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Design of an Automation System for Preforming Processes in Aerospace Industries

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Abstract— **Due to their material properties, carbon fiber-reinforced plastics have become more and more important in aerospace industries since the 1980s. However, their efficient use is still limited by a largely manual manufacturing process. In this paper, we present a novel automation system for preforming and draping dry carbon fiber textiles into a mold. It consists of a multi-functional robot end-effector, which integrates the three essential functions gripping, draping and fixation, as well as a software solution which supports the automation of the process. Experimental results gained on industrial reference toolings show the feasibility and flexibility of the approach.**

I. Introduction

Structures made of carbon fiber-reinforced plastics (CFRP) have an outstanding potential for a lightweight and stress-optimized construction [1]. Moreover, they exhibit further benefits like uncritical fatigue behavior, high resistance to corrosion, or free-shape design possibilities [2]. Due to these material properties, the spread of CFRP components in aerospace industries has increased exponentially during the last years [3]. Modern airliners like the Airbus A350 or the Boeing 787 prove this development.

Currently, the most common manufacturing technology is the prepreg method where thin sheets of pre-impregnated fibers within the matrix resin are used. The prepreg plies are cut into shape and, after the removal of a protection foil, are manually placed onto the mold surface. Finally, the prepreg layer build-up is compacted and cured in an autoclave. As the prepreg technique causes high capital investment costs (e.g. for an autoclave) as well as high running costs (e.g. storage at sub-zero temperatures), new injection methods, e.g. resin transfer molding or vacuum infusion techniques, have gained more and more relevance [4].

Fig. 1 shows the current assembly process using the Vacuum Assisted Process (VAP) technique developed at EADS [5]. Non-resinous dry carbon fiber textiles are allocated on fabric rolls and can be fed fully-automatically to a cutter table. Based on CAD data the plies are automatically

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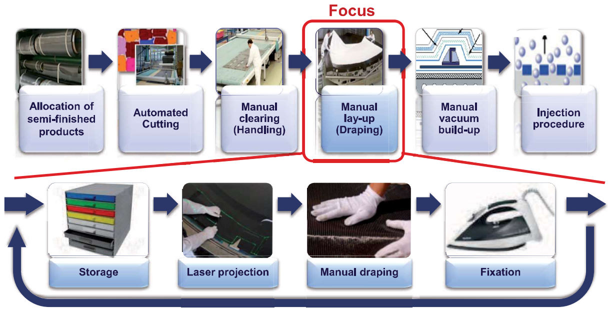

Fig. 1. Typical current industrial process chain for manufacturing composite components from dry carbon fiber textiles. Our research focus lies on the automatic preforming and lay-up by using a robot-based draping system.

cut. Usually, clearing the cutter table and storing the cut plies are the first manual step of the current manufacturing process. A robot-based approach of automating this step is suggested in [6]. The next step is the manual lay-up of the plies into a mold. It is comprised of a laser-guided, but still manual positioning and draping of the plies. To fix the plies, a thermoplastic binder material is melted by bringing in heat. Before the resin is injected, the layers are covered with an vacuum build-up which is also created manually. Finally, it is processed to an oven for curing.

Despite their advantages, the spread of techniques using dry carbon fiber textiles is still limited by high production costs. In particular, the manual draping is very time-intensive and the labor costs higher compared to prepreg [7]. This is, especially in high-wage countries, a major factor in the total economics of the production process. Moreover, manual draping is one reason for high rejection rates of resulting CFRPs. According to [8] the aerospace industry requires, besides a weight reduction of 30%, also cost reduction of 40% compared to traditional metallic light-weight structures in order to use CFRPs efficiently. Hence, adequate automation techniques are essential for future market penetration in aeronautics [9] as well as in other industrial sectors.

In literature several approaches for cost-effective automation of carbon fiber preform manufacturing can be found. Mills [10] suggests a high-speed tape laying system where an automated gantry and a tape deposition head is used to lay unidirectional fiber tapes. In [11], Greb et al. introduce automated, preforming technologies for multi-axial warp-knitted non-crimp fabrics. A multi-functional robot end-effector for the automated manufacturing of textile preforms is described in [12]. The robot end-effector consists of an adaptive end-effector to grasp and lay-up the fabric onto a flat or curved mold and a second system which consists of a convex and a cylindrical roll to drape the fabric in the mold.

In this paper, we present a novel robot end-effector and a sophisticated software solution for automating the preforming and draping process for dry carbon fiber textiles, achieving a tight integration with the aforementioned automated step of clearing the cutter. The end-effector integrates three basic functions, i.e. gripping, draping and fixation, and is designed modularly in order to cope with small as well as large textiles. The system requirements for the preforming process are presented in Sect. II. In Sect. III, the design of the new robot end-effector for draping limp carbon fiber textiles is explained. The design of the automation software is described in detail in Sect. IV. Sect. V illustrates experimental results gained with industrial reference components from Premium AEROTEC GmbH, Augsburg, and eurocopter Germany GmbH, Donauwörth. Finally, a conclusion is drawn in the last section.

II. System requirements

A detailed analysis of the current preforming process is the basis for the definition of the system requirements and the development of the end-effector [13]. Especially in aeronautics there exist various demands regarding the process, material and geometry. On the one hand, the used CF material is limp, permeable for air, anisotropic and of instable structure [14][15]. Due to high diversity of variants, large-scaled cuts must be handled as well as small reinforcements. Furthermore, the 3D-molds vary enormously in size and contour of the surface. The selected reference toolings, i.e. *spant*, *diaphragm*, *torque panel*, are good examples of this diversity (cf. Fig. 2). On the other hand, high quality standards must be met in aeronautics. This requires a gentle gripping process without causing any defects and an accurate positioning of the cut on the 3D-mold.

The low number of units and the high diversity of variants call for a highly flexible and modular design of the end-effector [16], so that different toolings and cuts do not require a dedicated end-effector, but can be draped fully automatically by an adaption to the scenario with only few and quick changes. A detailed analysis showed that the end-effector has to integrate three fundamental functions for the preforming process: gripping, draping and fixation. With respect to the process sequence the cut must be gripped from a storage system and transferred to the tooling. There, the textile must be draped onto a three dimensional shape of the tooling and fixed as soon as the textile is on the right position. Then, the end-effector can release the part and move back to the storage system. Software-supported path planning and control of the end-effector have to assure a consistent work flow of the preforming process.

III. Design of the end-effector

An appropriate design of the end-effector has to fulfill the system requirements described in Sect. II. As a first step, it is necessary to identify the optimal operation principles for the three basic functions gripping, draping and fixation, since they define the interaction between the end-effector and the textile [16]. Out of a great solution space, a planar suction method is selected for a gentle gripping of limb textiles without any contamination or damage of the cuts. During the draping process the gripped textile has to be deformed from a flat into a three-dimensional contour of the tooling. At this crucial process step mechanical stress and damage of the textile must be prohibited. Using a bended shape of the end-effector, it is possible to perform a rolling motion along the surface of the tooling with a linear contact between tooling, end-effector and textile. This reduces the stress on the textile. Additionally, an elastic layer is essential for a compliant behavior of the end-effector and a passive adaption to the surface. For the textile's fixation the thermoplastic binder on the back of the cut must be melted. By melting the thermoplastic binder fleece the textile is fixed on the requested position. The melting temperature can be obtained by the use of conduction heating, which achieves a defined local heating of the textile.

Based on the identified operational principles, the design of the preforming end-effector is conducted as the next step of the development process. Therefore an experimental setup consisting of a storage table, a robot and an industrial reference tooling as well as a first proof of concept are established and tested [17]. Driven by the promising results of the experimental tests an end-effector with target dimensions was built up and included in the demonstration facility [18].

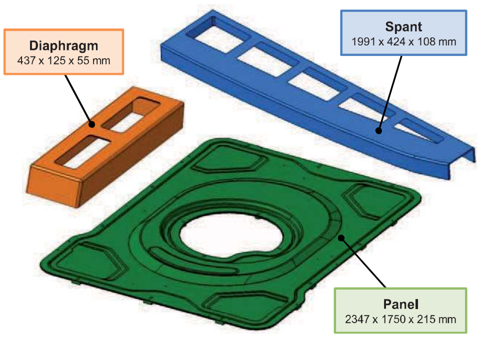

Fig. 2. The selected reference toolings

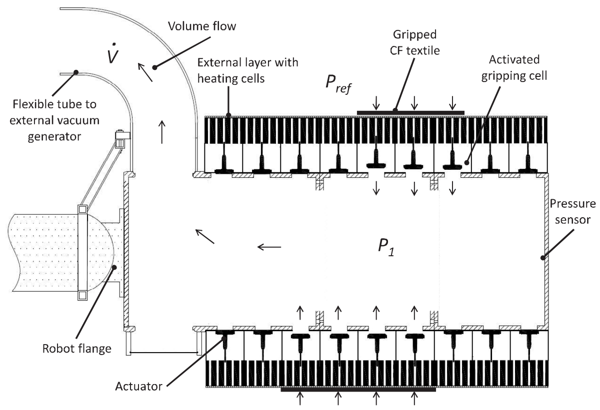

Fig. 3. Concept of an automated preforming end-effector.

Its principle of operation is shown in Fig. 3. A central vacuum generator creates an under-pressure P_1, which is lower than the ambient pressure P_{ref}. This causes a material-specific pressure difference ΔP, which is measured by a pressure sensor, and a volume flow $\dot{V}$. A fabric on the storage table can be gripped by activating certain gripping cells. To achieve this dedicated gripping cells can be opened by an integrated actuator. The resulting handling pressure p_H creates a holding force F_H, which is able to grip the part. The rolling motion of the end-effector peels the fabric off the storage table and fixes it with the holding force F_H at the perimeter of the end-effector (cf. Fig. 4) .

After the transfer to the mold, the end-effector performs a rolling motion over the tooling and closes those gripping cells which have contact to the surface to disengage the textile. Since it is necessary to fix the cut at its predefined position, the gripping cells also include heating elements, which are mounted on an external layer. By activating those heating elements which have contact to the surface, the textile is fixed on the tooling. The subsequent cells are also activated and preheat the textile in order to reduce the required time for melting the binder fleece. Fig. 5 shows the described functions during the draping process.

Due to the selective heating and gripping, the preforming end-effector exhibits high flexibility which is necessary for an automated preforming in several process steps. The approach is shown in Fig. 6 for the *diaphragm* reference tooling. The end-effector fixes the textile on the front, the top and the back by performing a rolling motion on the surface of the tooling according to the primary lay-up curve. The fabric is fixed on the side faces of the mold by the use of secondary lay-up curves. After a reorientation of the preforming end-effector, the side faces are fixed by a rolling motion along the secondary lay-up curves.

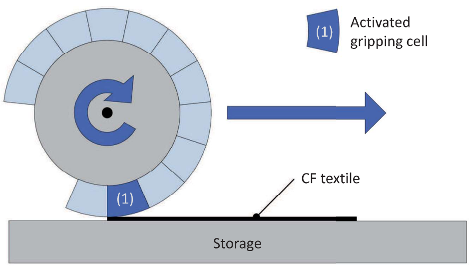

Fig. 4. Process for gripping a CF textile from the storage system.

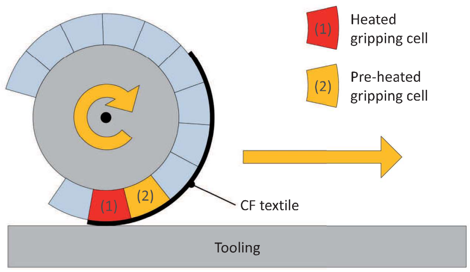

Fig. 5. Process for draping a CF textile on a tooling.

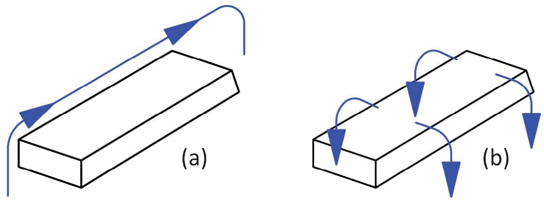

Fig. 6. Primary (a) and secondary (b) lay-up curves on the *diaphragm* reference tooling.

IV. Design of the Automation Software

A software system for controlling the preforming and draping process of carbon fiber fabrics has to fulfill several requirements. On a technical level, it has to control several different subsystems: The storage system which stores the carbon fiber textiles, the industrial robot that carries the end-effector and of course the draping end-effector itself, which comprises controlling the vacuum flow, the actuators and the heating elements. Those subsystems have to be orchestrated in an appropriate way to realize the draping process. In particular, the movements of the robot and the actions of the end-effector have to be tightly synchronized to achieve the desired results (e.g. heating the appropriate cells to attach the fabric cuts to the forming tool). However, on an algorithmic level, the crucial part of the control software is clearly the generation of robot movements which are suitable for draping textile cuts of various shapes onto a variety of forming tools in a reliable way.

The draping process was already described in the previous section: It consists of a movement along a so called *primary lay-up curve*, followed by movements along *secondary lay-up curves*. The definition of those curves is highly specific to the tooling that is used as well as to the material that the cuts consist of and how they have been cut (e.g. respecting the fiber direction of a specific layer in the fabric part). Furthermore, it is difficult to determine automatically how to deal with various types of complexity in the shape of the tooling. For example, small notches of the tooling can be compensated by adequately pressing the draping end-effector onto the surface, making use of the end-effector's flexible layer (cf. Sect. III). Small convexities, on the other hand, can be ignored and compensated by the flexible layer as well. In that case, maintaining contact to a large surface area of the tooling with the draping end-effector is preferrably to following the small convex part of the tooling. However, it is difficult to define such behavior automatically and, in particular, predict how it affects the quality of the draping result. Therefore, a fully automatic determination of suitable layup curves is not intended. Instead, process experts should be involved in specifying layup curves and testing their validity according to the draping results.

Hence, the automation software consists of two parts: For defining and testing suitable lay-up curves and the resulting draping movement (which is not fully specified by the lay-up curves alone) a software component named *CFK-Tex.Office Draping Assistant* was developed. It is designed for process

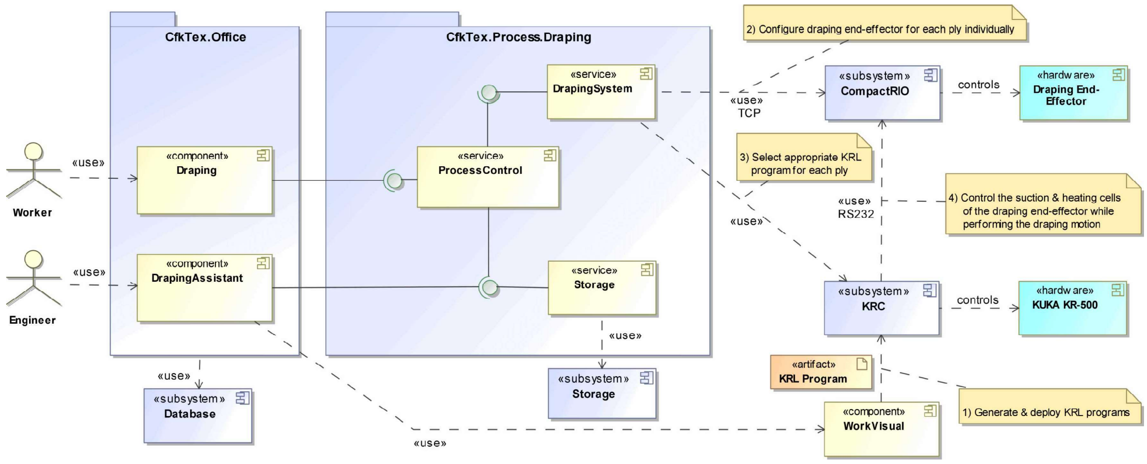

Fig. 7. UML component diagram showing the architecture of the automation software for the draping process.

experts in order to incorporate their knowledge into the automated manufacturing process. For productive use of the automation system, the component *CFK-Tex.Office Draping* was designed. It monitors and executes the manufacturing process by controlling and coordinating all subsystems and employs the layup curves that were defined previously via the *Draping Assistant*.

Fig. 7 shows an UML component diagram [19] giving an overview of the software architecture we developed for *CFK-Tex.Office Draping* and *CFK-Tex.Office Draping Assistant*. Both software parts were embedded into the software *CFK-Tex.Office* which was previously only able to control the automated cutting and handling of carbon fiber fabrics as presented in [6]. The component *WorkVisual* on the lower right of the figure is used to as a basis for the *Draping Assistant* as explained in the following section.

A. *CFK-Tex.Office Draping Assistant*

The *Draping Assistant* is based on the off-line robot programming environment *KUKA.WorkVisual* [20] which integrates a 3D visual editor and allows the definition of robot movements and end-effector actions with respect to physical objects (e.g. workpieces). Moreover, KUKA.WorkVisual incorporates a plug-in mechanism which we used for creating the *Draping Assistant*. The plug-in is aimed at process experts and guides them through the various steps of creating appropriate draping movements, which includes:

- importing a CAD model of the tooling,
- importing user-defined lay-up curves,
- importing 2D shape data of carbon fiber cutouts, that are to be draped, and
- the positioning of the cutouts on the surface area of the draping end-effector.

The definition of the primary and secondary lay-up curves *on the surface of the tooling* requires also process knowledge and must be done beforehand using an appropriate CAD environment. Currently, for importing lay-up curves, the IGES data format is supported.

After the above information has been provided, the *Draping Assistant* automatically calculates the trajectory of the robot end-effector and a segmentation of the trajectory according to the borders of the gripping and heating cells. To let the end-effector perform a rolling motion on the surface of the tooling, the calculation of the trajectory consists of

1) calculating a motion for the center of the end-effector that matches the lay-up curve and
2) calculating a rotational velocity for the last robot axis that matches the translatory velocity of the center of the end-effector.

The center of the end-effector is defined to be on its rotational axis which coincides with the last robot axis. Furthermore, the calculation takes the positioning of the cutouts on the surface area of the end-effector into account to determine an appropriate starting orientation.

As mentioned above, the resulting trajectory is split into single segments that correspond to the motion across one of the physical segments of the end-effector. Because the vacuum flow (via the magnet actuators) and the heating elements can only be controlled per gripping cell, those trajectory segmentation points are used as triggers for performing the respective tool actions. The positioning of the fabric on the draping end-effector is used here to determine which gripping cells have to be activated or deactivated.

The plug-in uses functions of KUKA.WorkVisual to build up the resulting robot trajectory. The segmentation points of the calculated trajectory are defined as nodes in the geometric model that KUKA.WorkVisual provides. Furthermore, motion primitives between subsequent nodes are defined. KUKA.WorkVisual also allows the definition of so called action nodes which are special geometric nodes. At action nodes user-defined (robot) program code written in the KUKA Robot Language (KRL) can be executed. This mechanism is used to trigger actions of the draping end-effector by defining KRL functions that send commands to the tool via RS-232.

The result of the automatic steps described is a combined specification of robot movements and corresponding end-effector actions. Process experts that use the *Draping Assistant* can test and modify the result in WorkVisual's 3D simulation environment. After that, WorkVisual generates a KRL program from this specification and deploys it onto the robot controller for further tests (e.g. adaption to the detailed contour of the tooling) and finally productive use.

B. CFK-Tex.Office Draping

KUKA.WorkVisual and the *Draping Assistant* plug-in are used to semi-automatically create robot programs for each ply of the CRFP components to be manufactured. These programs can be automatically transfered to the KUKA Robot Control (KRC) controlling the KUKA KR-500 robot we use in our experimental setup. The real-time execution of those programs inside the KRC guarantees perfect synchronization of robot motions and tool actions. Due to this tight integration of robot and end-effector control, both subsystems can be treated as a monolithic draping system which can perform draping operations for given plies. However, during productive use, this system needs to be coordinated with the storage system and the draping end-effector must be configured individually for each ply (e.g. proper vacuum flow). For that, we created a service-oriented software architecture [21] as shown in Fig. 7. It consists of separate components, called *Services*, that represent a closed part of the system with a defined purpose and interface.

The main service is *DrapingSystem* which offers an integrated interface to the robot and the draping end-effector. The service implementation uses a TCP network connection to communicate with the end-effector control which is implemented in LabView [22] and deployed on a CompactRIO device from National Instruments. The service directly communicates with the end-effector controller to initialize the system and to configure heating temperature, heating time and vacuum pressure separately for each ply. Furthermore, the *DrapingSystem* service communicates with the KRC to start the appropriate robot programs for gripping a fabric on the storage and draping it into the mold. As mentioned, these programs have previously been generated and deployed by KUKA.WorkVisual and the *Draping Assistant* plug-in. They are identified by a unique name that incorporates e.g. the identifier of the carbon fiber layer that is to be draped. Internally, the robot control uses RS-232 to communicate with the end-effector controller.

The *Storage* service offers an interface to the system that stores the already cut fabric parts which should be draped. The interface contains operations e.g. for fetching a single tray to a retrieval station. Furthermore, the package contains a *ProcessControl* service that coordinates the actions necessary for the preforming and draping process. Since the component *Draping Assistant* is intended for process experts (represented by the UML actor *Engineer*), the *Draping* component forms the graphical front-end for the worker for supervising the manufacturing process.

The automation software was implemented using the object-oriented programming language C#. For realizing the service-oriented architecture, Microsoft's Windows Communication Foundation was used. It is fully compatible to common Web Service specifications and supports eventing mechanisms which are important for asynchronous communication with services representing devices.

V. Experimental Results

For testing the functionality and performance of the end-effector and the automation software, the complete system was evaluated using the reference tooling *diaphragm*. First of all, it is necessary to import the tooling into a CAD environment and design the lay-up curves on the surface of the tooling. In order to grasp the fabric from the storage, the primary layup curve is transformed from 3D into a corresponding flat line on the textile's surface. Subsequently, the layup curves are imported into the Work Visual plug-in. There, the placement of the fabric on the surface area of the end-effector is defined via drag and drop. The according gripping and heating cells are chosen by a simple manual selection process. Additionally, adjustments regarding the configuration of the end-effector are made (e.g. the compression of the elastic layer or the preferred draping direction). Based on this information, the lay-up curves are automatically transformed by the software. The frames of the generated trajectories are aligned in such a way that a rolling motion of the end-effector on the tooling's surface is performed (cf. Fig. 8). The generated trajectories are tested in the simulation where collisions can be revealed and reachability of all points can be ensured. The corresponding robot code is generated out of the transformed curves and deployed on the KRC.

To validate the end-effector and the off-line path planning, several fabrics were allocated on the storage table and draped on the reference tooling *diaphragm* by use of the generated robot code (see Fig. 9). The experiments were performed with different material types with varying air permeability and flexural rigidity, which cover a broad range of grammages from 220 g/m^2 to 556 g/m^2. The tests included woven fabrics as well as non-crimp fabrics. An evaluation

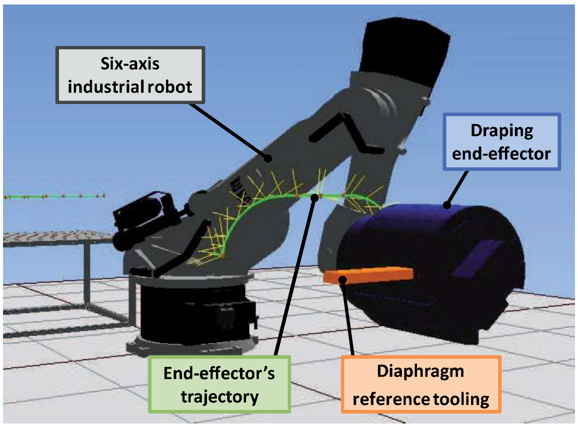

Fig. 8. Transformed lay-up curve in KUKA.WorkVisual for the *diaphragm* tooling. The frames are aligned in such a way that the end-effector performs a rolling motion on the surface of the tooling.

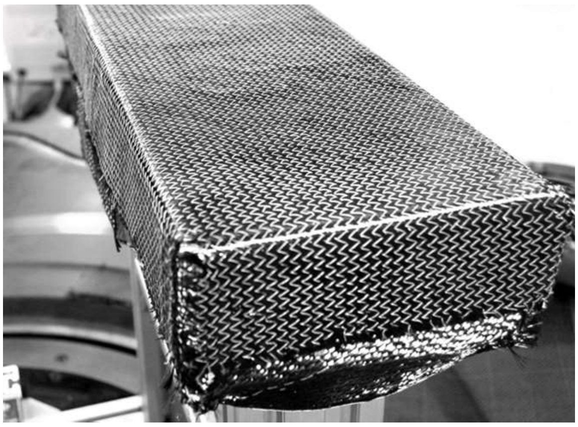

Fig. 9. Draping result for the *diaphragm* reference tooling.

of the automatically draped preforms showed reproducible results in repeated runs. The fabrics were positioned within the demanded tolerances of 1 mm without any destruction of the textile structure or fiber orientation. In addition to the *diaphragm* reference tooling, typical cuts of the *spant* and *panel* were successfully evaluated by draping them onto the complex surface of the corresponding tooling [18]. Since the *spant* exceeds the reachability of the draping end-effector, it was necessary to use a linear unit for adjusting the position of the tooling individually for each cut. The additional axis had to be integrated into the off-line robot programming environment and synchronized with the movement and actions of the draping end-effector.

VI. Conclusion

In this paper, we described a system for automatically preforming and draping non-resinous dry carbon fiber textiles. The main contributions are the design and construction of a robot end-effector, its integration into an industrial robot system and the design and implementation of an appropriate software solution. To capture and meet the aerospace industry's requirements, we performed a detailed analysis of the system requirements and designed a single draping end-effector which integrates the three essential functions, i.e gripping, draping and fixation. The software *CFK-Tex.Office* was extended to control the complete automation system, i.e. the robot itself, the end-effector and a storage system that keeps the previously cut carbon fiber textiles.

With this work, we are able to automate the most time-consuming step in CFRP manufacturing that is until now mainly performed manually. While the process of creating appropriate draping movements involves process experts and must thus be considered semi-automatic, productive operation is possible in an autonomous way. Combined with previous work (cf. [6]), we are now able to present a largely automated CFRP manufacturing approach.

For transferring the results to industrial use, there remain certain steps to be done. While we achieved promising results with our draping experiments, a detailed analysis of the achieved quality level has to be performed. This has to be done in conjunction with an analysis of the productive performance in terms of draped layers per time unit. Both aspects (quality as well as performance) have to be included in a complete economic analysis which, of course, has to consider also the initial and running costs of an automation system as proposed. As in most areas, this will determine the spread of such a system in industrial applications.

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