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Simulation based draping of dry carbon fibre textiles with cooperating robots

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Abstract

Carbon fibre-reinforced plastic (CFRP) is a promising material for aircraft and other lightweight applications. To be competitive with low-cost metal based solutions highly effective and flexible production technologies are required. For this purpose production systems comprising automated fibre placement or automated tape laying technology are on the market for several years and widely spread. However, there is still a lack of automated systems capable of producing preforms efficiently and flexibly from textile semi-finished goods. Non-crimp fabrics (NCF) and weaves have to undergo considerable shear and reshaping during the layup of 3D-curved preforms in order to properly fit the 2D cut pieces to the moulds.
At the Center for Lightweight Production Technology (ZLP) a digital and automated process for the easy draping of large NCF and weave cut pieces with several robots according to the previous draping simulation has been set up and tested in a robotic work cell. The details of converting the draping simulation into correct and easy to setup motions for cooperating robots and how to execute the entire process autonomously, i.e. without teaching the robots, are described. On the basis of preliminary tests the system's capabilities on a large scale demonstrator part resembling an airplane's rear pressure bulkhead are evaluated. An overview of the system's architecture from simulation based planning to detecting, correct gripping, collision free autonomous transport and laydown of the cut pieces is also given.

Keywords: Cooperating robots; autonomous production; digital process chain; computer vison in manufacturing

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1. Introduction

For the production of CFRP parts and components the fibres have to be arranged properly according to the CAD model in a preforming step in order to meet the part specifications. Though a wide variety of materials and processes for preforming is available, automation is mostly focusing on tape laying or fibre placement, where the material is fed continuously from bobbins. Preforming from semi finished goods commonly involves manual labour while automation is limited to cutting and material supply, since the material has to be draped to the correct shape by skilled workers. Automation of the preforming of semi-finished goods has been investigated during the last years [1, 2, 3]. Next to preforming directly from the material roll robot teams can be used in order to handle large cut pieces [4, 5]. Since draping is simulated during the design for flattening the cut pieces, ensuring that the 2D cut pieces fit to the desired shape and fibre orientation after draping, the usability of the draping simulation's results for automated production was investigated.

2. Experimental Setup

Previous work in the field of autonomous robotic pick and place preforming proved the suitability of the process for single curved parts and nearly single curved parts [7, 8]. A robot cell with two KUKA Quantec KR210 R3100 on a common linear axis was used to cooperatively handle 1 m wide and 1,6 m long cut pieces for preliminary system and draping tests. In a second step a bigger robot cell with two KUKA Quantec KR270 R2700 suspended on a topside-down gantry linear axis was used to demonstrate the suitability of the process for 5 m long cut pieces as part of an experimental future factory test for the automated production of a rear pressure bulkhead (Fig. 1).

Fig. 1: Experimental setups for the preliminary and factory tests.

It is worth mentioning that the preliminary test was conducted solely in 2D, so that the grippers did not need any three dimensional shapeability, while in the factory test 3D-reshapeable grippers were used that were adjusted to the surface normal of the calotte-shaped tooling, following the cut piece's edge, in a separate shaping station. The adjustable gripper is built as a kinematic chain of up to seven identical modules that are connected by ball joints. Each module is equipped with a vacuum ejector that can be switched individually in order to pick up plies sequentially. Both setups comprise a cut piece detection system (Fig. 2 left) described in earlier publications [6, 7, 8]. The camera system determines the position of the cut piece by template matching considering the desired 2D shape thus giving the best possible match. Since the cut piece's geometry is imperfect due to cutting deviations and may change notably during material supply the deviations are measured in order to improve cutting and transport (Fig. 2 right).

Fig. 2: Camera for cut piece detection mounted to one of the robots with detection result. The deviations from the ideal shape are drawn in enlarged form.

3. Digital process chain

As was shown in [6, 7, 8] the draping simulation’s results, as shown in Fig. 3, can be used for automated and even autonomous production on 2D and nearly 2D shaped parts. Since the situation is more complicated for 3D shaped parts it is necessary to consider several new aspects. Either the gripper must undergo a reshaping between grip and drop or the gripper is adjusted to fit the 3D shape and moves perpendicular to the gripping table while the gripper is only in partial contact. For the drop the gripper’s curvature may fit or surpass the tooling’s curvature and the gripper is either plainly dropping or -similar to the gripping- only in zonal contact during the drop. In either case the positioning of the gripper to multiple grip- and droppoints in combination with switching the ejectors has to be handled. Current research with reshaping grippers [9, 10, 11] showed that, since the hinges of the reshaping mechanism can never be in the cut piece plane, there is always a slip between the gripper and the cut piece that has to be measured and compensated. In this work static grippers were considered which are adjusted to the geometry before gripping with a curvature matching the tooling.

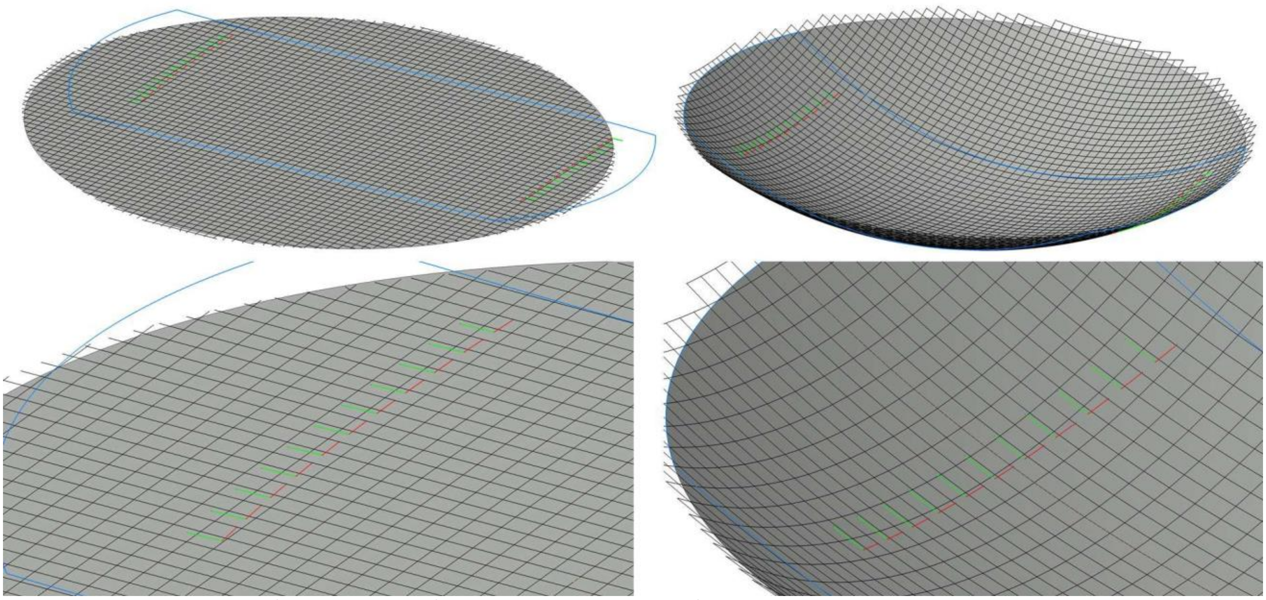

Fig. 3: Draping simulation of 2D cut piece (before grip) and 3D cut piece (after drop) executed with CATIA V5. Note the small coordinate systems for the gripper on both sides in the zoomed image.

Deriving the grip- and droppoints from the draping simulation leads to further considerations. First, the shape of the gripper has to match or to surpass the toolings 3D-curvature whilst the modules have to be located near the cut piece's edges. Assuming the curvature fits the modulewise contact points to the 3D cut piece the grippoints can be determined for instance by choosing each module's centrepoint in the suction plane. Since the orientation has to be considered as well the grippoints are 6D (contact points plus orientation). Depending on the chosen curvature either the modules' 6D tool centre points (TCPs) are chosen or the TCPs that would fit to the increased curvature. The next step is transferring the contact points to 2D by using the interpolated meshes resulting from the draping simulation with respect to the orientations. Assuming that the z-direction is normal to the cut piece, the following situation arises: since the local Frenet trihedrons follow the draping meshes both in 3D and 2D the x axis (Fig. 3 red lines) and y axis (Fig. 3 green lines) are no longer perpendicular after the transfer to 2D. This has to be compensated by making assumptions about the gripper. In our case it can be assumed that the material is fixed in the direction of the long side of the gripper and bends only in the other directions. Having now found a "strong" x and a "weak" y-direction one can obtain the new y-direction by taking the cross product of the z and x direction. Normalization of the Frenet trihedron is advisable since there is no guarantee that a unit length vector retains it's length in the draping simulation mesh. This compensation is absolutely necessary because if omitted bogus Euler angles for the robots are derived which lead to significant angular deviations that may be out of plane and thus can lead to collisions of gripper and tooling.

4. Execution layer

Today industrial robots rely heavily on teaching and offline programming. For the given application two problems arise: the quantity of different cut pieces each with several grip- and droppoints and the necessity to do teaching or offline programming for cooperating robots. The combination of both makes the conventional approach extensively time consuming. Tests at the DLR site in Augsburg roughly yielded teaching times of several hours to several days and offline programming times in the range of 15 minutes to several hours (excluding testing) per cut piece, depending on the complexity of the scenario. This time has then to be multiplied by a factor of 100..200, depending on the number of cut pieces in the layup. Therefore, it was decided very early to focus the research on autonomous production with the goal of a system that is capable of doing the preforming without further instructions. For this purpose, dedicated algorithms pass via-points generated from an abstract job description to the robots which then execute their paths with their specific path execution and synchronization controllers (Fig. 4).

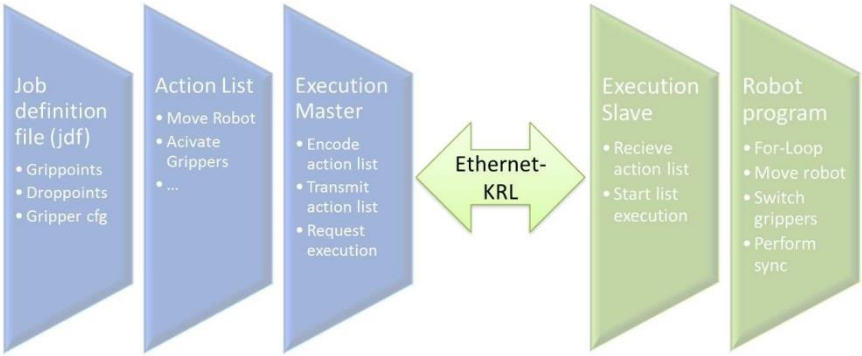

Fig. 4: Execution layer. High level systems (left) communicate with robots (right).

Grip- and droppoints as well as gripper relevant informations (e. g. active vaccum cups) are stored in a job descrip- tion file (jdf) that can be shared among all participating computers. Since the software modules are under development a human-readable and easy changeable file based format was chosen, while in the future a service-based architecture may be advantegeous. The jdf is parsed by a manufacturing execution system and transformed to an action list which basically contains robot motions and TCP-modifications together with gripper cup activations or deactivations. The execution master connects to one or several execution slaves via KUKA's Ethernet-KRL technology package and sends commands and parameters. Every slave acts as a server running a program that checks for incoming commands which trigger appropriate code snippets or subroutines providing the necessary execution parameters. After the inten- ded action is completed a handshake is performed in order to either continue or to stop with an error. If execution takes too long, a timeout is issued.

The robot's built in synchronization commands (here: MotionSync from KUKA's RoboTeam technology package) are used to ensure a proper cooperation of multiple robots. Additionally it was shown that via-points from a path planning simulation can be provided to the MES and then passed to the execution layer. This allows the transport of the gripped cut pieces to the tooling even in complex scenarios [12, 13, 14]. Therefore, the planner must be provided with actual and desired positions as well as with an accurate and actual cell layout.

5. Preliminary test

Goal of the preliminary test was to test the execution layer and to prove the feasibility of draping with a static gripper. A rectangular shaped cut piece sized 1600 mm by 1040 mm was detected and lifted from a table and directly dropped again while undergoing a draping of 25 mm (Fig. 5). For this purpose a cycloidal curve perpendicular to the y-axis and along the x-axis with a radius of 100 m was used for the grippoint calculation, resulting in a maximum lift off of 2.49 mm in the gripper's z-direction with a rotation around the y-axis of 0.4°. For the droppoint calculation also a cycloidal curve with radius 10 m was used, but this time perpendicular to the table's z- and along the x-axis resulting in a circular arc with 24.76 mm height. Additionally, the cut piece was rotated by 1° to test the overall orientation. The execution test was completed successfully three times. Measuring the cut piece with a ruler and a gauge yielded an arc height of ≈ 27 mm and a rotation of ≈ 1.1° in good accordance with the expected values (Fig. 5).

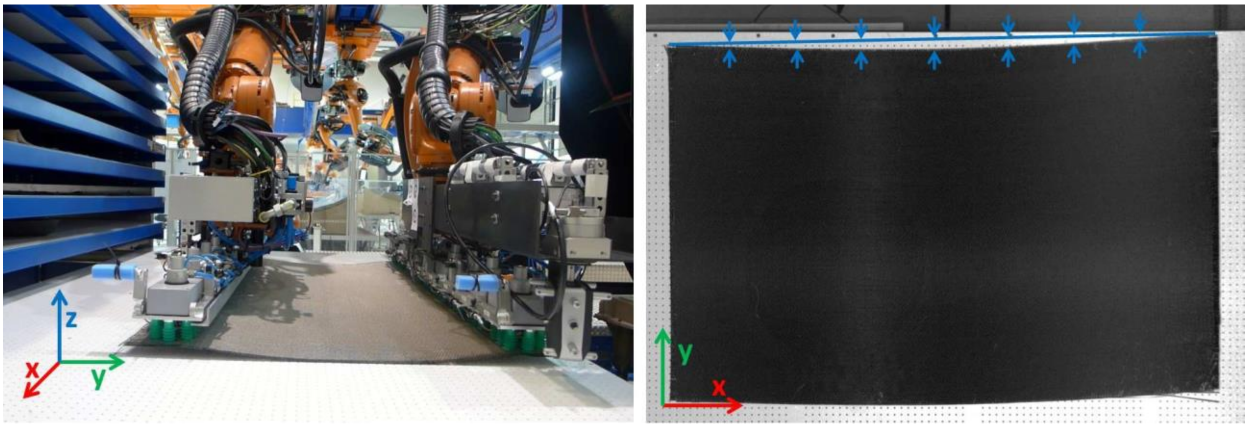

Fig. 5: The preliminary test shows good consistency with the expectations.

A more exact measurement was not feasible, since the cut piece itself already deviated from the desired shape by 1 to 2 mm, caused by deformations induced during the transport on the underlying supportive paper from the cutting process. Since this is not acceptable, measures were taken for the future factory test to preserve the cut piece shape during logistics.

6. Future factory layup

6.1. Grip and drape

In order to avoid unwanted deformation of the cut pieces during transport, the cut pieces were rolled up on a transport sleeve on the cutter and subsequently unrolled on the gripping table (Fig. 6 left side). A set of four differently shaped cut pieces was processed. The cut pieces were detected by the computer vision system autonomously according to the job description. Afterwards they were gripped and pre-draped by rolling the gripper module-wise over the cut piece according to the predetermined grippoints by passing the 6D-points to the execution layer (Fig. 6). The grippoints lay on the rolling curve of the pre-shaped gripper and were surface normal to the table.

6.2. Transfer and drop

After gripping, a collision free path was requested from the collision control system. Again, the 6D support points were passed to the execution layer and the cut piece was transferred without any user interaction (Fig. 7). Finally, the cut pieces were dropped into their final position by moving the grippers to the desired points.

Fig. 6: Future factory layup: Detection, start of gripping, end of gripping

Since the outer modules were not needed for every cut piece, in this cases they were not part of the simulation and thus not positionally well-defined. Therefore material undulations during the drop due to unwanted contacts between the cut piece and the inactive extra modules could be observed in several cases. The grippers, equipped with high flow vacuum ejectors, worked well even with the permeable material.

6.3. Problems and improvements

Since the suction force was limited by both air leakage through the material and pressure losses in the tubes supplying the pressurized air, the robot's maximum velocity of 2 m/s had to be reduced drastically down to 0.25 m/s during transfer and 0.05 m/s during gripping and dropping. Several cut pieces in the layup could not be processed by the robots in the present constellation, since a collision free transfer path could not be determined. This was based upon a poor cell layout and collision-prone system components (e.g. cable tow, power supplies) mounted to the robots. Another problem was lying in the robot's A1 axis limits: the robots root coordinate systems have the same orientation so the robots can't "face" each other since the cut pieces have to be turned around the z-axis during the transport from the table to the tooling. This means the "left" robot's elbow can easily collide with the "right" robot's gripper during transfer (Fig. 7).

Fig. 7: Future factory layup: Cut piece lifted, transferred and ready to drop.

7. Conclusion

The usage of cooperating robots with reshapeable, stripe-shaped grippers for the draping of large cut pieces of dry carbon fibre textiles showed high potential both in the preliminary and in the field tests. In order to obtain the desired draping, simulation results were successfully used to determine grip- and droppoints and the gripper's module orientations. The use of a hardware abstraction execution layer for handling the grip- and droppoints as well as the transfer was demonstrated. It proved reliable and far more flexible than conventional approaches, although speed optimization is definitely necessary. The material supply proved to be of crucial influence for the quality due to unwanted material deformation. Further tests concerning reliability, accuracy and speed are to be conducted in the future. Concerning the cell layout we believe that the collision control must be incorporated far earlier in the process allowing a optimized cell layout where all cut pieces can be processed at shortest time. This way constellations with unprocessable cut pieces can be avoided in advance and a flexible, automated production directly from the CAD data becomes possible.

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