Automated Draping of Wide Textiles on Double Curved Surfaces

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Abstract: In many different industries like aviation, shipbuilding or the production of wind turbines, the draping of textiles is a common issue. Especially large components in long- and medium-haul aircraft have a high potential of weight reduction by using composites. In many cases increasing material and manufacturing costs are caused compared to metal design. Therefore automation is one approach to achieve profitability. A robot end effector for the automated deposition of 50 inch wide fibre fabrics was tested. The experiments were performed in full scale, with plies of an aircraft pressure bulkhead. When depositing these fabrics on curved surfaces, defects such as waves or wrinkles appear. In order to solve this issue, the end effector was extended by adding an adaptable material buffer. The development regarding mechanical design, calculation for determining the axis movement as well as the axes control is presented. Compared to previous attempts without an adaptable material buffer, an improved deposition quality was achieved. The results of the experimental investigation are shown.

1 INTRODUCTION

In the field of aviation, wind turbines and ships, large components made of fibre composites are used, as these have a very good strength to weight ratio. During the production of these components in the process step referred to as preforming large textiles have to be deposited on shape-giving moulds. This can be done via precut plies or by direct deposition from the supply roll in a rolling motion. In order to reduce production costs, a high deposition rate (kg/h) is targeted. In this context, the influencing factors for a specific automated process are the process speed and the type of fabric used. One approach to increase the deposition rate is the use of wide textiles with a material width of up to approximately 1270 mm (50 inch).

During preforming, the textiles have to be manipulated to conform to the mould surface. In case of double curved geometries draping is necessary. (Elkington et al., 2017) In this process the textile is distorted in a defined way, meaning that the angle between weft and warp roving (shear angle) is modified locally. The maximum achievable change of the shear angle (locking angle) depends on the geometry of the mould and the type of textile. (Manson et al., 2000) The use of wide textiles in terms of preforming poses special challenges, as larger areas have to be manipulated at the same time. If draping is insufficient, fabric imperfections will appear. Thus, out-of-plane deformation in form of wrinkles can occur at the inner radius of curved plies (Olsen and Craig, 1993). Since the components mechanical properties depend to a large extent on the quality of the preforming, measures must be taken to prevent fabric imperfections. Therefore the main challenge is the development of a process that allows the draping of textiles to be controlled in a defined way. In this respect, the main influencing factors in the automated rolling deposition of textiles must be considered, such as synchronization of the rotary movement of the supply roll and end effector movement, contact pressure on the mould surface and length differences between inner and outer radius of curved plies. The compensation of these length differences was investigated in the present work by developing an adaptable material

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buffer for a robot end effector used for the rolling deposition of carbon fibre fabrics.

2 STATE OF THE ART

In the manufacturing process of fibre composite structures, the layup and draping of textiles is often still carried out manually, such as for the rear pressure bulkhead of particular aircraft types (Schnitzer, 2013), wind turbine blades (Zhu, 2015) or shipbuilding. For this purpose, precut textiles are used. The final draping is done by manually applying pressure on the fabric. The worker's level of skill and experience is decisive here in order to avoid inducing fabric imperfections and achieve the desired positioning tolerance.

The most well-established automated processes in the industrial production of composite components are the rolling deposition of textiles with Automated Tape Laying (ATL) and Automated Fibre Placement (AFP). These processes can be carried out completely automated with systems from various manufacturers, such as Fives (France) or MTorres (Spain). (Sloan, 2008, Marsh, 2011) Here a respective placement head end effector is guided by an industrial robot or a gantry system. In most cases an active system to prevent wrinkles during depositing is not integrated. These are avoided by adhering to the process constraints ensuring that the process-specific minimum depositing radii are not exceeded.

The ATL process consists of applying one or more tapes from supply rolls to the mould surface simultaneously. The tapes have a width of approximately 75 - 300 mm (3 - 12 inch). A maximum material width of approximately 600 mm (24 inch) can be achieved in a multitape configuration. Since steering is only possible to a limited extent due to the material width, the process is mainly used for large flat or simply curved components, such as wing skins, fuselage panels (Gardiner, 2011) or wind turbine blades (Black, 2009).

One approach for applying tapes to more complex geometries is the advanced ply placement process (APP). (Szcesny et al., 2017) Here, precut plies are gripped and guided by two robots to the correct position. Simultaneously, a third robot drapes the textiles onto the mould surface with a roll end effector.

The AFP process is comparable to ATL. Here, up to 32 narrow textile strips (tows) with a width between 3.175 and 12.7 mm (1/8 - 1/2 inch) are depositioned at once. An overview of the process can be found in (Kozaczuk, 2016). Compared to ATL, smaller steering radii can be achieved due to the use of smaller textiles. Depending on the degree of curvature, gaps or overlaps between the tows can occur, which can only be tolerated to a certain degree, since they have a negative influence on the mechanical performance (Croft et al., 2011). A summary of the capabilities and limitations of the ATL and AFP process is given in (Lukaszewicz et al., 2012).

Another approach of depositing textiles on double curved surfaces shows (Zhu et al., 2017). The automated layup of 280 mm wide dry glass-fibre non-crimp fabric (NCF) was tested with a method called shifting. Hereby the fabric is manipulated in such way that no out-of-plane waviness occurs.

Few publications regarding rolling deposition of textiles with widths over 600 mm can be found. As part of the research project "mapretec" (Ohlendorf et al., 2014) an end effector was developed which can be used to wind up precutted plies with a maximum width of approximately up to 1270 mm (50 inches) and apply them to the layup position by rolling. However, only deposition on flat surfaces without contact to the mould surface is possible, since the rigid structure of the end effector does not allow adaptation to the mould geometry. Draping is carried out separately by means of a form variable tooling. Likewise, end effectors with comparable properties were developed in the research projects "preblade" (Weigel and Müller, 2007) (material width: 300 - 1300 mm, max. ply length: 10 m) and "PRO-CFK" (Müller, 2007) (max. material width: 1400 mm). In the latter, the direct deposition of the textiles from the supply roll into the contoured mould was additionally tested. Here no precutted textiles are used. The ply length is only limited by the material quantity on the supply roll. The draping takes place without active control via the depositing movement of the textile.

The layup process of the Precision Feed End Effector (PFE) developed by Automated Dynamics (Groppe, 2007, Black, 2003) is comparable to the process of the end effector used in this study. The PFE features a flexible compaction roller design and can accommodate curved panels with a 40-ft minimum radius. It is possible to process textiles with an approximately width of 150 - 1500 mm (6 - 60 inch). The end effector developed in the context of the research project "BladeMaker" (Richrath et al., 2017) is also capable for layup on double curved moulds. The precut plies can have a material width of up to 1270 mm (50 inch).

A general overview of existing roller gripping and draping systems is given in (Ehinger, 2013).

3 RESEARCH ISSUE

One big issue according the automated handling of textiles is: how to apply a two-dimensional fabric onto a three-dimensional mould without creating waves, wrinkles or other critical defects. In this context waves are out of plane defects characterized through their width and height while wrinkles are defects in which the fabric doubles over itself (Wade, 2012). The compensation of different lengths between the two textile edges is one approach to an automated draping of textiles.

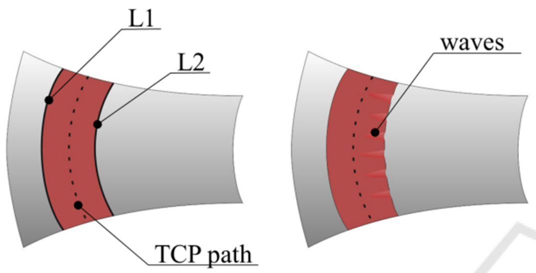

Figure 1: Generic sketch of a textile ply on an aircraft fuselage with the path of Tool Centre Point (TCP).

Looking at the geometry of a generic aircraft fuselage and the ply placed on it, one can see that L2 in Figure 1 is shorter than L1. Depositing the ply without further measure would cause waves due to the surplus material on L2. A compensation of the difference in lengths of L1 and L2 is necessary.

Dependent on the process conditions one solution could be to perform an optimized path generation to overcome this issue (Schmidt-Eisenlohr et al., 2019). In the considered scenario, the fibre angles are critical to the mechanical properties of the component. Therefore it is not possible to modify the ply orientation. A different approach for a defect free draping process had to be found.

4 APPROACH

One approach to buffer the different length of the ply in the robot end effector is a mechanical solution. Therefore an adaptable material buffer was developed.

The concept was to create a mechanical buffer that could independently add or absorb material from both sides of the fabric as needed. Assuming that the curvatures on large aircraft components are not subject to strong fluctuations, a system was conceived that contains an additional deflection roller between two independently movable and electrically driven linear guides. With this setup it should be possible to influence the lengths of the two edges of the fabric without affecting the layup position. Figure 2 shows a sketch of this concept.

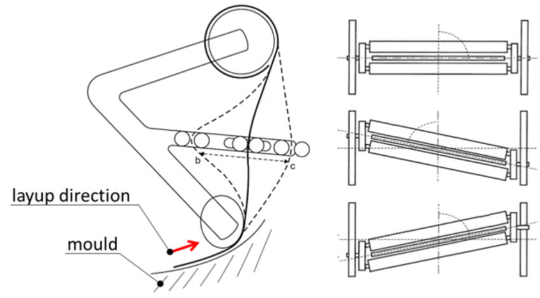

Figure 2: Material buffer concept.

4.1 Process Description

The use case considered in the work for draping textiles is the automated preforming of a rear pressure bulkhead of an airplane. This component is located at the end of the aircraft cabin. It is highlighted in Figure 3.

Figure 3: Rear pressure bulkhead in an aircraft.

In Figure 4 the used end effector guided by an industrial robot together with the mould and one ply is shown. There are three curves highlighted: L1 as the length of the left edge and L2 as the length of the right edge of the ply and the path of the Tool Centre Point (TCP). The TCP is located in the middle of the draping roll (see Figure 5 and Figure 6) and has contact to the mould during the deposition process. The draping roll can be adapted by five linear units to ensure a compliant contact over the whole width of the draping roll. Further it is driven by five stepper motors at the bearing points of the linear units. The stepper motors are synchronised to the robot movement.

The deposition process starts with a robot movement into the start positon. Then the contour of the draping unit is adapted to the mould surface by moving the linear units. After that the robot moves perpendicularly into the mould and presses the draping roller onto the surface. The torque control of the linear units is switched on and the deposition process starts.

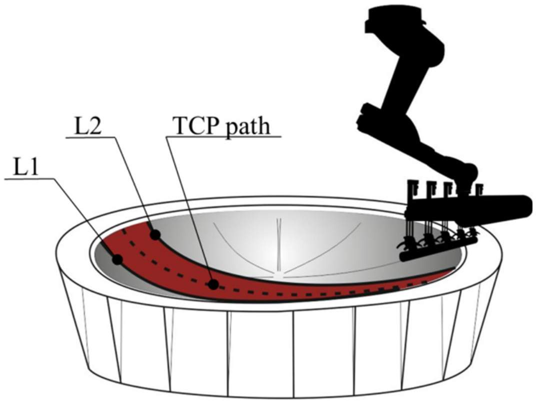

Figure 4: Experimental setup.

The trajectories for the depostion process have to be perpendicular to the mould surface. Thus the paths generation is quite complex and would be to imprecise and time consuming by hand. Therefore the robot movement is generated by Offline Programming (OLP). The OLP is based on a CAD model of the robotic cell, the mould and the end effector. It can generate the programs for the robot motion.

4.2 Mechanical Design

As mentioned, the motivation for adding a material buffer was the occurrence of waves during previous layup test. The end effector used was designed by Premium Aerotec as part of the project AZIMUT (Niefenecker, 2014) and is shown in Figure 5

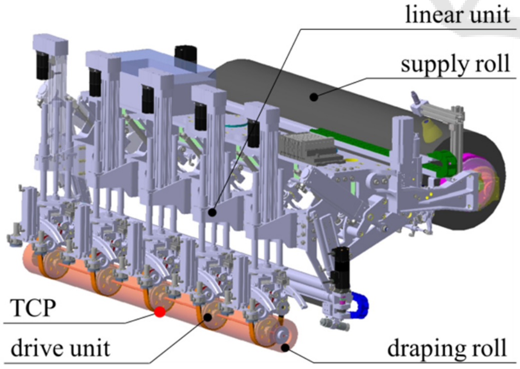

Figure 5: End effector without material buffer.

With the scope of the design of the material buffer various requirements had to be observed. The main technical requirements are:

- The added weight to the end effector must not lead to an overload of the robot.
- The maximum moment of inertia of the entire end effector, including the buffer, is decisive for the movement processes of the robot. It has to be taken into account when designing the storage capacity.
- The end effector together with the material buffer must not collide with outer or inner interfering contours during the deposition process. Therefore an OLP path planning should be carried out beforehand by means of a simulation tool.

An accessibility analysis was carried out to determine the installation space for the material buffer and to prevent collisions with the mould. According to this offline simulation there is no interfering end effector contour allowed in between the red-marked area shown in Figure 6. Therefore the arrangement of the material buffer took place as an extension in the longitudinal direction of the end effector. The solid line in Figure 6 represents the edge length of the material at the maximum deflection of the material buffer. The dotted line represents the edge length of the material at its minimum deflection. A yellow double arrow indicates the direction of movement. Since both sides of the material buffer work according to the same principle, only one side is described in the further example. The buffer system consists of the parts shown in Figure 7.

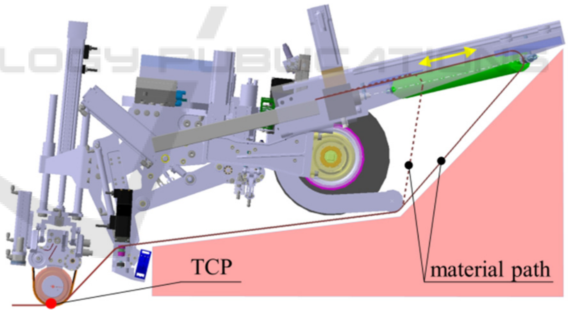

Figure 6: Side view of the end effector with material buffer.

The fabric coming from the supply roll is guided over the angle adjustable roll to the fixed guiding rolls where it is passes through. After that the fabric is guided to the draping roll and is finally applied on the mould surface. For controlling the length of the material edges the angle adjustable roll has a linear guiding system. During the deposition process the carriage of the guiding system is moved by a gear screw jack which is driven by a servo motor. The control of the buffer system is described in chapter 4.4.

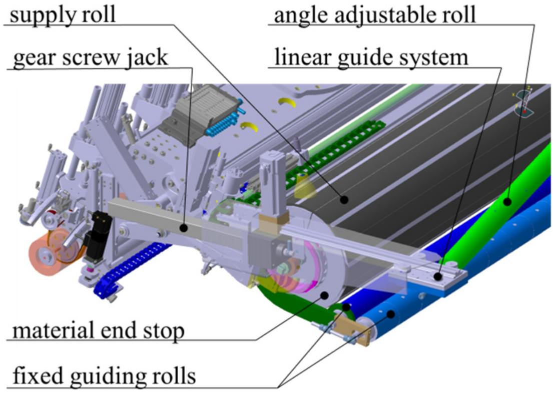

Figure 7: Material buffer in detail.

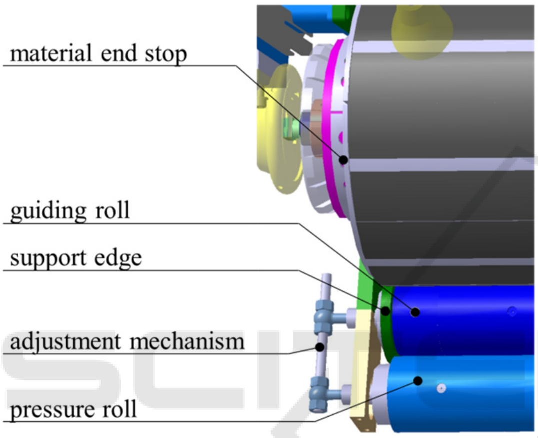

Figure 8: Material guiding.

In previous test there were two additional issues according to the material guiding and buffering. Depending on the robot position, single textile layers on the supply roll can lose position by sliding to one side. By shifting the material layers the occurring offset also effects the fabric position on the mould. Therefore a mechanical end stop was added to the supply roll. Further it has to be considered, that as a result of moving the angle adjustable roll differently on both sides, a material guiding is created were one axis is not parallel to all the other guiding rolls. This can cause a material drift whose strength and direction depends on the inclination of the angel adjustable roll. Therefore fixed guiding rolls were added to the end effector. Design details are shown in Figure 8. One guiding roll was designed with support edges which should prevent the material from drifting. The other roll can press onto the material to prevent wrinkling. The pressure can be adjusted by a mechanical mechanism.

For the control of the material buffer it is important to know the exact geometrical conditions within the buffer system. By moving the linear guide of the material buffer the length of the material edge changes nonlinear in relation to the axis movement. Therefore the target position of the two linear guides of the angle adjustable roll must constantly be calculated during the applying processes. The exact geometrical calculation is shown in chapter 4.3.

4.3 Capacity Calculation

For simplifying the calculation of the storage capacity, only the two material edge lengths are calculated. The difference between the edge lengths is the theoretical storage capacity. The maximum deflected end of the roll is, decisive for the maximum length of the unrolled material. The edge length of the minimally deflected roll end provides a base value for the calculation of the edge length change.

Regarding the formulas shown in chapter 4.3, it was assumed that the minimal radius of the supply roll r_{ma} is greater than the radius of the angle-adjustable roll r_1 (see Figure 10). The planes of the material edges intersect the longitudinal axis of the deflected angle-adjustable roll (see Figure 9). In the following formulas, a simple circle contour is assumed as a simplification. With the construction, the maximum error is less than 1 mm.

4.3.1 Track Calculation of the Carriage

The length l_{gr} is defined as the length between the gear screw jack and the center of the first roll (see Figure 10). For this purpose, the gear screw jack was projected into the material edge plane. The length difference Δl_{gr} of the lengths l_{gr2} of the right side and l_{gr1} of the left side (see Figure 9) can be calculated according to formula (1).

$$\Delta l_{gr} = l_{gr1} - l_{gr2} \quad (1)$$

The calculation of the material edge length is described in chapter 4.3.2. All geometrical quantities on the opposite sides are indicated with the indices 1 or 2 (see Figure 9).

The roll width l_{ma} as well as the lengths between the axis of the gear screw jack and the rolls of material l_{am1} and l_{am2} are known. The difference Δl_{gr} must be calculated beforehand (see chapter 4.3.2). Thus the stroke change Δs of the carriage can now be calculated with formula (2).

$$\Delta s = \frac{l_{ma}}{\Delta l_{gr}} \cdot (l_{am1} + l_{ma} + l_{am2}) \tag{2}$$

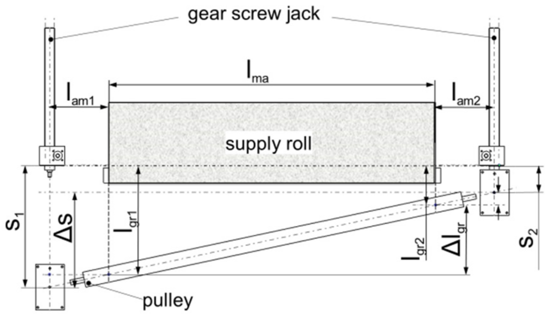

Figure 9: Geometric quantities for calculating the difference Δl_{gr} of the lengths l_{gr1} and l_{gr2}.

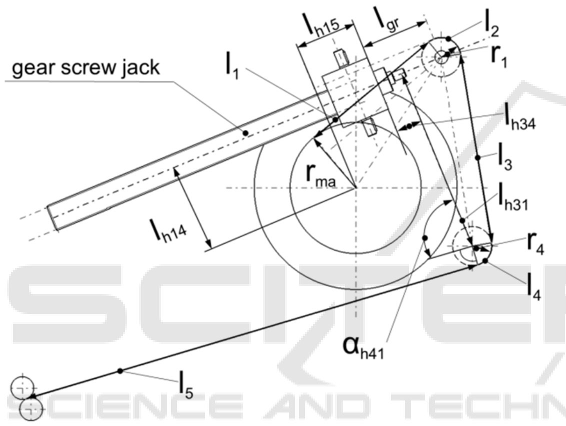

Figure 10: Geometric quantities for calculating the lengths l_1 to l_4.

With the stroke change Δs the new stroke s_1 can be calculated.

$$s_1 = \Delta s + s_2 \tag{3}$$

4.3.2 Edge Length Calculation

The illustrated geometric quantities are differentiated into the types of constructively determined quantities, measurable quantities and variables. These quantities are described below.

All geometrical quantities with the index "h" are auxiliary quantities. These are determined constructively, as well as the radii r_1 and r_4. The radius of the supply roll r_{ma} can be measured by a sensor or calculated based on historical values. The length l_{gr} is the length in the material edge plane between an edge of the projection of the gear screw jack and the centre of the angle-adjustable roll. The total material edge length L is calculated with formula (4).

$$L = \sum_{i=1}^{5} l_i \tag{4}$$

The equations (5) to (8) describe the calculation of the lengths shown on Figure 10.

$$l_1 = \cos\left(\arcsin\frac{r_{ma} - r_1}{\sqrt{(l_{gr} + l_{h15})^2 + l_{h14}^2}}\right) \cdot \sqrt{(l_{gr} + l_{h15})^2 + l_{h14}^2} \tag{5}$$

$$l_2 = \frac{2 \cdot r_1 \cdot \pi}{360} \cdot \left[\arctan\frac{l_{h14}}{l_{gr} + l_{h15}} - \arcsin\frac{r_{ma} - r_1}{\sqrt{(l_{gr} + l_{h15})^2 + l_{h14}^2}} + 90 + \arctan\frac{l_{gr} - l_{h34}}{l_{h31}}\right] \tag{6}$$

$$l_3 = \frac{l_{h31}}{\cos\left(\arctan\frac{l_{gr} - l_{h34}}{l_{h31}}\right)} \tag{7}$$

$$l_4 = \frac{2 \cdot r_4 \cdot \pi}{360} \cdot \left[180 - \alpha_{h41} - \arctan\frac{l_{gr} - l_{h34}}{l_{h31}}\right] \tag{8}$$

The length l_5 is also a constructive determined length. All rolls in contact are stationary with respect to the end effector. According to the geometry of the mould, the length difference Δl_{gr} per time unit or distance unit is determined. Due to this length difference, it is possible to calculate the stroke change Δs, necessary in this unit, according to equation (2).

With the given quantity L of the length of the material edge of the roll, the implicitly contained quantity l_{gr} can be calculated with equation (9).

$$0 = L - \sum_{i=1}^{5} l_i \tag{9}$$

This can be done, for example, with the help of the zero approximation method named "false position method" or "Regular Falsi". This method is described in (Bronstein et al., 2008) and (Kiusalaas, 2013). These calculations can be done by the robot controller.

4.4 Control Architecture

The control architecture for the experimental investigation is as follows. The industrial robot with its linear axis is controlled by the KUKA Robot Control (KRC). All other actors and axis of the end effector as well as the axis for the material buffer are controlled by a PLC. The communication between the KRC and the PLC goes via EtherCAT. Since both systems act as masters, there is a master/master bridge between them. For controlling the material buffer there are three points that need to be considered:

Robot Speed. For buffering the correct amount of material it is important that the axis movement of the material buffer is synchronised to the velocity of the TCP. The synchronisation is done via the submit interpreter of the KUKA robot by transmitting the current robot speed (speed of the TCP).

Geometric Characteristics of the Mould. Further, it is important to consider the geometric characteristics of the mould for the deflection of the material buffer. For calculating the axis movement in context of the length difference between the material edges one has to consider the ratio of the side lengths and the length of the TCP path for calculating the axes speeds. Therefore a CAD based plybook contains the target positions of all plies. Out of this plybook a CSV file was created with the 3D length information of the two material edges and the TCP path. With this information it is possible to calculate the target position of each material buffer axis. In order to achieve an exact material buffering not only the target position but also the buffering speed is decisive. For this purpose the three paths were divided into equal pieces with a defined length and imported into the CSV. During the deposition process a position counter detects the current sequence and transfers the length information into the geometrical calculation part of the software. There a geometrical induced offset is calculated for controlling the two axes speeds of the material buffer. This approach provides some inaccuracies related to the number of pieces in which the path is divided, but it is a good approximation of reality. The calculations become more accurate by an increasing number of denominations.

Geometric Characteristics of the Material Buffer. Locking at the mechanical design of the material buffer (chapter 4.2) it is clear, that the axis movement of the buffer is neither equal nor linear to the buffered material length. Therefore it is necessary to calculate the axis movement in consideration of the geometrical behaviour of the material buffer. A more detailed description of the calculations is described in (chapter 4.3). Figure 11 shows the control architecture for the material buffer.

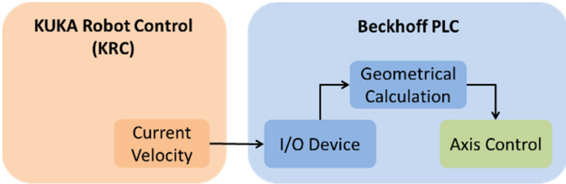

Figure 11: Schematic sketch of the control structure for the adaptable material buffer.

5 VALIDATION

The adaptable material buffer was validated in an experimental investigation

5.1 Setup and Implementation

For validating the material buffer an exemplary ply (P0011) was chosen. Table 1 shows the basic geometrical characteristics of ply P0011.

Table 1: Geometrical characteristics of the ply P0011.

Ply No.	P0011
L1	3599 mm
L2	4060 mm
Length difference	461 mm

For increasing the adhesion, a thin film of epoxy resin was sprayed onto the mould surface. The ply was at first laid up without using the buffer system. After that the mould was cleaned and the resin film was renewed. Then the same ply was laid up by using the material buffer. The process parameters are shown in Table 2. Apart from the buffering, all other settings remained the same, including the Parameters of the geometrical velocity offset for the draping rolls as well as the robot speed and the amount of resin. The general setup for the experimental investigation is shown in Figure 4.

Table 2: Process parameters of the experimental investigation.

Fabric type	Satin wave
Material width	50 inch
Weight per unit area	370 g/m²
Process speed	0,1 m/s
Layer fixation	Yes (epoxy resin)
Velocity offset for the drives of the draping roll	Yes

5.2 Results

The results of the experimental investigation are shown in Figure 12. Picture (1) shows the ply depositioned without using the material buffer. There are four out of plane defects (waves). The first wave is a large one on the left side in picture (1). The second one is a midrange wave in the middle of the ply and the last two waves located in the rear section are quite small. Picture (2) shows the ply depositioned by using the material buffer. One can see a small wave at the beginning of the ply. The rest of the ply is without any defects.

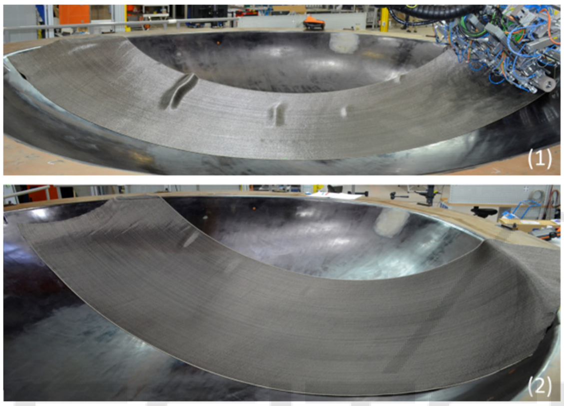

Figure 12: Results without buffer (1), with buffer (2).

Figure 13 shows the condition of the material in the end effector after finishing the layup. Picture (1) shows the end effector after applying the fabric without using the material buffer. One can see the loosley material tension in between the guiding rolls by the accumulation of the surplus material on the right. Further one can see the strongly distorted fibre angel roughly indicated by the red line. Picture (2) shows the end effector after applying the fabric by using the material buffer. One can see the material with more tension and less surplus material. Also the distortion of the fibre angle is less, indicated by the red line. A summary of the experimental results is shown in Table 3.

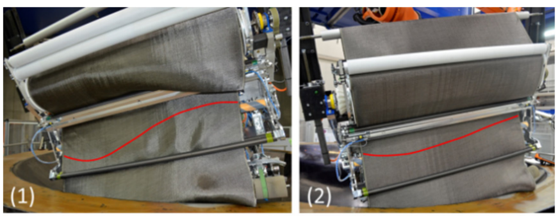

Figure 13: Material tension and fibre angle without buffer (1) and with buffer (2).

Table 3: Results of the experimental investigation.

Ply No.	P0011	P0011
Material Buffer	yes	no
Material tension	tight	loosely
Fibre distortion	small	high
Out of plane defects:		
▪ Number	1	4
▪ Type / Classification	wave	wave
▪ Size	small	big - small
▪ Location	start	continuous

6 DISCUSSION

The implementation of the adaptable material buffer improved the results of depositioning wide textiles onto double curved surfaces. It could be shown, that the material guiding in between the end effector improved. The material tension was higher and less surplus material was left in the end effector Figure 13. Also undesired shearing of fibre angles within the end effector has been reduced.

But there are also disadvantages that have to be mentioned. As described in chapter 4.2, inserting an inclined axis causes a material drift. The strength and direction of this drift strongly depends on the angle between the buffer axis and the other guiding rolls. Also the implemented support edge could not completely prevent the material drift. By using the buffer system in its rear workspace this undesired material movement can be reduced, but not completely avoided. This would require an online position correction of the robot movement.

Additionally there are still small waves on the ply were at least the bigger one would be critical in the industrial production. One reason that could be determined was an influence of the buffer system on the supply roll. For providing a constant tension the supply roll is controlled by a torque limitation. By moving the angle adjustable guiding roll of the buffer system an additional force acts on the supply roll. This force can lead to an increasing output of material which causes waviness. Therefore an improvement of the control settings for both systems (material buffer and supply roll) is necessary.

Further it has to be mentioned that the experimental results shown in Figure 12 were both reached with the use of a geometrical velocity offset on the drives of the draping roll. It has to be pointed out, that the use of just one of these two methods would not be enough to reach proper results. The geometrical velocity offset for the draping roll will be presented in a further work.

7 CONCLUSION

In this paper a buffer system is introduced that acts as an assisting system for the automated draping of textiles. The issue of length differences when depositioning textiles on double curved surfaces is addressed. As a solution, an adaptable material buffer which can independently control the two edge lengths of the fabric during the application process is proposed. For this solution the mechanical design, the control architecture and the mathematical background for controlling the buffer system are presented. The suggested approach was implemented and evaluated by an experimental investigation. The results were emphasized and improvements like layup quality, material guidance as well as the occurring disadvantages are discussed. Future works have as goal the improvement of the interaction between the supply roll and the buffer system, as well as the correction of the material drift by deflecting the adjustable roll of the material buffer. The geometrical velocity offset, passed onto the drives of the draping roll, must also be fully integrated. Nevertheless the present approach is a promising solution which can contribute to the automated draping of textiles.

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