AUTONOMOUS COMPOSITE PRODUCTION BY ROBOTIC PICK & PLACE

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ABSTRACT

During the last decade the DLR Center of Lightweigth Production Technology (ZLP) in Augsburg investigated the potential of the autonomous production of composite parts by means of pick and place executed by industrial robots. Starting from conventional teaching the research focus was extended to the development of technology bricks for computer vision based gripping, automated derivation of grip- and drop coordinates from CAD data, digital process description and workflow, autonomous cut-piece transfer by means of collision free path planning and a multi-robot synchronization and execution layer. The technology bricks are enriched by a process data acquisition system and controlled by a manufacturing execution system embedded into a high-level process control system. In this work we give an overview of the developed technologies and achievements based upon several use cases from the field of composite production.

1. INTRODUCTION

The DLR ZLP was founded ten years ago with subsidiaries in Augsburg and Stade. While ZLP Stade was involved in tape-laying technologies the focus in Augsburg was put on pick and place technologies and we investigated the digital production of large composite parts by using industrial robots on the basis of numerous projects and demonstrator parts. Since there are plenty of possible materials and associated manufacturing technologies, one major challenge is to identify what is common for a certain scope of materials and which technologies can be applied for the specific material group. We investigated the processing of dry non crimp fabric with and without binder, several thermoplastic prepregs and aluminum foils for glare production for 2D, 2.5D and 3D applications with one or more robots from small demo-parts up to full scale demonstrators with a focus on technologies for digitization and autonomous production.

2. EXPERIMENTATION

Industrial robots are a competitive production resource for automation. Today, they are mostly programmed by teaching and subsequently repeat a couple of predefined jobs. Beside this, offline programming technologies are available on the market, which allow programming and coordination of several robots along a production line, but are limited for quickly changing or highly dynamic scenarios. Since composite production requires complex layups with hundreds of cutpieces it became clear that teaching and offline programming would be very important and time-consuming and thus not desirable for this purpose. After some preliminary work with conventional teaching, ways to make the production more flexible, i.e. to go more directly from the CAD-data to the production, were investigated. In order to allow an autonomous production, several important technology bricks were identified, developed and tested.

2.1 Preliminary investigations

Found in 2009 the DLR ZLP in Augsburg took up its work with two robots on a common linear axis. Taking on the work of iwb et al. [1], gripping and simulation technologies with the goal of a cooperating layup of cutpieces up to 6 m wide, were developed. Since quality control is essential for aerospace parts, research on non-invasive NDT-methods (thermography and air coupled ultrasound) was also started with the later goal of inline-usability (Table 1, row 1). The first tests relied heavily on teaching and manual extraction of CAD-positions, demonstrating both the potential of cooperating robots and the limitations of teaching. For example, every cutpiece has to be put in the predefined gripping position and to be aligned properly, so the worker is basically busy serving the robot, thwarting the thought of autonomous or robot assisted production. The workflow proved to be costly and error-prone, thus preventing to tap the full potential. Nevertheless technological gaps could be clearly identified for further research. During the last decade different research groups have worked on the topics, but except DLR none with such a strong focus on digitization and autonomy [2-4]

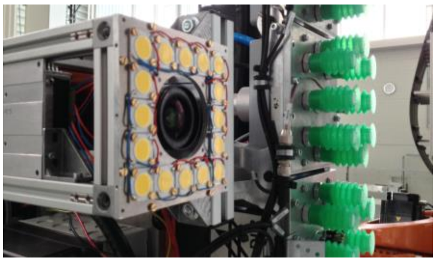
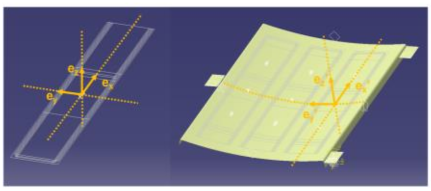
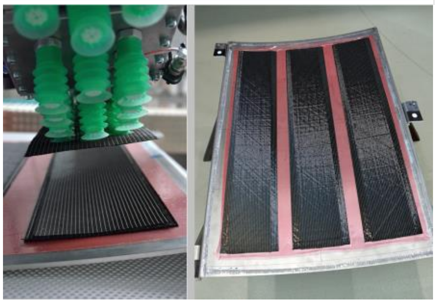
2.2 Computer vision based gripping

Cutpieces are prepared on specialized cutter systems and have to be transferred to the manufacturing cell, unless the cutter is part of the cell. Since the material is sometimes sensitive to handling and often randomly shaped it is desirable to avoid time consuming alignment procedures for robot processing. This was solved by combining the robot with a computer vison system that was first limited to smaller cutpieces and upgraded later with features for bigger cutpieces, distinguishing small deviations, measuring the contour deviations and recognizing the material direction (Table 1, rows 2-3, 5-9). During six years of research we encountered numerous events which gave valuable insights in the system's limitations and helped to make the detection more reliable and accurate [5-9]. Template matching with transparency was used to robustly detect the cutpieces, and subsequently a border detection following the contours proposed by the matcher was executed, which sorts out not perfectly matching cutpieces. This two-step algorithm proved excellent accuracy and stability in all situations. Fourier analysis was shown to allow the detection of the material direction and structure, avoiding mixing up equally shaped cutpieces of different materials.

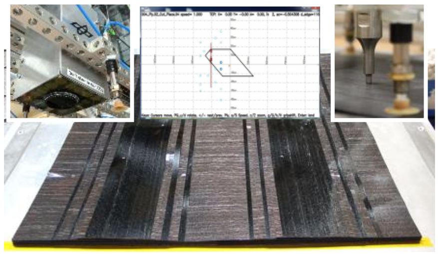
2.3 Automated derivation of grip- and drop coordinates from CAD data

After detection the next issue is on how to grip and where to drop the cutpieces. Not only the plybook information is of importance, one needs the entire results of the draping simulation as well as the gripper's shape and abilities in order to derive sensible grip-drop-combinations. Starting from gripping plain cutpieces and stacking them one over the other the planning got more elaborate and formed a separate software module ("plylander"), including parametrized grippers, TCP-adjustment, coordinate-transformations and transfer from 2D to 3D and vice versa. For this purpose the layup was designed in CATIA CPD, and for each cutpiece both a 2D and a 3D-mesh was generated, exported and provided to the plylander software (Table 1, rows 3-4, 7). This way it is assured that gripping and dropping is in perfect accordance with the intended layup [5-9].

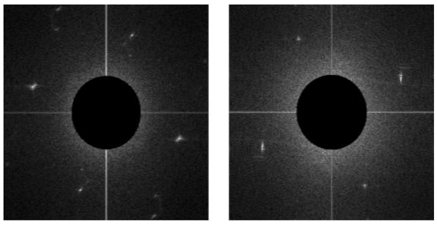
Table 1: Timeline of technology brick development

1	**2009-2011:** Development of first gripping and simulation technologies at DLR ZLP Augsburg. Setup of robotic work cell with two cooperating robots, first cooperating layup of single cutpieces up to 6 m wide. Establish Thermography and Ultrasound NDT. Investigation of automated handling and layup of large-area, dry NCF textiles in three-dimensional toolings in continuation of project CFK-TEX [1].	
2	**2011-2013:** Development of cutpiece detection technology, improved gripping technologies, first investigations of digital process chains and offline programming, start development of autonomous path planning. Implementation of a robot interface in order to allow a manufacturing execution system (MES) to control robots in an abstract manner.	
3	**April 2013:** Plane organo sheets made of **thermoplastic prepreg fabric**. Dynamic suction cup switching and TCP-change for each cutpiece, stacking onto one fixed drop point. First demonstration of cutpiece detection, limited to small cutpieces due to limited algorithm performance.	
4	**Sept. 2013:** Enhanced digital process chain for 3D layup according to CAD Data. Grip and drop planning for rectangular cutpieces by calculating the contour center, manual geometry transfer and storage of robot frames in job definition file (**jdf**).	
5	**March 2014:** Manufacturing of the “Demo Panel” stringer base. Autonomous preforming of small, 2.5D parts with cutpiece detection and dynamic grip and drop points (nine preforms of eight cutpieces each). Material is **bindered biaxial con crimp fabric (NCF) (0/90, ±45, 90/0, ∓45)**. First implementation of dynamic layup execution depending on material availability. Implemented cutpiece contour detection.	
6	**June-August 2014:** Manufacturing of full scale demonstrator “Demo Panel” with cooperating robots and prototypical digital process chain. Robotic preforming with pre-calculated grip and drop points. Subpart assembly of stringerbases, stringer assembly. Material is **bindered biaxial NCF (0/90, ±45, 90/0, ∓45)**, 112 cutpieces of ≈1040 mm x 1980 mm size, automated tacking by hot stamp binder activation.	

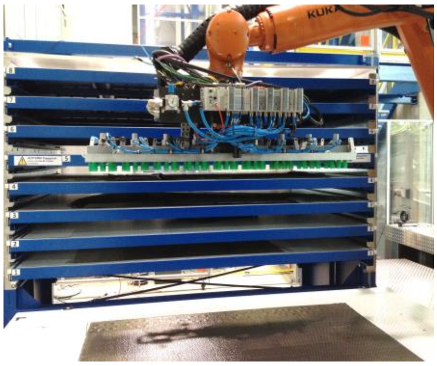
7 **April 2015:** Manufacturing of three thermoplastic skins of **CF/PES UD tape (**108 cutpieces each). Ultrasonic spot welding for tacking the stacks. First implementation of semi-automatic grip planning (Plylander-software), export of grip and weld info for 108 cutpieces, drop points generated in CATIA by manual geometry transfer of the grip frames to 3D.



8 **June 2015:** Manufacturing of organic sheets of **thermoplastic preimpregnated atlas fabric**. Detection of material direction by fourier analysis developed, since cutpieces were quadratic. Despite of the camera's low resolutions peaks corresponding to the binding (4-1 Atlas) can be clearly identified.



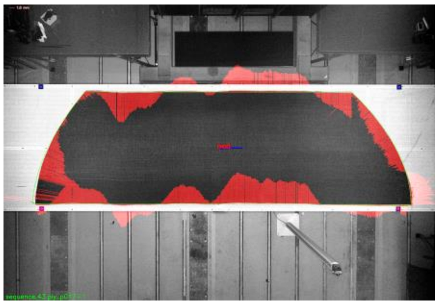
9 **July 2015-January 2017:** Adaption of cutpiece detection for bigger cutpieces, implementation of multi-robot MES and job description (**jdf** file), implementation of grip point based draping, commissioning of cutpiece drawer storage logistic system operated by a robot. Cross validation of system with carbon fiber (**NCF**) and aluminum foils (**FML**). Autonomous cutpiece transfer by coupling with a collision free path planner (CoCo). Preforming with full operative drawer storage.



10 **April 2017-April 2018:** Manufacturing of four thermoplastic skins of **UD PEEK and PEKK,** 104 cutpieces each, laminate 11..28 layers (2.2..5.6 mm), four material directions, staggered splices, all cut-pieces different. Low-force energy chain, base drift correction by dedicated camera. Meta and process data logging to time series database. Accuracy comparison drawer storage - vacuum table.

11 **December 2018-January 2019** Manufacturing of a rear pressure bulkhead demonstrator in **NCF**. Prepare integration into superseding process control system. Coupling with further process steps (cutting, cutpiece delivery, gripper shaping, accuracy measurement with laser scanner, fiber angle measurement) via OPC-UA interface. Cutpiece draping with single robot and collaborating robots.

12 **April-May 2019** Second **NCF** RPB Demonstrator with extended process control system and extended logging to database. Job description, cutpiece image, cutpiece deviations, process info and meta info as well as process control measurements are checked in to a MongoDB, time series data go to an Influx database, superseded by a graph oriented Neo4j-Database which "glues" related datasets together.



2.4 Digital process description and digital workflow

The next technology brick is to make all this information digitally available and to allow the robot's hardware abstraction layer (cf. 2.5) to execute this very generic job description. What we did was to collect all the information in a job description file (jdf) [7]. For our purposes it proved valuable to have the chance to edit or "tweak" the file on the shopfloor, since DLR is conducting highly varying research projects where intense flexibility is necessary all day. In an industrial production line this is not tolerable, and the future will most likely be to supply all information no longer on a file basis, but as a software service providing the information to the manufacturing units as applicable. Process description and workflow were subject to major improvements during six projects over a period of six years (Table 1, 4-12). Major effort was put into coordinate standardization both in the software and in the CAD.

2.5 Multi-robot synchronization and execution layer

For the high-level operation of multiple robots a multi-robot hardware abstraction layer (HAL) was developed. One or more KUKA robots are connected to the HAL client via TCP-IP connections. Every robot runs the corresponding HAL server program written in the robot's native KUKA KRL (the robot-side HAL can be adapted for other robotic platforms in the future). We implemented a basic set of commands for moving the robot, reading and writing bases and tools, controlling the grippers and transferring and executing point lists. Synchronization of the robots happens by waiting for the program execution if realtime is not required or by the robot's MOTIONSYNC synchronization mechanism if realtime is required. By transferring point lists for a complete motion and afterwards executing the lists with MOTIONSYNC we experienced excellent, smooth, jerk-free robot synchronization, which could be observed best when handling large carbon fibre cutpieces (Table 1, 5, 7). Dynamic team formation is under development in the case that several subsets of the robot team have to be selected for different tasks.

2.6 Autonomous cut-piece transfer by means of collision free path planning

As long as there is only a table for gripping and a low-curved mould for dropping autonomous production can take place without further limitations. As soon as there are two or more robots involved or there are obstacles in the path, the transfer of the cutpieces from the post-grip to the pre-drop position becomes challenging [7-8]. Since there is a big variance in the gripping position, which can be modelled only approximately in CAD due to the underlying cutpiece logistics, the planning of the transfer path cannot be done offline. A path planning and collision avoidance system (CoCo) was developed in order to overcome such limitations [10-12]. In combination with the HAL (cf. 2.5) both carbon fibre NCF-sheets and aluminium foils for fibre metal laminates (FML) of approximately 1m x 2m size were handled with two cooperating robots in a complex scenario (Table 1, 9). With the CoCo software path planning could be done in minutes, while teaching took up to one day per cutpiece for this scenario, thus the time savings are in the range of more than 99%. Another advantage is the ability of the system to consider the cutpiece catenary-like shape while teaching is only possible with a fixed geometric link between the robots which excludes the consideration of the catenary.

2.7 Manufacturing execution system

The bricks 2.2 to 2.5 were combined in a manufacturing execution system (MES) [7]. The job description from section 2.4 is parsed and transformed in an action list which holds information about what should be done with every cutpiece, for example where and how to grip, where and how to drop and the weld information for tacking (Table 1, 9). Once the MES is invoked (cf. 2.9) it executes the autonomous layup of one or more cutpieces and returns control after the execution is finished. The reason for a dedicated MES is that there are plenty of coordinate transforms or coordination tasks to be performed that are very near to the basic hardware and thus out of the scope of a high level process control.

2.8 Process data acquisition system and digital twin

The need of collecting quality data inline led to the implementation of a process data acquisition system, which collects all available machine data and acquires additional data by reading dedicated sensors for quality control. For example we collected log data from a ultrasound generator together with robot positions and compaction sensor readings during tacking thermoplastic cutpieces to preforms (Table 1, 10). Having collected those data we were able to identify possible defects in thermography images as local clusters of those weld points and could subsequently avoid clustering [8, 9]. In another project based upon preliminary research [13] we stored production relevant measurements (draping, fibre angle) and machine parameters in two different databases (Influx and MongoDB) that are subordinate to a Neo4j graph oriented database which is responsible for a sensible grouping of the different measurements (Table 1, 12) [14, 15, 16]. The data acquisition and storage system is under further development, but by today it is absolutely clear that one database for all purposes will not be satisfactory, and there will be a couple of application specific databases superseded by a (probably) graph-oriented database that will manage the ordering and grouping of heterogeneous data and allow access to related datasets. For time-series machine data we relied on the OPC-UA protocol, while event data were conventionally uploaded to the database.

2.9 High-level process control system

Beside the layup there are further process steps to consider. The manufacturing of a rear pressure bulkhead (Table 1, 11-12) also involved cutpiece generation and supply, preparation of cutpiece tacking, the a. m. layup, quality measurements (geometry and fibre angle [15]) and finally vacuum bag application. Self-contained process steps were orchestrated directly by executing predefined modules while the MES was invoked only temporarily for the layup [16]. The collected datasets were tagged by unique process IDs managed by the process control system in order to allow grouping of related measurement data and machine readings. The process control system communicated to the subsystems by the OPC-UA protocol and for the very first time connected all subsystems along the workflow. Further investigations concerning layout and communication models have to be performed in order to clarify and optimize the system’s future architecture.

3. RESULTS

Gripping proved to be always specific to the material and yielded good results concerning accuracy and reliability after some optimization loops. It was found that an overall accuracy in layup better than ±1mm is hard to establish and gets harder with the part size. Computer vision aided gripping can help to improve accuracy [5-7] as long as there is not too much material undulation [8-9]. The use of several tool bases may help to enhance the accuracy when manufacturing full scale aerospace parts. As soon as draping is involved the parameter space tends to get very complex [14, 15], and tolerances have to be extended. Without a flexible automation composite layup with industrial robots is only conceivable for large-scale production due to the excessive time needed for teaching. Since aerospace production rates are comparably low automated derivation of grip- and drop coordinates from CAD data together with a digital process description and a digital workflow proved to be an enabling technology for the necessary flexibility. The hardware abstracting manufacturing execution system with integrated collision avoidance in conjunction with the high-level process control allowed the production to become almost autonomous. The implemented process data acquisition system helped to make first steps towards a digital twin of every manufactured part and showed the potential to implement continuous improvements in a digital production by establishing a closed loop. It was found that open system architecture is of uttermost importance, since every composite part implies modified or even new technology bricks for production.

4. CONCLUSIONS

During the conducted tests the robotic production system got more and more elaborate and more autonomous. Established workflows were connected by a high-level process control system and for the very first time every subsystem along the process chain could be integrated. In numerous projects technology bricks for the autonomous production of lightweight aerospace composite structures were developed and tested. The suitability of industrial robots as flexible and reliable means of production of such parts in conjunction with the a. m. technology bricks was confirmed. It was also shown that a robot out of the box is not sufficient for the required flexibility and autonomy, since too many requirements for composite production are out of the robot manufacturer's scope. Application specific technology bricks can fill the gap between robot and composite manufacturing in order to allow a flexible automation for enhanced productivity and reliability. With every new part the technological portfolio grows and with open software architectures new technologies can be added promptly in order to satisfy the demands of a highly dynamic market.

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