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Automated Cutting and Handling of Carbon Fiber Fabrics in Aerospace Industries

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***Abstract*— The use of composite components in aerospace industries has become more and more important since the 1980s. Especially structures made of carbon fiber-reinforced plastic are well suited for aircrafts where highly stressable but lightweight constructions are required. However, the efficient use of this technology is still limited by a largely manual production process. To increase automation, the paper presents a completely new approach which allows the automated cutting and handling of carbon fiber textiles. This includes a detailed analysis of the current industrial process and its automation potential, the construction of a special handling tool and the development of a suitable automation software. Experimental results show the flexibility and feasibility of the approach.**

I. Introduction

The spread of composite components made of carbon fiber-reinforced plastic in aircrafts has increased exponentially during the last years as shown in Fig. 1. Especially modern airliners like the Airbus A350 or the Boeing 787 apply composite components for highly stressable lightweight constructions. In addition, more and more other sectors like wind energy, transportation, building, sports and plant industries use these innovative materials due to their convincing properties that include e.g. low density, high stiffness and strength, resistance to corrosion and stress optimized design [1].

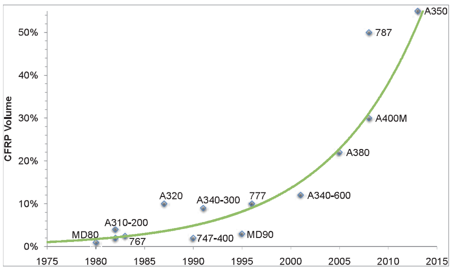

Fig. 1. Development of carbon fiber reinforced plastic in aircrafts (cf. [2]).

Preimpregnated composite materials (prepregs) dominated the carbon market for many years, because they achieve a high fiber content and part strength. However, since the conventional prepreg technique causes high costs (e.g. high capital investment for an autoclave and high efforts for a cooled storage), new injection methods have gained more and more relevance [3]. Therefore, non-resinous dry carbon fiber textiles are manufactured to preforms, infiltrated with resin and processed to an oven for curing.

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Fig. 2. Typical industrial process chain for manufacturing composite components from dry carbon fiber textiles. The research focus lies on the automatic clearing of the cutter table by using a robot-based material handling system.

The current industrial assembly process is shown in Fig. 2. The dry carbon fiber textiles are allocated on fabric rolls and can be fed fully-automatically to a cutter table using a loading device. Based on CAD data, the cut parts are automatically generated on the cutter table. Clearing the cutter table, which is the first manual step, is followed by the manual lay-up of the parts into a form. Before the resin is injected, the layers are covered with an vacuum build-up which is also created manually.

Despite the advantages of dry carbon fiber parts and their growing relevance, an efficient use and spread of this technology is limited by missing automation in the production process. So far, manual steps dominate the production process and lead to increased production costs and high rejection rates. Additionally, repeatability of the produced parts and intelligent process linking are missing. Although an automation of the process chain is needed, no solution could be found yet due to various challenges of the process. Efficient automation sets high requirements regarding the process, the material and the geometry of the cuts. The handling of carbon fiber textiles and especially the clearing of the cutter table contain several difficulties, because the cuts are limb, permeable to air and highly anisotropic. In particular, the task to separate single parts from the rest complicates efficient automation, since the cuts vary in material, dimensions and outlines [4].

Due to these challenges, an appropriate handling tool must be able to grip any fabric part shape without interfering with other parts or clippings on the cutter table while clearing it. Besides the complexity of this function itself, the material properties, geometry conditions and demanding process steps require a highly flexible system, as specialized approaches for single parts or materials cannot be deployed economically [5]. In other industries, various approaches for the automated handling of limp material can be found. However, their emphasis lies on automatic manipulation of sheet material in applications concerning garment or fabric processing. The special requirements of clearing complex and diversely shaped fabric parts from a cutter table are not addressed at all. Concerning the gripping principle used in such systems, many different approaches can be found in literature, mainly based on needle or suction gripping as well as innovative cryogen methods [6]. But yet none of them could be implemented in an automated system which meets the requirements regarding flexibility and material integrity. According to this, Szimmat [7] reported in 2007 the results of a survey in industry which stated that in none of the 39 participating companies the clearing of the cutter table is automated so far.

The presented research work focuses on the automatic clearing of the cutter table because of the high automation potential and the transferability to other branches of textile industry. A completely new concept for automated cutting and clearing of the cutter table was developed and successfully tested. The process analysis for this approach is presented in Sect. II. In Sect. III, the design of a new robot end-effector for gripping limp carbon fiber textiles is explained. The design of the automation software is described in detail in Sect. IV. Sect. V illustrates the experimental results. Finally, conclusions are given in the last section.

II. Process analysis

The first step in constructing the intended system for cutting and handling carbon fiber fabrics was a detailed analysis of its scope and the requirements that must be fulfilled. This includes the observation of the current, still manual manufacturing process as well as considerations concerning in-company logistics within an automated process. Therefore, different station layouts have been evaluated, taking into account material waste, station times and costs. The resulting layout includes a material delivery system, a single-ply cutter with conveyor, an industrial robot with a gripping end-effector and a tray storage system. The layout is shown in Fig. 3 using the robot simulation tool KUKA.Sim Pro.

For analyzing and capturing the functional requirements, the technique of *use cases* [8] was applied. A use case is an informal description of how a future system should interact with its intended users and external systems to achieve a specific goal, represented as a sequence of simple steps. In order to capture the requirements as exact as possible, it is important that end users as well as domain experts actively participate in the iterative process of writing use cases [9]. In the present case, experts in manufacturing composite structures from Eurocopter in Donauwörth, Germany, and Premium Aerotec in Augsburg, Germany, have been involved in this process.

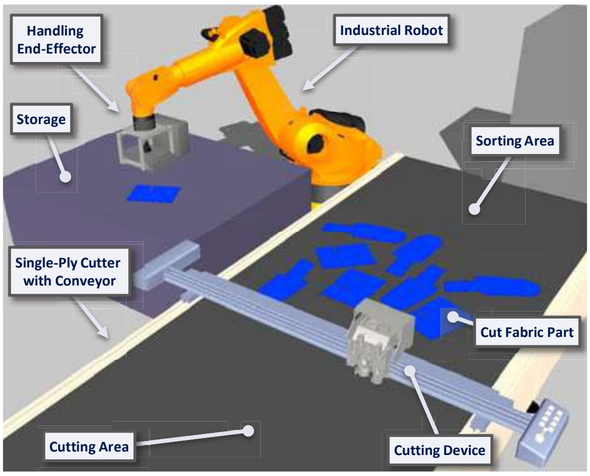

Fig. 3. Simulation of the process in KUKA.Sim Pro using the process layout including a material delivery system, a single-ply cutter with conveyor, an industrial robot with a gripping end-effector and a tray storage system.

Preliminary to writing use cases, relevant actors in the scope of the system must be identified [9]. Actors are defined as *components* with behavior that can influence the system state. An actor in this sense can be a human user of the system as well as a subsystem that interacts with the main system. For the cutting and handling system, two human actors have been identified:

- The *Worker* uses the system to start and supervise the process of cutting and handling fabric parts.
- The *Engineer* uses the system to plan tasks for cutting new fabric parts and defines details of the process.

Considering the in-company logistics solution, the following subsystems have been identified to be actors:

- The *Marker Making System* offers a nesting algorithm to generate optimized fabric part layouts minimizing material waste. These layouts are called markers.
- The *Cutter* is a computer-controlled device for fast and reliable cutting of textiles. It has a loading and winding device for fabric rolls as well as a conveyor for transporting the cut fabric parts into sorting area.
- The *Handling Tool* is a specially developed robot end-effector for gripping limp carbon fiber fabric parts. Its design is described in Sect. III.
- The *Handling Robot* is a standard industrial robot with the handling tool mounted at its flange.
- To control the quality of the cutting process, a *Cutting Inspection System* could be used.
- After the cutting process, the fabric parts are stored inside a *Storage* for further processing.

After having identified the actors, around 50 use cases defining the capabilities of the system were formulated. While some of them only describe interactions between the software and its users (e.g. viewing currently planned tasks or changing system settings), others involve one or more of the subsystems including hardware devices (e.g. executing a planned task). The use cases describe the participating

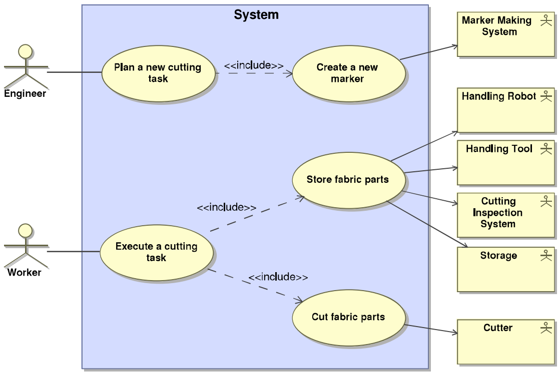

Fig. 4. UML use case diagram showing only the main use case of each primary actor.

actors, the pre- and postconditions of the relevant actions, the main success scenario showing the successful flow of actions and finally a set of extensions and exceptions. The two most important use cases are planing a new cutting task, and subsequently executing this task by cutting and storing fabrics parts. The first use case is triggered by the engineer while the latter is achieved by the worker. Both major use cases and their corresponding actors – the users as well as the subsystems – are depicted in Fig. 4.

Based on the second use case, the work flow of the cutting and handling process was modeled in UML [10]. The main process flow is illustrated in Fig. 5 using a sequence diagram. It contains the process-relevant subsystems as parallel vertical lines (called *lifelines*) and shows how these systems interact with each other by sending messages. The main system is represented as *Process Control*. The *Handling System* can be seen as a "facade" [11] hiding the interaction between the robot, the handling end-effector and the cutting inspection system. The rectangles in the diagram denote special regions for loops (labeled with *loop*) and concurrent execution (labeled with *par*). Each region requires a guard (in brackets) which defines a condition for the region to be executed.

The process starts by sending a marker description containing fabric parts to the cutter where the marker is divided into several segments according to the size of the cutting area. After cutting of the first segment is finished, the cut parts are transported into the sorting area using the conveyor. Simultaneously, the handling system is initialized, i.e. a valid grip configuration and position is calculated for every part, and the storage allocates the required number of trays. Subsequently, the sorting area is cleared using the handling system, and the cutter continues to cut remaining segments. The coordination between the robot, the handling end effector and the cutting inspection system is hidden inside the *Fetch* and *Release* operation. The sequence is repeated until all segments are cut and every cut fabric part is cleared. The process is completed by finalizing the marker, i.e. cutting off the fabric roll, and by moving the handling system into its park position.

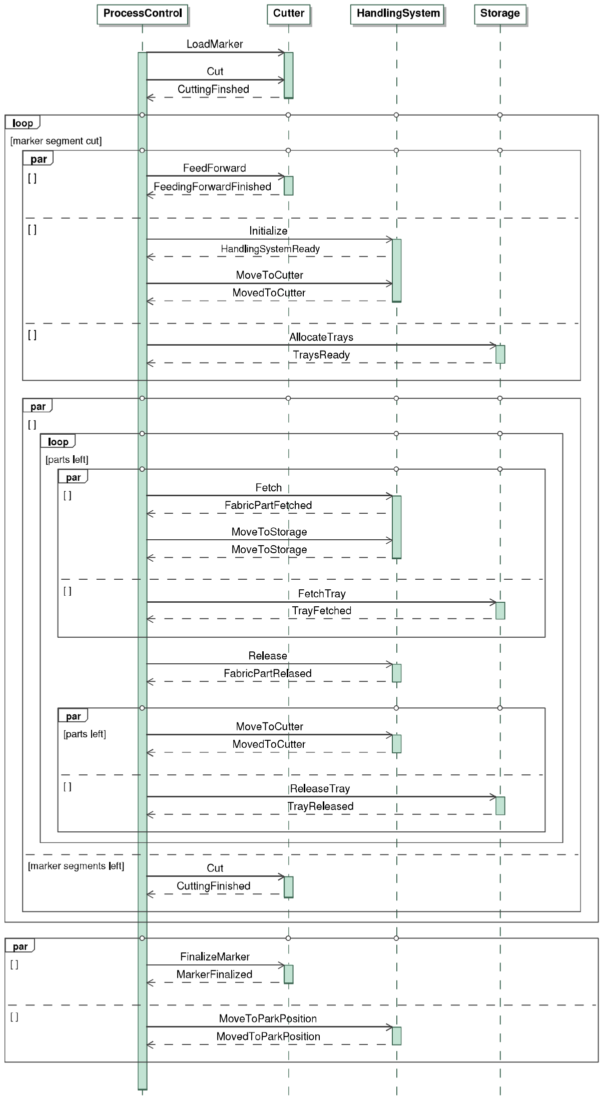

Fig. 5. UML sequence diagram showing the main process flow.

III. Design of the End-Effector

The development of a highly flexible robot end-effector for handling dry carbon fiber textiles was structured using a methodical approach. As the operation principle has to meet the essential functions and defines the interaction between the gripper and the fabric parts, a research focus was on the selection of the optimal physical principle [12]. In literature, many different operation principles are published which could be adopted for gripping and handling limp materials. Needles, pins, card elements, hook and loop systems as well as vacuum-based applications (e.g. suction cups, Bernoulli suckers) and adhesive grippers using corresponding materials or the hydro adhesion method are suggested. Mechanical grippers (e.g. finger grippers) are also taken into account. Most of them are used in garment, fabric or leather dominated industries [13], but some like the hydro adhesive, the needle and suction principle have also been successfully examined at carbon fiber textiles [6] [14].

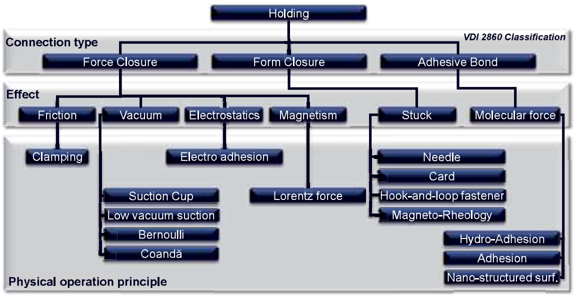

Fig. 6. Possible solution space of different physical operation principles for gripping limp carbon fiber textiles.

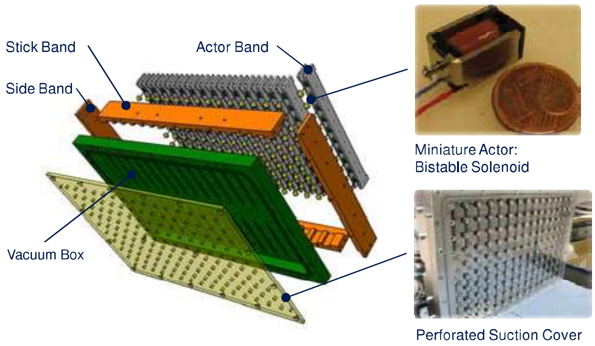

Fig. 7. Design of the end-effector with bistable solenoids and a perforated suction cover

As the decision of an operation principle is very important, a valid solution space was determined. Fig. 6 shows an overview on physical principles and their effect classified into force or form closure and adhesive bond according to VDI Guideline 2860 [15]. Using expanded tests and a benefit analysis, the principles were analyzed regarding their applicability. The suction method with low pressure difference was found to be the optimal principle. Besides the possibility to transmit very high forces without any damage to the textile, it obtains an efficient gripping of large areas although the material is permeable, and, due to low vacuum, it can be operated at reasonable costs. Furthermore, the principle offers a great potential for applying it to fabric parts which exhibit large surfaces.

A demonstration system including a cutter and an industrial robot was established as a part of the research presented in this paper. Fig. 7 shows a detailed view on the first evaluation model which offers the possibility to examine the design of the end-effector system and to evaluate the required performance. It was realized by using a perforated suction cover at the bottom, whose drill holes can be individually closed by miniaturized actors. Therefore, bi-stable solenoids are mounted in an actor band and their lifter is directed into a vacuum box which contains a defined pressure difference inside. Due to this design, the solenoids can adapt to any contour of one or more different cut parts. Thus, the suction area can be defined and the specific carbon fiber textile can be gripped out of surrounding clippings (cf. Fig. 9). To assure process stability despite the low bending stiffness of non-crimp fabrics normal to the fiber orientation, a high drill hole resolution of 25 mm was realized for the first evaluation model and the later prototype which consists of 15 independent modules. Together they cover a size of 2250 mm length and 1200 mm width and are able to handle small as well as huge-sized cut parts. Due to the resolution of the gripper, an amount of 4320 actors, 15 vacuum generators and several pressure sensors are used which all have to be controlled efficiently.

IV. Design of the automation software

The process of cutting and handling carbon fiber fabrics is controlled by an automation software called *CFK-Tex Office*. This software was developed during the research project *CFK-Tex* to support the execution of the analyzed process by coordinating and synchronizing the subsystems involved. Moreover, it offers a graphical user interface supporting different views, targeting both user groups and their interaction with the system as identified in Sect. II.

The software *CFK-Tex Office* is built according to the principles of a Service-oriented Architecture [16]. As such, it consists of separate components, called *Services*, that represent a closed part of the system with a defined purpose and interface. Furthermore, by definition, services can be exchanged by other services offering the same interface (and functionality), but using different implementations. In that way, changes in hardware or algorithms used can be reflected in the software. Such an exchange can happen without recompiling by only reconfiguring the software. Hence, the software structure is highly modular and reusable.

Fig. 8 gives an overview about the services that constitute the *CFK-Tex Office* software and their relations using a component diagram [10]. The central part of the diagram, the package *Cfktex.Process.Cutting*, contains the services that interface with all relevant subsystems:

- The *Cutter* service offers an interface for controlling the actions of a cutter table. The interface contains operations e.g. for loading a new marker to the device, for cutting a marker segment and for transporting already cut parts to the sorting area using the built-in conveyor.
- The *HandlingSystem* service coordinates the actions of the robot and its gripping end-effector. The interface contains operations e.g. for fetching and releasing cut fabric parts as well as for transferring these parts between cutter and storage.
- The *HandlingRobot* service offers an interface to the industrial robot that is moving the gripping end-effector. The interface contains operations e.g. for positioning above fabric parts, for slowly moving down and up as well as for moving to the cutter table and the storage.
- The *HandlingTool* service offers an interface to the gripping end-effector. The interface contains operations e.g. for adapting the perforation matrix to the desired contour by operating the affected solenoids and for adjusting the pressure difference.

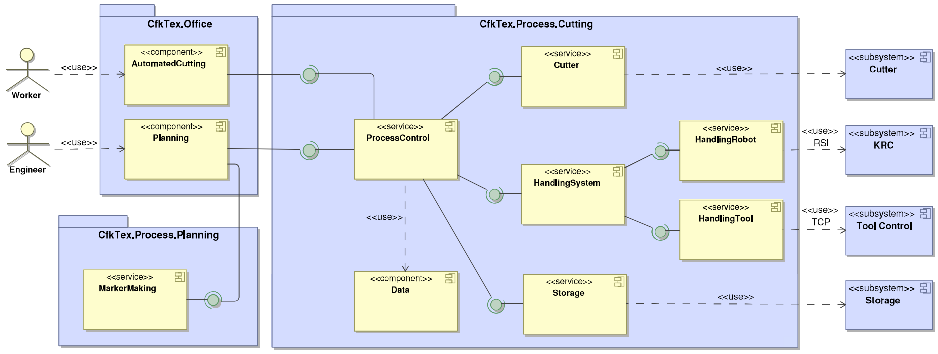

Fig. 8. UML component diagram showing the architecture of the automation software.

- The *Storage* service offers an interface to the system that stores the cut parts. The interface contains operations e.g. for allocating trays and for fetching a single tray to the retrieval station.

Additionally, the package contains a *ProcessControl* service that coordinates the actions necessary for the process, and a *Data* component with common data transfer objects [17]. Apart from the *HandlingSystem*, the concrete service implementation for a subsystem is dependent on the underlying device, its interface, and its communication protocols.

The package *CfkTex.Office* in the upper left part of Fig. 8 contains the components *AutomatedCutting* and *Planning* that form the graphical front-end for both user groups, i.e. the worker and the engineer. Those components use the *ProcessControl* service to plan, execute and monitor the process of cutting and handling fabric parts. Hence, the automation software represents a computer-aided manufacturing (CAM) system with both a manufacturing planning and manufacturing control part as described in [18]. The *MarkerMaking* service located in the package *CfkTex.Process.Planning* is responsible for calculating a nesting strategy to generate optimized fabric part layouts. This functionality was modeled as a separate service, because different nesting algorithms and software packages exist and might be interchanged to match specific process requirements.

The automation software was implemented using the object-oriented programming language C#. For realizing the service-oriented architecture, Microsoft's Windows Communication Framework 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

A first experimental evaluation of the end-effector prototype at the demonstration system offers very promising results. Based on a test scenario, it was possible to automatically grip different contours (e.g. parts of letters) on the cutter table, transport them to a storage system and drop them at a defined place with high process reliability and precision. In the example shown in Fig. 9 the system – consisting of the cutter, the robot and the first end-effector prototype – is able to grip dispersed parts of the lettering "CFK" out of a marker and place it in right position on a table which represents a potential storage system. Even different semi-finished products like non-crimp fabrics and unidirectional tapes with grammages up to 556 g/m^2 and varying permeability can be processed covering a wide majority of commercially available carbon fiber textiles.

To achieve this, the pressure difference in the system is measured by a sensor and the the vacuum generator's volume flow is adjusted in order to establish the required holding force. Hence, it is possible to extract cut fabrics parts from the cutter table which requires – due to an interaction between the gripped part and the cutter fleece as well as other parts – greater forces than just holding (about 10 mbar to 25 mbar). The required data on material properties, the contour and position on the table is gathered by the automation software and processed by the gripper control system in order to calculate an optimal end-effector position over the parts to grip and to activate the right solenoids. During transportation the holding force is lowered by reducing the pressure difference (about 2 mbar to 6 mbar) in order to save energy and prevent damaging the textile's structure. For the deposition at the final position, the end-effector is orientated in the right position and the solenoids close the relevant drill holes. Thus, it is even possible to grip several parts at the same time and release them individually which can lead to smaller cycle times for the clearing process.

For testing the functionality and performance of the *CfkTex.Office* software at the current stage of system development, simulated versions of all hardware parts were developed. This has the advantage of decoupling software and hardware development and allows evaluating the software without permanent access to the full hardware setup. In particular, the development of the main hardware component, the gripping end-effector, took place in parallel with the software development, which made the use of simulation tools unavoidable. However, each of the simulated hardware components is controlled by a service that exposes exactly the same service interface that the control service for the respective hardware will provide, which allows for a seamless exchange between simulated and real hardware.

The tool KUKA.Sim Pro was used for modeling a simula-

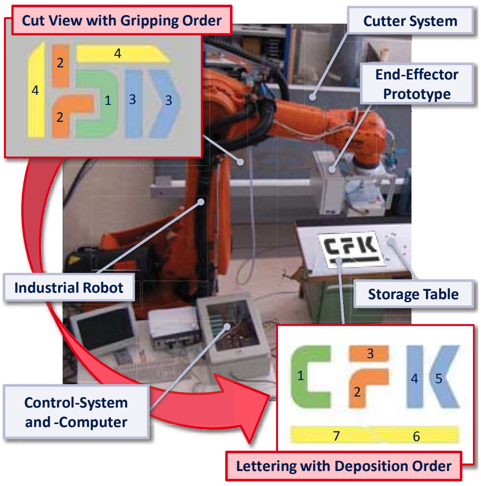

Fig. 9. Validation scenario: Clearing and sorting different parts of the letters of "CFK".

ted version of the complete system setup determined during process analysis (cf. Fig. 3). A big advantage of this tool is the integration of the KUKA Robot Control (KRC) software for controlling the simulated robots. This allows for an offline development of robot programs that can later be transferred to the real robot control with little to no adaptations.

CfkTex.Office was implemented using the software design as described in Sect. IV. It supports all steps of the defined handling process and both controls and monitors the involved (simulated) subsystems. As a result, *CfkTex.Office* is the first integrated solution for automated cutting and handling of limp carbon fiber fabrics. First tests show that the simulated process steps are executed reliably and fast. In-depth tests have yet to be performed, in particular in conjunction with the real hardware setup (which consists of a Zünd L-2500 cutter and a KUKA KR270 industrial robot) to determine the final process quality and performance.

VI. Conclusion

In this paper, we have described the realization of a robot end-effector and an appropriate software for setting up an automatic process of cutting carbon fibre textiles and transferring them to a storage system. To capture and meet the aerospace industry's requirements, we performed a detailed analysis of the current industrial process and the optimal process layout, which includes a single-ply cutter, an industrial robot and the presented robot gripping end-effector. Relevant actors in the scope of the system were identified and detailed use cases of the cutting and handling process define the system functionality.

The process requirements can only be met by a highly flexible gripper system, whose mechanical design has been described. Based on an extensive analysis of operation principles for gripping and handling limb materials, the suction method with low pressure difference was chosen because of its convincing advantages. Despite the high challenges regarding the process details, the geometry and the material requirements, the developed tool is able to grip single cut parts out of surrounding clippings. Optimal process parameters for the gripping and the transportation of different fabrics were determined by certain analyses (e.g. air flow analysis) and tests. The service-oriented automation software *CfkTex.Office* was presented and its internal structure explained. This software controls the cutting and handling process and coordinates all subsystems involved. Experimental tests showed that for the first time it is possible to realize a fully-automatic process chain. Diversely contoured cuts can be gripped, transported to a storage system and dropped with high repeatability, which is clearly superior to the conventional manual manufacturing steps.

For the future, it is planned to also automate the manual lay-up of dry carbon fiber textiles into 3-dimensional shaped toolings. Another special end-effector will be able to grip, drape and fix the cuts at the tooling in order to create a complex preform layer by layer. Together with the approach for automatic cutting and handling presented in this work, a completely automated process chain for carbon fibre composite components is possible. An economic analysis will be conducted to determine scenarios for the application of this system in real industrial environments.

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