to reduce the weight is the use of carbon fibre reinforced plastics (CFRP) for structural components. More than half the structural mass of the Boing 787 and Aircraft A350 is made of CFRP. Up to now the production of CFRP parts consists of a high proportion of manually performed process steps.

The German Aerospace Centre (DLR) in Augsburg addresses this problem by working on process automation for these parts. A special part of this work is the realisation of automated production processes of large structural components, for example fuselage panels and pressure bulkheads. The DLR focuses on thermoset processes for these parts. Therefore a preform with dry carbon fibre textiles has to be prepared before it is infused by a vacuum-assisted process..

In this paper an automated preforming process for the rear pressure bulkhead of a next generation long-haul aircraft is shown. More precisely the handling properties for the large cut-pieces covering the whole diameter of the double curved tooling are investigated. The process is realised by cooperating robots which handle the cut-pieces with passive adjustable grippers. The large cut-pieces are used to form the shape of the part. In present production lines they are handled manually by two workers. They pick-up the cut-piece by hand from a table and transport it to the tooling. Due to the high positioning requirements and the size of the cut-piece, the exact positioning of it is a difficult requirement. This results in non-ergonomic handling positions for the workers and high process times.

In a previous automation approach the overall handling qualities of these cut-pieces with cooperating robots were investigated. The cut-piece was placed by hand at the tooling surface. From this position the cut-piece was picked-up and placed again at the same position by cooperating robots. Fig. 1 shows the test set-up. As material a non-crimp fabric was used. This material has a higher shear strength compared to the material which is used for the production of the component. The result of these first investigations showed that a general handling of large cut-pieces in a double curved tooling by cooperating robots is possible [1].

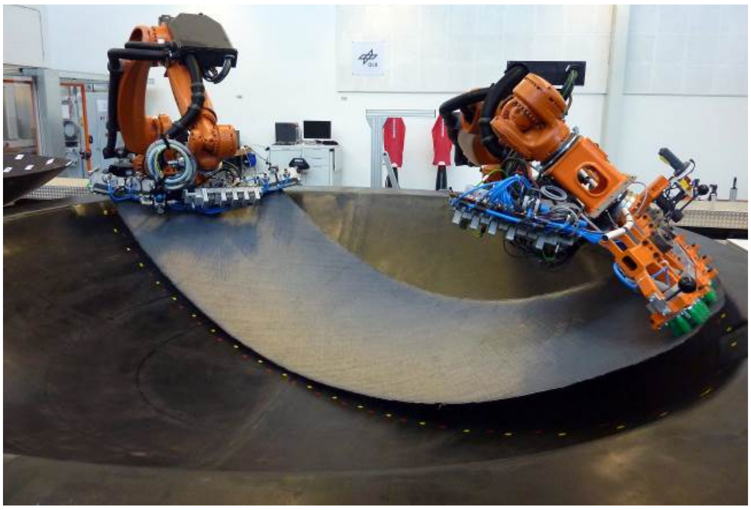

Figure 1: First handling test of large cut-pieces with cooperating robots [1]

This paper is based on this approach and attempts to achieve a complete automated handling process of the cut-pieces. The paper starts with the definition of the use case where the target structure and the test set-up are explained. The next chapter gives a clarification about general characteristics of draping and states the draping properties based on the use-case investigated. After that the procedure used to adapt the grippers to the lay-up surface is explained. Subsequently the robot offline programming is detailed. This is followed by a description of the performing tests, consisting of the strategies for material pick-up, the optimisation of this movement, the handling and the lay-up. Finally a summary of the results, a discussion and a conclusion is given.

For the automated processing of smaller cut-pieces in the preform refer to [2] and [3].

2 TARGET STRUCTURE

As a target structure the rear pressure bulkhead of the Airbus A350 is used. The tooling is double curved and its cross section is about 3600mm in length and 650mm in height. For the tests a tooling half of the original scaled rear pressure bulkhead tooling is used.

The plybook of the rear pressure bulkhead consists of two different categories of cut-pieces. On the one hand it includes cut-pieces for reinforcement. These cut-pieces have small dimensions and exist in different shapes. Due to their dimensions they are not appropriate for a handling with cooperating robots. Handling procedures for these cut-pieces can be found in [2] and [3].

On the other hand large cut-pieces are part of the plybook. These are up to four meters in length and cover the total length of the tooling. Four of them cover the complete surface and therefore form the shape of the rear pressure bulkhead. For the investigations in this paper one of the large cut-pieces is used to perform the tests. This cut-piece is modified in its position to fit the tooling half. The cut-piece is around 4100mm in length and 1150mm in width. As material a 1270mm wide satin fabric made of 6k carbon fibres is used. The mass per unit-area is 370gsm. Fig. 2 shows a schematic view of the tool half and the cut-piece used for the investigations.

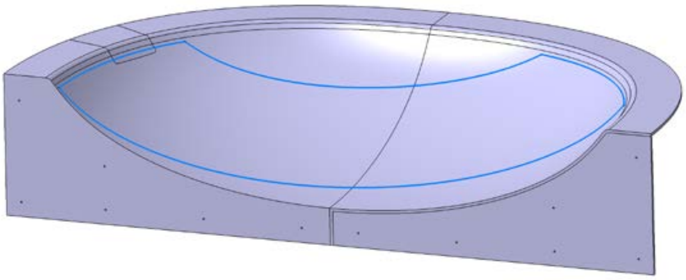

Figure 2: Tool shape and sample cut-piece

3 EXPERIMENTAL SET-UP

For the investigations a test bench of the DLR Augsburg is used. In this test bench two industrial robots are assembled on one linear axis. For the test with cooperating robots two identical grippers are attached. These grippers were developed to handle non-crimp fabrics to build a preform of a cylindrical half shell with local reinforcements [4]. The original grippers consist of nine elements which are connected by ball-joints. Due to the low width of the cut-pieces used in these tests compared to the cut-pieces used for the cylindrical half shell, the number of elements is reduced to five. This reduction results in a higher stiffness of the gripper which leads to better handling properties of the material. The element in the middle is fixed and the other ones can be rotated in x, y and z direction. Due to this characteristic the gripper can be adjusted to different surface geometries. At the bottom of each module eleven vacuum cups are placed. In [5] and [6] tests were made which show that these cups are appropriate to handle dry textiles.

On one side of the linear axis the tooling half is placed and on the other side a flat table is positioned to pick-up the cut-piece. Fig. 3 shows the test set-up.

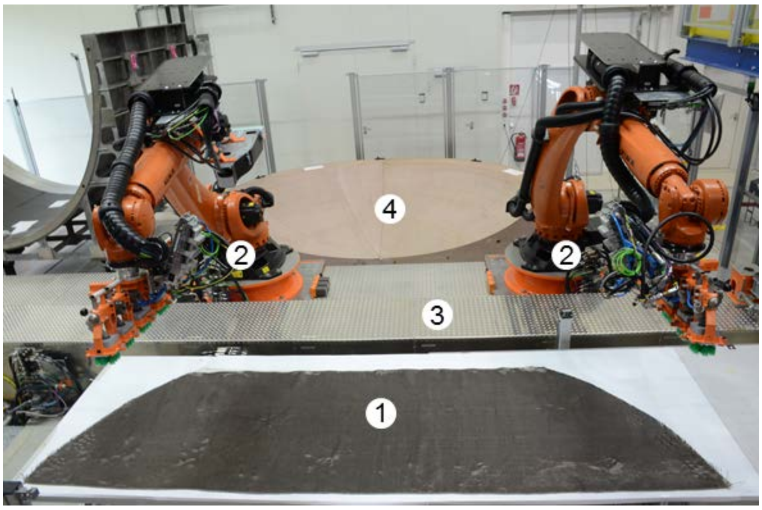

Figure 3: Test setup with pick-up table (1), robots and end-effectors (2), linear-axis (3) and mold (4)

4 CHARACTERISTICS OF DRAPING

For the investigations the material is picked-up from the table and placed in a double curved female tooling. Due to their passive adjustability the grippers have to drape the cut-piece during pick-up.

As mentioned in [4] there are different possibilities to drape dry fiber cut-pieces. A seed point or seed curve is chosen which is defined as the start point of the draping process. From this fixed point or curve the cut-piece is draped in all directions until it is lying at the surface of the tooling. For manually processes draping is almost unreproducible and often fiber deformations occur. Fig. 4 shows different fixations for the draping process.

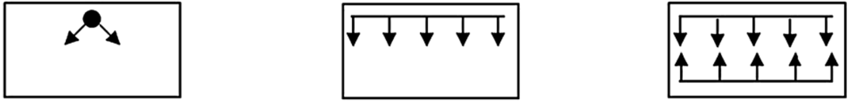

Figure 4: Point fixation (a), line fixation (b), double-line fixation (c) [4]

For automated processes the type of draping depends on the gripper, the tooling and the material properties. In the majority of the draping processes for dry textiles, the cut-piece is provided at a flat table. From this table the cut-piece is picked up by one or more robots. The amount of robots which are used to pick up the cut-piece depends on its size. Cut-pieces with a small size and/or complex shapes are often handled by one robot. In this case commonly kinematic grippers are used. These drape the cut-piece when it is completely picked-up from the table. One disadvantage of this type of grippers is the high complexity of the construction and the need of a control system. Fig. 5 shows an example for draping by a kinematic gripper. A test scenario with this gripper can be found in [7].

Figure 5: Draping by a kinematic gripper

In contrast, cut-pieces with almost rectangular shapes and a length of more than 2m are often handled by two robots. Both robots have to do synchronized movements to handle the cut-piece. The grippers which are used here are only passive adjustable. This means that the orientation of the grippers must be adapted to the surface geometry before the pick-up process starts. The final gripper orientation is equal to the curvature of the tooling where the cut-piece is placed. It follows that draping takes place during the pick-up process. When this process part is finished the cut-piece is already draped in the orientation of the tooling surface. Then the cut-piece can be placed at this surface without further deformations.

The surface geometry has an influence how complex draping is. When a cut-piece is placed at a single curved tooling, draping is less complex because only one orientation has to be adapted. This kind of draping can be performed with mostly all type of material with a low thickness. For draping in a double curved tooling the orientation of the draped material has to be adapted at least in two directions. A draping simulation is used to figure out if the material can perform the desired draping. Here woven fabrics are mostly suitable for draping at a double curved surface.

For the investigations in this paper the pick-up process is described in more detail. It starts with the first element of the gripper moving to the cut-piece surface. After placing this element, the vacuum flow is activated. Due to this the cut-piece is fixed at the first element. From this point the gripper is moving until the second element of the gripper is placed at the cut-piece surface. During this movement the material between the first and the second element is draped. Draping ends when the second element reaches its pick-up position. Compared to Fig. 4 there are in total five line fixations which are generated by the five elements of the gripper. The material of the cut-piece, each located between two line fixations, is draped. Fig. 6 shows this type of draping schematically.

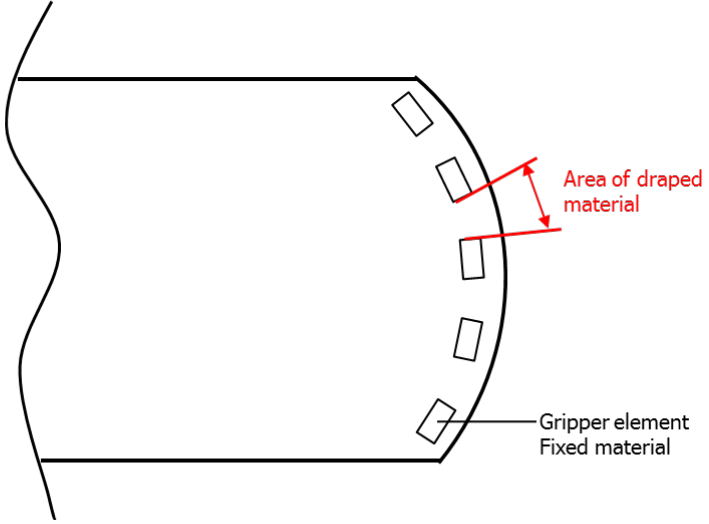

Figure 6: Draping area between the gripper elements

5 ROBOT OFFLINE PROGRAMMING

The robot programming is done via Dassault Delmia V5 in combination with CATIA V5. The cut-piece mentioned in chapter 3 is constructed on the mold surface and with the composite design workbench a flattening (2D-geometry of the cut-piece) is generated. This gives a possible geometry for the cut-piece as well as an indication for the robot movement design. Starting by defining the robot positions for the lay-up, the movements are reverse engineered to the pick-up.

First a tool center point (TCP) is determined for each end-effector element. Afterwards coordinate systems are generated on the three dimensional model of the cut-piece for each lay-up position of every gripper element. As a result five coordinate systems on each side of the cut-piece are needed. Therefore a visual basic program has been written to resemble the kinematic structure of the two grippers to create these coordinate systems. For each short side of the cut-piece a parallel curve is generated and the centre point of the curve is determined. This point together with a straight line perpendicular to the outer edge of the cut-piece defines the first coordinate system and the position of the centre element of the gripper. It is used to construct spheres to each side to resemble the ball-joints to the next elements. The outer intersection between the parallel curve and the two spheres provides the TCPs for the next two elements. Together with additional perpendicular lines they determine the corresponding coordinate systems. This step is performed for all ten gripping points.
In order to determine the coordinate systems for the pick-up, the TCPs have to be transferred to the flattening of the cut-piece. The composite design workbench provides the functionality to transfer additional geometries according to the internally calculated cut-piece transformation. This function is used to transfer the TCPs on the flattening and create coordinate systems together with perpendicular lines to the cut-pieces outer edge on its short sides.

With the coordinate systems in the mold the adjustments of the individual elements can be calculated. Therefore the four transformation matrices ${}_{0\text{-}0}T_{0\text{-}1}$, ${}_{0\text{-}1}T_{0\text{-}2}$, ${}_{0\text{-}0}T_{1\text{-}0}$, and ${}_{1\text{-}1}T_{1\text{-}2}$ between the elements are calculated and the Euler angles between the elements are determined.

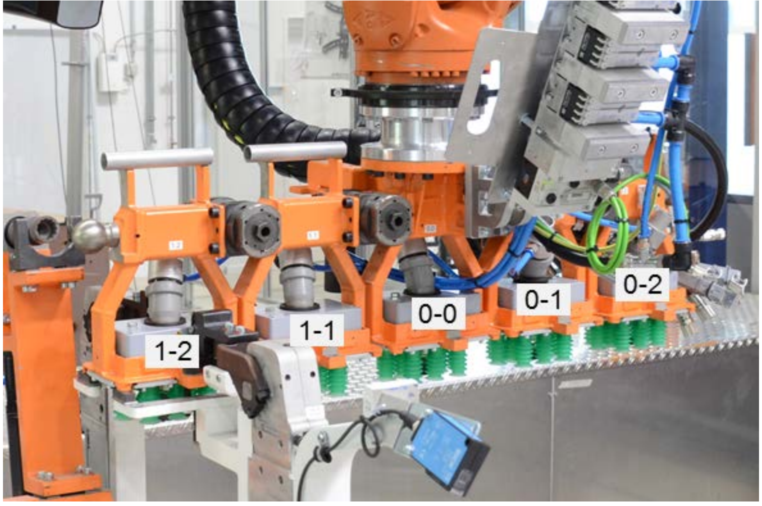

Figure 7: End-effector in the automatic adjustment station

Fig. 7 shows the end-effector in the automatic adjustment station with the designation of the elements. This adjustment station can be used to adapt the gripper elements to fit its position in the mold. Although the system is designed to do these adjustments automatically it is done manually for this paper. In [8] the automated adjustment station is described in more detail.

6 STRATEGIES FOR MATERIAL PICK-UP

In total four different pick-up strategies are investigated:

1. a rolling movement, short to long side,
2. a contrary rolling movement
3. a seesaw movement
4. a rolling movement, long to short side

The best strategy is used for optimisation and further tests. For all described strategies the grippers are adapted to the surface geometry where the cut-piece is placed. The movements of both grippers occur at the same time.

For the first strategy the cut-piece is picked-up by both grippers from the short side to the long side of the cut-piece. The first element of the gripper is placed closed to the short side. Than a rolling movement is performed until the fifth element is placed close to the long side. From this point the cut-piece is lifted (Fig. 8, R01 and R02: EDCBA).
During the material pick-up from element 1 to 5 the distance between the grippers increases. This generates tension in the material. At one point the tension is too high to be compensated by the vacuum cups which hold the cut-piece and as a result the cut-piece peels off.

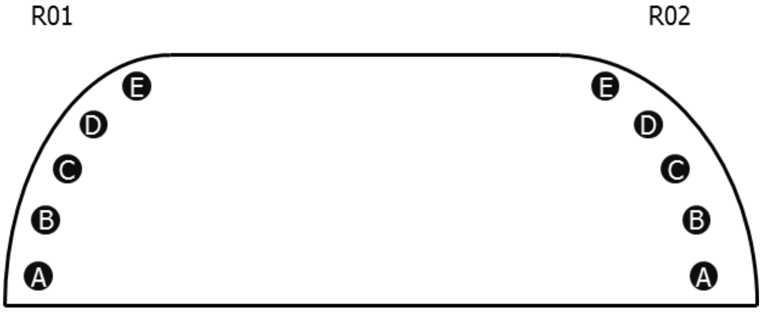

Figure 8: Material pick-up strategies for robots R01 and R02

The contrary rolling movement is performed with the grippers picking up the material in the opposite direction. One gripper (R02) picks the material from the long side to the short side and the other one (R01) from the short side to the long side (Fig. 8, R02: ABCDE, R01: EDCBA).
Both grippers start with the material pick-up at opposite sides of the cut-piece. During the material pick-up by the first element of each gripper the material which should be picked-up by the fifth element is not fixed at this time. During the pick-up by the first element a material displacement occurs at the other edge which results in a deviation of the grip points generated in CATIA.

For the third strategy the grippers start the pick-up movement in the middle between both cut-piece edges. From there a rolling movement is performed to pick-up the material with the next two elements in the direction of the long side. After that a rolling movement is done from the long side to the short side, to pick-up the material with the last two elements. This is resembled by the combination of CBADE in Fig. 8 for both robots.
The problem of this strategy consists in the second rolling movement from the long side to the short side. During this movement the cut-piece is already fixed at the elements A, B and C. As a result the material is dragged over the table, the vacuum cups bend and finally the material peels off. Due to this and the result of the contrary rolling movement the pick-up strategy of the seesaw with contrary moving grippers was not investigated further.

Strategy four picks up the cut-piece with both grippers from the long side to the short side (Fig. 8, R01 and R02: ABCDE). The first element of the gripper is placed close to the long side. Than a rolling movement is performed until the fifth element is placed at the cut-piece close to the short side. From this point the cut-piece is lifted.
During this movement the material is draped between the elements. The distance between the grippers decreases within the whole material pick-up. A generated tension in the material can be compensated by the flexible vacuum cups. The cups prevent a material deviation of the picked material and therefore a displacement of the grip points.
This last pick-up strategy shows the best properties and is used for further investigations.

7 OPTIMISED PICK-UP MOVEMENT

Although the first approach for generating the pick-up coordinate systems is a good approximation it became evident that further requirements have to be fulfilled. Especially for cut-pieces with a strong curvature on the short sides the end-effector orientations in the last gripping points are crucial (Fig. 8, element E).

It can be observed that the material detaches on the first gripping element (Fig. 8, element A) due to great rotations around the z-axis between the first and the last element. Thereby the z-axis is defined as surface normal of the pick-up table oriented in the table plane. This can be explained by the increasing distance between the first two elements (Fig. 8, E-E) of each end-effector. The satin weaved material contains carbon fibres running through the material preventing it to stretch. As a consequence no end-effector element pair (A-A, B-B, C-C, D-D, E-E) may increase their distance after they picked up the cut-piece. To ensure the pick-up movement is compliant two key factors have to be considered: the adjustments on the end-effector and the orientation of the coordinate systems for pick-up. Since the end-effector adjustments are crucial for the lay-up, only the coordinate systems orientation can be modified. In case of the cut-piece used in this paper an adjustment of 5° for position E of robot 1 (compare Fig. 8) from 43° to 38° was sufficient.

8 LAY-UP

The transportation to the mold has to be done with a fixed distance between the robots and tilted end-effectors to resemble an average catenary between the cut-piece and the robots. When the position above the mold is reached the final lay-up movement starts. By lowering the end-effectors in the direction of the mold the material touches the mold first in the middle of the cut-piece and spreads to both sides. Sliding of the material on its short side can be countered by the robot movement. Therefore the material on the short side has to touch the mold first. Here is the maximum slope of the mold. Then the robots perform a rolling and lowering movement. Thus material in the critical part of mold is placed first and then dragged to its ideal position.

9 RESULTS

The used satin weaved material shows a high drapability and associated a good permeability to air. Both characteristics are a challenge for the robotic handling of this material with vacuum cups and especially for large cut-pieces. Its drapability is necessary for a wrinkle free lay-up in the highly spherical bulkhead mold though. The required draping of the cut-piece has to be done by the robot movement strategy due to the fact that the end-effectors are only passive adjustable. Even though this reduces weight on the robot it adds complexity to the process.

The investigations show a proof of concept, the pick-up and transport as well as the lay-up of the test cut-piece was successful.

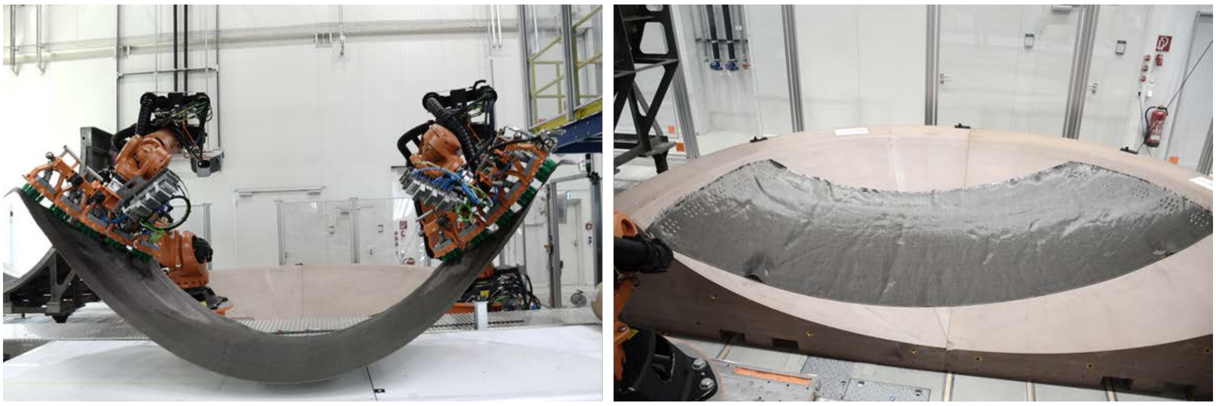

Figure 9: Transportation of the cut-piece (left), lay-up result (right)

Fig. 9 shows the transportation and lay-up result of the cut-piece. While picking up the cut-piece folds are introduced. They are built because the grip points and the drop points are located in different positions on the cut-piece. This allows the described draping process. On the right the lay-up result is presented. The positioning of the cut-piece is ambivalent: on the right side it is in the tolerance of the laser projected contour. On the left hand side the cut-piece is out of tolerance. Two main folds are visible on the cut-piece, one on the left of the long side and the other one on the right hand side. In addition several wrinkles cover the cut-piece and the traces of the suction cups are visible.

10 DISCUSSION AND CONCLUSION

As seen in the results cooperative handling of large, air-permeable carbon fiber fabrics on the principle of volume flow is possible. Although the error tolerance for robot movements regarding jerks, translation and rotation differences between the robots and work angles for the end-effectors is low. The higher stiffness of the grippers due to reduction to five elements reduces vibrations and therefore increases reliable handling of the material. It is conceivable that the two significant folds could be prevented with a slight end-effector rotation or a single movement of one robot with one element correcting the placement position. Regarding the areal wrinkles the authors suggest that previous handling trials affected the cut-piece.

This suggests that a passive draping is possible although the quality of the process should be enhanced. Further work has to be done to adjust the grippers with the automatic adjustment station to minimize the positioning errors. In addition the quality of the lay-up has to be examined and compared to a hand laid cut-piece. Assessing the robot programming, a more automated tool for all cut-pieces in the part is preferable, i.e. a software tool that implements cooperating robots. This would reduce the programming efforts significantly. [9] and [10] show a possible approach for an automated path planning.

11 ACKKNOWLEGEMENT

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