Automated composite manufacturing using robotics lowers cost, lead-time and scrap rate

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ABSTRACT

In the aerospace industry, the labour intensive part of producing composite components still is the manual layup and draping of (prepreg) materials. Despite the high production costs due to this intensive manual work during processing, the use of this technology has been necessary so far for a broad range of components to meet the quality requirements of high-performance composite parts for aerospace applications.

This paper will outline historically used manufacturing techniques and the transition towards currently used state-of-the-art technologies and materials, and future developments to be implemented shortly. It will address automated fiber placement (AFP) used for larger and/or complex structures using unidirectional (UD) fibers and new draping and preforming concepts by means of advanced pick & place techniques to replace manual labour. Different state-of-the art robotic pick & place production processes will be detailed by means of prototype manufacturing of different aerospace parts. Both dry fabrics and prepreg materials will be addressed.

According to cost calculations, the use of automation over manual labour shows potential recurring cost saving of 40-50 % compared to the baseline parts. Robotic pick & place activities also show a significant reduction of lead time compared to manual layup. Part quality will easily be more consistent due to the improved repeatability of the automated process and independency of the human-factor. Due to this independency and high repeatability, scrap rates will go down. The impact on quality assurance (QA) and inspections is discussed and compared to the current baseline inspections.

In contrast to, for instance an AFP machine, no standard plug-and-play pick & place production systems are available for aerospace manufacturing applications. But as this equipment is relatively simple and industrial available, the automated preforming technology using pick & place, is very affordable. Due to limited setup cost and programming effort for robot pick & place, this process is already competitive for smaller sized parts or low volume production. Another advantage of automating composite manufacturing processes is the integration with new possibilities originated from Industry 4.0. A fairly new and even more powerful concept is the integration with so called “Digital Twins” allowing outside real-time monitoring and control possibilities converting the production into more “smart” solutions for near future.

The overall effect of these new manufacturing concepts regarding availability of spare parts, manufacturing technologies and tooling for a long time is at least similar and can be argued to be better than composite parts currently manufactured. The independency of skilled manual labour, which is expected to become scarcer in future also, is an advantage compared to current more manual manufacturing processes.

1 AEROSPACE MANUFACTURING

1.1 Past to present

The origin of the aerospace industry dates to 1903 when the Wright brothers demonstrated an airplane capable of a powered, sustained flight. At the start, the aircraft-manufacturing industry was virtually self-contained in the producer's plant, with the exception of a few key products such as engines and tires. The majority of labour was associated with woodworking and sewing of fabric for the fuselage, wings, and empennage. All skilled labour was used and tooling was limited. The few machined parts and even components, such as seats, were fabricated by specialized groups within the aircraft producers' factories. The advent of metal airframes changed both the character of manufacturing processes and the skills required of production workers. At first, only the wood framework of fuselages was replaced by tubular aluminum trusses connected with mechanical fasteners or welding; coverings were still sewn and glued fabric. From the mid-1930s, as thin rolled aluminum alloys became available, all-metal structures for fuselages and then wings became prevalent. Skilled craftsmen were required to operate the metalworking machines, and new emphasis was placed on flush riveting and welding.

As aircraft became more sophisticated, the demand increased for machined parts, castings, forgings, and extrusions, which all required different machinery and different skills. This also resulted in the growth of the group of suppliers from whom specialties were procured. Especially, when around both world wars, the demand for combat aircraft grew rapidly, facilities of existing plants were expanded, new facilities erected, non-aircraft producers (mainly automobile manufacturers) brought into the industry, qualified personnel recruited and trained, and new production processes developed. Non-aircraft producers obtained licenses to build entire products developed by the aircraft industry or acted as subcontractors for aircraft manufacturers. As a result, a revolutionary change in the technology of airframe production occurred, shifting from "job shops" with craft labour to assembly lines with workers of lesser skills. This necessitated greater standardization of parts and job processes because of the complexity of the product. By the end of World War II, airplane production in the United States and Britain had assumed the character largely maintained to the present day. This meant that design, major assembly, and integration of systems made by suppliers in the makers' factories became the emphasis, rather than the complete manufacture of an entire vehicle. [1]

From the 1960s and 70s the use of first Glass Fiber (GF) and later Carbon Fiber (CF) composite material on the airframe was increasing quickly. This again asked for a different type of skilled manual labour and supply chain. Helped by technological developments and the rise of computers, the efficiency and quality of composite manufacturing and inspection has improved since. For instance, through the use of automatic ply cutters and, later on, (automatic) nesting software, speed, quality of the cut plies and "buy to fly" ratio improved significantly over manual cutting. Another example is using laser projection cameras for accurate ply positioning and projection of the correct stacking sequence of plies. This also improved manufacturing speed, quality and buy to fly ratio, as it assists the manual operator during layup and limits possible errors that reduces scrap. But still today, a significant amount of skilled manual labour is necessary to do the so-called layup[1] of composite aerospace parts.

Today, the application of composite materials in aerospace structures of the latest generation aircraft has reached a high degree of maturity. The current trend is towards the development of more cost effective components; one way to achieve this is to automate the production processes [2]. Over the last decade efforts to automate composite layup have increased and as a result also matured significantly. One of the pioneering techniques used to automate manual layup of CF/GF plies is tape laying (TL) and automated fiber placement (AFP). With these techniques, it is possible to automatically lay down unidirectional (UD) fiber material in a

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[1] layup = creating a stack of plies of different sizes, fiber directions and or shapes on top of each other to create a laminate, either flat or directly onto a 3D contoured mould

predefined area and programmed order and fiber direction. This is currently the most common form of automated layup seen in composite aerospace industry. Fiber placement is used either directly on a mould or layup surface (Figure 1 & Figure 2) or to manufacture a flat semi-finished preform that can be used in other automated processes like hot press forming or hot drape forming.

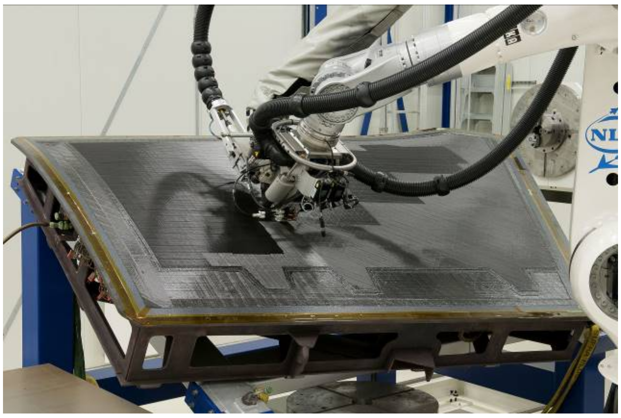


Figure 1: AFP of a (partial) wing skin

Figure 2: AFP of a 6 meter thermoplastic pylon spar for an engine pylon

Fiber placement is not limited to a specific kind of composite material. It can be used to process thermoset prepreg materials (i.e. CF/GF that are pre-impregnated with the exact amount of resin necessary for the application), dry fiber materials and thermoplastics. However, materials used for fiber placement are different from those mostly used for manual layup processes with fiber plies cut out of fabric material. Fiber placement materials are always unidirectional (UD) meaning the CF/GF fibers only run in one direction of the material (lengthwise only). From the point of view of composite properties, this is not a drawback, but it means that the design and layup of a composite part using UD material is different from the design of the same part using fabric material where usually two fiber directions are already present in the fabric ply.

A limitation of AFP can be found in the equipment cost, the setup cost and material and energy costs for this manufacturing technique. These costs are rather high and therefore not always competitive for smaller sized complex parts, which are currently still laid up by hand using CF/GF fabric material. Also downtime of AFP equipment is challenging. Numbers around 50% are not uncommon, for instance as a result of necessary quality inspections, cleaning, maintenance or material related issues, such as fiber breakage or material reloading. With possible continuous fiber placement speeds of around 800-1000 mm/s, while laying down multiple tapes of 0.25” or 0.5”, this manufacturing process has great potential to lay down a significant amount of material per hour. However as aerospace industry is struggling to rely on robotic repeatability and sensorial data, manual 100% ply-by-ply visual inspections are very common and cause considerable downtime of AFP equipment lowering possible output. As vision techniques to assist on ply-by-ply inspections are also developing rapidly, maybe in future it will be possible to reduce downtime and make better use of the potential of AFP.

There have been many other initiatives often based on robotic pick & place that attempted to find an automated and competitive solution for these kinds of fabric parts that are currently still laid up by hand [3]. However the majority of these initiatives were dedicated to only one kind of product and focus on so called dry fabric materials, meaning there is no matrix material included, but only the CF/GF material. Hence dry fabric is easier to process because the material is not tacky and more flexible so that wrinkles are easier to avoid [3] compared to prepreg material.

For automated pick & place solutions standard industrial robots can be used. The pick & place tool itself is often built with simple industrially available components, but some hardware needs specific tailoring for different part sizes, shapes and materials. For this reason no standard plug-and-play pick & place production systems are available in contrast to, for instance, a fiber placement machine. But as all necessary equipment and dedicated tooling needed for automated pick & place is relatively simple and industrial available, the automated preforming technologies using pick & place, is very affordable. Due to limited setup cost and programming effort for robot pick & place, this process is already competitive for smaller sized parts or low volume production.

A successful attempt with robotic pick & drape of prepreg GF plies has been demonstrated by the Netherlands Aerospace Centre NLR together with UMECO in the FP7 program COALESCE [2]. In COALESCE several efficient and automated manufacturing techniques were investigated and demonstrated successfully, as will be detailed in paragraph 1.2.2. The system developed in COALESCE was found to be very cost effective, but with some drawbacks also. Even after the design was transferred to a composite design some re-design was necessary to make a high degree of automation possible. Also the entire process development and complex programming of the robotic pick & drape was based on trial and error. This resulted in a large set-up effort, which has to be done over and over again for each new part, which is manufactured with the same technique. Still the developed process showed large potential for new applications.

1.2 State-of –the-art and beyond of composite manufacturing

Besides automated techniques like fiber placement and tape laying that have been around for quite some time already, recent studies – presented at conferences, such as SAMPE 2017 Paris, JEC 2017, Carbon Fiber 2017 and CAMX 2017 and also reported in CompositesWorld articles [4][5][6][7] – confirm increased activities in the market to automated composite manufacturing. As the volume of the composite industry keeps growing and expanding to other industries, the developed solutions for automation focus more on high volume output of less complex parts by combining different automation processes efficiently. Not for the first time in aerospace manufacturing history, automation solutions for aerospace are driven or challenged by solutions found and developed in the automotive industry. Progress made in automation on composite manufacturing in other, less critical and conservative industries, triggered the development that also for more complicated aerospace parts, (partial) automated solutions can be possible and have definitely potential. Most solutions presented so far describe a combination of 2D or 2.5D sub-preforming (semi-finished preform) with dry fiber or thermoplastic fiber plies using pick & place combined with a Hot Drape Forming (HDF), hot press forming or a Resin Transfer Moulding (RTM) process to automatically manufacture composite parts. A good example of combining automated manufacturing techniques is the "Innovative Robotized Preform Cell Providing 3D Stacking and Control" from the Composite Alliance Corporation (CAC) in Dallas, which won the 2016 Award for Composites Excellence at CAMX (the Composites and Advanced Materials eXpo) in Anaheim in the Manufacturing Equipment and Tooling category [4]. Although they developed a highly automated setup for the layup of CF fabric plies, it was again limited to 2.5D applications and mainly focussed on dry fabric material combined with hot debulk or hot drape forming followed by RTM. Similar remarks can be made about the IAI and TechniModul automated “one-shot” helicopter seat [7], which combines an automatic layup of dry fiber plies using robotics and RTM injection for the resin to automatically manufacture a helicopter seat.

The Netherlands Aerospace Centre (NLR) recently also demonstrated an Automated Composite Manufacturing Pilot Plant (ACM-PP) using dry fabric materials stacked on top of each other by a special developed multi gripper grid (Figure 3). The process also uses hot drape forming after the automated pick & place of fabric plies to create the 3D shapes. Those preforms are combined and overbraided before injecting those with resin using an automatic RTM process. This automated process, which prototyped a number of flying parts, will be described in more detail in paragraph 1.2.1.

Figure 3: Automated Composite Manufacturing Pilot Plant

NLR also uses similar techniques in the H2020 program called “HECOLAG” to automatically preform again landing gear components. But similar to the CAC solution described above, this is a different manufacturing technique addressing a different product category than the more complex 3D layup on a contoured layup surface with prepreg fabric plies.

Although research and development efforts in automated preforming technologies such as described above have increased enormously over the last couple of years, applications still mainly focus on high volume or relatively simple 2D and 2.5D applications mostly using dry fiber materials. As development costs for this complex automated processes and equipment are high, tooling engineering and manufacturing companies logically rather focus on the increased interest for composite parts from high volume markets like automotive, wind turbine or bicycle industry. For these markets specifications/requirements and certification are often relatively relaxed and hence less challenging, which allow manufacturing processes to easily be changed from manual to automatic.

This leaves a gap for parts that are manufactured with prepreg fabric plies. Due to specific weight advantages of these prepreg composite materials for high performance applications in aerospace, automotive and other industries, they are widely applied. The presence of the resin makes the material more challenging to handle as the resin causes tackiness (it is sticky) and adds stability to the fibers making it more difficult to position it correctly onto a layup surface. As a result, parts using prepreg fiber plies are nowadays still manufactured mainly by manual layup, making these parts relatively expensive to produce.

In aerospace, state-of-the-art airplanes from e.g. Airbus, Boeing, Gulfstream and Lockheed Martin use a great deal of prepreg parts using manual layup. As those parts will be manufactured over the next 20-30 years at least, an automated solution for this is “game-changing”, as it is expected to drive down manufacturing cost significantly. When developing parts for new aerospace applications, airframe developers are tempted to re-use existing manufacturing processes, as certification and qualification will be much more straightforward and therefore cheaper.

Currently a very interesting research project called FlexDraper is running in Denmark. This project investigates the combination and integration of mechanical, machine vision and software components for automated high precision draping of prepreg composite fabrics onto double curved moulds. This project researches the previously identified gap to offer an automatic solution for the manufacturing of prepreg fiber plies, while complying with necessary specification and certification challenges. Technical details and process techniques of FlexDraper will be outlined in paragraph 1.2.3.

1.2.1 Automated Composite Manufacturing Pilot Plant – Automated preform station

At NLR a fully automated so called preform station was set-up in co-operation with Fokker Landing Gear (FLG). This process combines a dry CF fabric weave and CF braiding material to create a dry preform, which is injected using a fully programmed RTM cycle.

It starts with nesting and cutting of the dry fabric plies on a cutting machine. From this location, a robot arm with a multi gripper grid using suction cups (Figure 5) picks individual plies with over one hundred different sizes, shapes and fiber directions (Figure 4). Suction cups are selected over vacuum cups to be able to handle the “open” fabric weaves. Depending on ply dimensions, only the necessary suction cups to handle the specific ply are activated during layup. Each ply is stacked/laid up in the correct order and predefined position on a vacuum table.

Figure 4: Robot picking plies from cutting machine in ACM PP

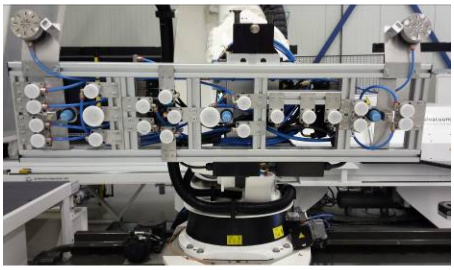


Figure 5: Example of multi gripper grid with suction cups

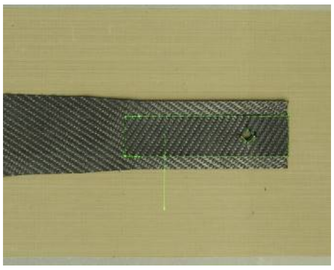


Figure 6: Ply inspection with laser vision

Sensor technology monitors any unexpected ply drop and signals an operator to intervene if necessary. On the flat layup table, a vision system is projecting the defined ply location of each ply automatically and stores the result by taking a picture of the ply and boundary after each ply is draped down (Figure 6). Typical layup speed is around 10 seconds per ply. The vision system can also scan for Foreign Object Debry (FOD) in the layup area and signals an operator again if FOD is found. The accuracy of the plies that are laid down is within +/-2.5 mm (+/- 0.1”) for all net-shape boundaries and drop-off’s inside the preform. As inspections are not causing down-time by slowing down the automatic layup, the layup of a 20 ply flat stack of dry fabric material takes only about 3-3.5 minutes. After a complete sub preform is stacked, the robot signals the vacuum table to close and to start a heat cycle combined with vacuum to “bond” the stack of flat plies together (dry fabric plies contain a bit of binder powder). Infrared (IR) is used to quickly heat up the carbon fiber material. In the meantime all process parameters are measured and logged and the robot takes a HDF mould from the storage and places that on a second vacuum table. After the individual plies are bonded together to a flat semi-finished sub-preform on the first vacuum table, it signals the robot again to pick it up. The robot then moves the flat preform from the first to the second vacuum table and places it on top off the HDF mould (Figure 7). By applying heat and vacuum again, the flat preform is hot drape formed to its final 3D shape. The robot then moves the HDF mould including the preform from the second vacuum table to a cutting stand. If necessary, depending on the application and tolerances, the robot can use an Ultrasonic (US) cutter to trim the preform to net-shape within +/- 1 mm (Figure 8). By process optimization, this is about the same tolerance that can be reached directly in the automated preform station after HDF. So less critical applications do not need to be US trimmed afterwards and can be directly preformed to net-shaped.

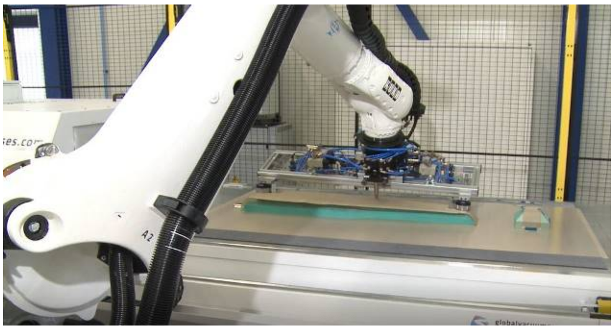


Figure 7: Placing Flat preform on HDF mould

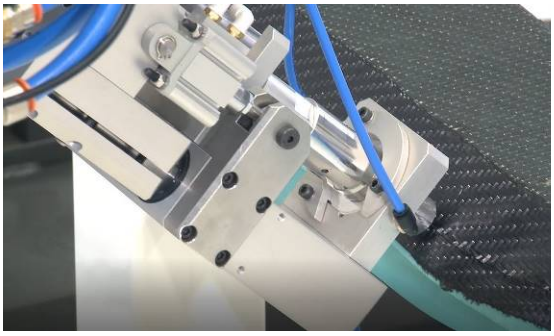


Figure 8: US cutting of preform to net-shape after HDF

From this point, the robot waits for the operator to remove the preform from the cell. After the operator has removed the net-shape preform, he/she signals the robot that the working area is cleared again and the robot re-enters the working area to pick-up the HDF mould and returns it to the storage. The activities of the operator in the whole process are limited to loading a roll of fabric on the cutting machine, starting the program in the preform station and retrieving the net-shape sub-preform from the cell. All quality inspections are performed and logged automatically during the process. These can be accessed by the operator or a specialised quality assurance (QA) officer, who signs of the preform before it enters the next process step. As all preforming tasks are fully automated and programmed, the quality of the parts is highly repeatable. On top of that, the process itself is very robust, resulting in a scrap rate for the automated preform production close to zero. Except for a more constant high quality and reduced scrap rate, the amount of manual labour also decreased over 90%, driving down recurring manufacturing cost significantly. The entire automated manufacturing process is certified along the way and parts have been tested and are scheduled for flight testing which will bring the entire process to TRL 7. Using and combining straight forward industrial available hardware components, equipment cost are limited compared to AFP equipment. Also programming effort is limited as most actions are driven by relatively simple pick & place programming making it approachable for many that have just basic robotic experience.

1.2.2 COALESCE – Automated prepreg layup

Within the EU project COALESCE automated manufacturing of a slat 1 fairing for the Airbus A320 was studied. The investigation aimed for cost reduction of the fairing using Automated Fibre Placement (AFP) on the one hand and automated laminating technology using so-called robotic pick & drape on the other hand [2]. Both were combined with an out-of-autoclave co-cure concept. The fairing consists of a rib and a double curved skin. With the AFP process, flat laminates from glass/epoxy unidirectional tapes were manufactured which were formed using a Hot Drape Forming (HDF) process. Furthermore, a variant of glass/epoxy fabrics was manufactured using a robotic pick & drape process. The preforms were co-cured using an aluminium mould and a heated press.

The baseline aluminium slat 1 fairing, which was aimed to improve cost and weight wise is located in the wing to fuselage transition area and consists of two separate parts; a rib and a double curved skin. For the AFP process two options are available; the first option is to place the material directly on a tool with geometry corresponding to the fairing shape and dimensions. The second option is to place a flat sheet and to drape form the sheet into the desired geometry with an additional process step. The second option, placing a flat sheet, was considered to be the most promising because of the possible high fiber placement speeds. As AFP is already state-of-the-art, it is more interesting to discuss the automated laminating technology pick & drape which was assessed in this project. The pick & drape work was done by Umeco. On the ply storage table (or cutting machine) several plies are available already in the correct size and shape. These plies are picked up with a gripper and using a vacuum cup and clamping hook, both backing foils are removed automatically. After removal of the foil a preforming gripper with an inflatable membrane picks up the plies and the robot moves to the IR heater which heats the ply to a predefined temperature. The final step is to place the ply directly on the mould (Figure 9).

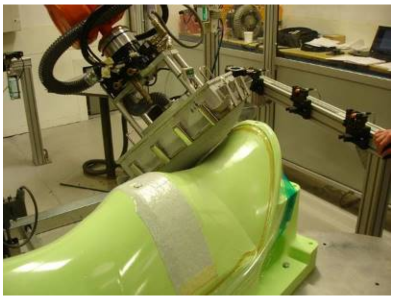


Figure 9: COALESCE pick & drape of Slat 1 fairing

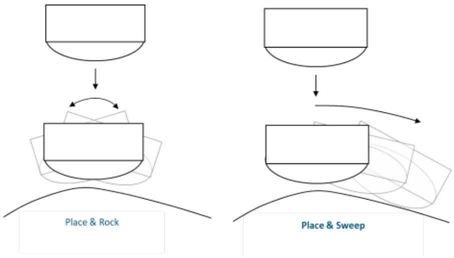


Figure 10: COALESCE robotic drape movements

With the help of the inflatable membrane combined with special robot movements, it was possible to drape very tacky thermoset prepreg material onto a double curved layup surface. The robotic arm was used for so-called pick & rock and pick & sweep movements during drape (Figure 10). The correct starting point, series of movement and interaction with the inflatable membrane was extremely difficult to program. Extensive programming based on trial and error was necessary to perform layup without wrinkling of the fabric plies. The desired accuracy of layup of +/- 1.5 mm was challenging and not always met, but expected to be possible.

Compared to the baseline aluminium fairing, a cost saving on labour was achieved. For the robotic pick and drape concept, costs were analysed and showed a possible reduction in labour costs of 63% due to process automation and reduction of assembly steps. Raw material costs are increased by 162% because of the use of GF material compared to the baseline aluminium fairing, but material costs are minor compared to labour costs. Therefore, the overall recurring costs for a single S2-glass fibre fairing made with robotic pick & drape was reduced with 58% (Figure 11).

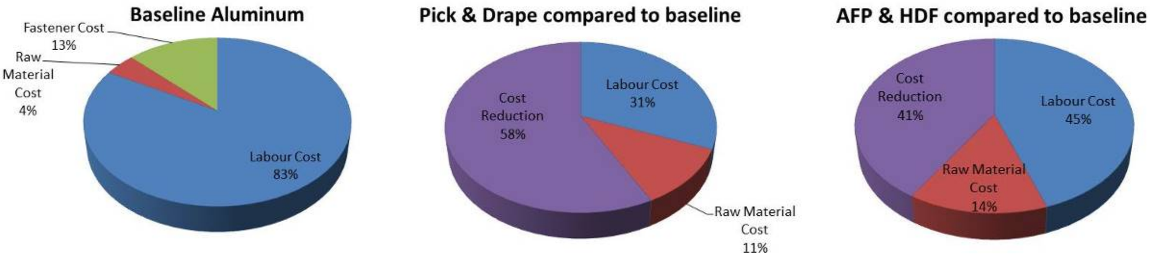


Figure 11: Cost comparison between baseline aluminium slat fairing and automated GF fairings

For the fairing manufactured by AFP and HDF, a reduction of 46% was found to be possible on labour costs. The raw material costs increase with 235%, due to the fact that slitted GF tape for fiberplacement is more expensive than the GF fabric used for the pick & drape process. Hence an overall cost reduction of 41% could be achieved with the AFP and HDF process (Figure 11). Furthermore, with both processes, a weight reduction of at least 40% (590 gram) compared to the aluminium baseline was realized. As there is pressure from within the aerospace market itself to focus more on affordability for the next generation aircraft, programs like COALESCE show significant potential for automated composite manufacturing solutions to realize cost and weight savings, especially over aluminium baseline designs.

1.2.3 Flexdraper

An example of next generation automated composite manufacturing technique is currently being developed in the Flexdraper project. Flexdraper is an R&D project focussing on fully automated layup of CF/GF prepreg fabric plies directly onto a 3D layup mould. In order to avoid large setup and programming effort, the system is more or less generic, and path programming and draping is also fully automated. The system targets not just a single component, but an entire product family within certain limits regarding dimensions and curvature. The project is running in Denmark and the partners are TERMA Aerostructures A/S, University of Southern Denmark, University of Aalborg, Technical University of Denmark, RoboTool (robot integrator) and NLR.

The current FlexDraper R&D system is shown in Figure 12. The layup task consists of picking pre-cut plies of prepreg fabric from a flat table surface and after automatic removal of the protective foil draping these onto a double curved mould. The pre-impregnated epoxy resin gives rise to a certain tackiness, which makes it challenging to grip this material, and to complete the task without wrinkle formation. The drape tool consists of up to 10 x 12 suction cups with individual linear actuators arranged in a rectangular grid and it is moved by a 6-axis industrial robot.

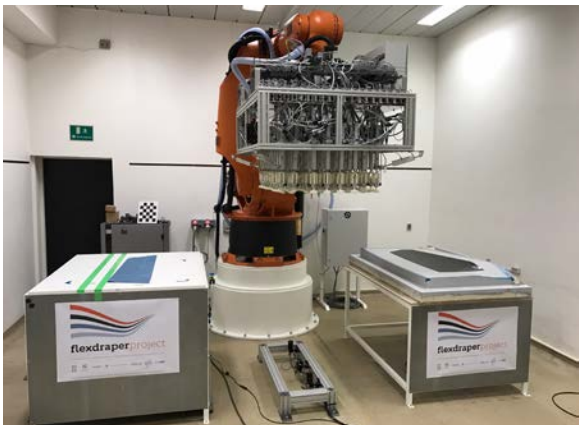


Figure 12: FlexDraper R&D system at TERMA

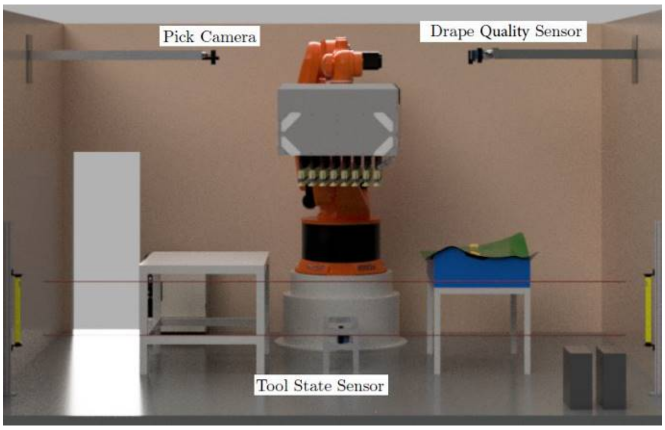
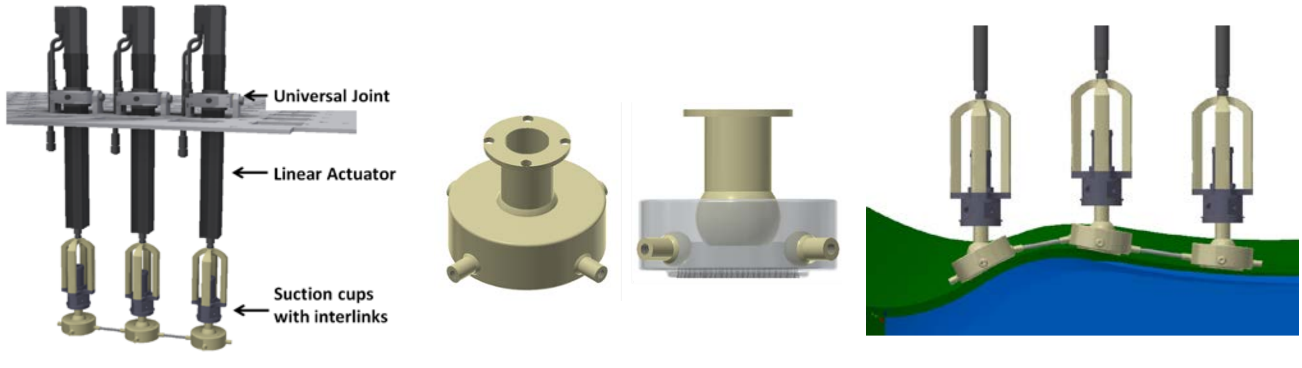


Figure 13: Picture of FlexDraper Digital Twin environment

Due to the complexity of the 10 x 12 individually controlled/actuated suction cups in the grid, it is almost impossible to program this manually for all different plies and different layup surfaces. So the most critical part of the design and control mechanism is to define some algorithms to automatically compute and execute strategies for draping. A strategy can be defined as a path initiated from a configuration where all suction cups and hence the ply are located above the mould in a so-called pre-shape configuration and ending at a configuration where all suction cups have been placed on the mould and the ply has been correctly draped. Finding the strategy involves computing the order in which the suction cups are placed onto the mould surface and in turn the detailed movements of the individual actuators. The initial strategy is inspired by manual draping, where the drape starts by touching down at a well-chosen location from which the drape propagates over the layup surface with a wavelike movement. Also the robotic movements between the pick-up location of the ply and the draping location on the layup surface of the mould are calculated off-line. The vision system locates the ply that has to be picked up using the Pick Camera (see Figure 13), checks the location on the gripper grid to be equal to the position modelled off-line using a Tool State Sensor (Figure 13). All this information is processed in the digital representation and used to adjust and control the equipment execution. In order to use, simulate and control all the different calculations done based on CAD data input, material and draping behaviour, vision input and other off-line algorithms, a so-called Digital Twin of the Flexdraper setup is used. This virtual representation fully describes everything involved with making the part. It defines exactly how various plies will be handled including the tolerances and the orientations, before sending instructions to the robot for completing the manufacturing process. So this Digital Twin is not only a real-time simulation of the operational environment generated a ply-by-ply quality log with all relevant data, its actually in charge of the operational FlexDraper environment and used to program and control the actual FlexDraper equipment. After draping plies on the layup surface a Drape Quality Sensor (DQS, Figure 13) will inspect, assess and log the drape result. The DQS checks the relevant positioning tolerance(s), fiber angle and absence of wrinkles by comparing this to the 3D (Fibersim) CAD data and simulated result. The accuracy of the DQS is impressively high for a vision sensor being around 0.2 mm from a 3 meter height.

Most of the hardware equipment used for the Flexdraper system is industrial grade and off-the-shelf making it easily accessible. To enable pre-shapes with medium curvature and details, distances between suction cups are rather close. This also supports the criterion for necessary lifting force and limited free hanging material. On the current FlexDraper tool running in experiments, a grid spacing of approximately 110 mm between adjacent suction cups is used. Featured part dimensions to handle are approximately 1150 mm x 1350 mm, which results in a 10 x 12 = 120 grippers grid. To be able to handle different ply shapes, suction can be activated accordingly, so that suction will only be applied to the relevant areas of the multi gripper grid. Considering the weight and complexity issue, the number of actuators is limited. It therefore uses only one linear actuator per suction cup for up/down movements, and employs passive joints and interlinks to allow the cups to adjust the horizontal position and comply to the orientation to the mould surface. An extract from the tool showing three suction cups with interlinks is shown in Figure 14a.

The Flexdraper system uses SCHMALZ Composite Grippers (SCGs), which creates suction by means of the injector/Venturi effect. The grippers are equipped with a custom designed suction cup housing (Figure 14b) with integral ball joints, which can turn up to +/- 40 degrees. A set of so-called interlinks between the suction cups have been attached to force the position and orientation of the suction cups to naturally adjust to a surface of changing height (Figure 14c).



(a) Subset of tool showing the relative placement of the universal joints, actuators and suction cups

(b) Close-up of suction cups with ball joints for connecting with the actuator and interlink structure

(c) Illustration of interlink structure when placed at different heights

Figure 14: Flexdraper Tool and suction cup design and functionality

The height of the suction cups is controlled by means of electric linear actuators with spindle drive. The actuators can be moved individually and can be controlled by traveling distance, time and force. The specified stroke (Z-direction) of the actuators used is 150 mm. The gripper sub-assemblies of linear actuators and SCGs with custom suction cup housings are mounted equidistantly on a base plate. To passively account for the changes in horizontal distance of the suction cups from a 2D flat surface to a 3D shaped contour, the actuators are mounted on universal joints allowing them to rotate thereby satisfy the constraints of the interlink structure. Already with this design using one actuator per suction cup, the total weight of the whole assembly due to the actuators, control boxes, power supplies, pneumatic controls, wiring and tubing adds up to approximately 250 kg. This Industry 4.0 oriented combination of the hardware functionality, programming, control and vision technology used in FDP is beyond the current state-of-the-art in composite manufacturing and considered to be unique. Some individual components itself are also beyond the current-state-of-art. For instance the vision techniques used are much better suitable for accurate measurements of the carbon fiber materials, including difficult so-called “black on black” inspections. Instead of time consuming inspections of sequential small area’s at the time, the system can retrieve and process a 3D image of 1500 mm x 1500 mm from a 3 meter distance below 10 seconds using a special structured light sequence making it relatively independent of environmental lightning conditions also. More advanced mathematical modelling which is forecasted to be implemented before the end of the program is 2019 will improve both accuracy and speed. The current layup speed of the FlexDraper equipment is around 40-60 seconds per ply, including quality inspections (independent of ply-shape and dimensions). Accuracy of the system is currently within the +/- 2.5 mm target of the demonstration part, but is expected to be improved to +/- 1 mm to allow the system to handle butt-joints within the ply geometry as well. With these numbers this Flexdraper process is very interesting for similar fuselage covers, leading edge panels, etc., while saving well over 50-75% (depending on part dimensions and layup) on manual layup related labour and cost. Even more interesting is that this development stays very close to currently defined manufacturing protocols and specifications. As also the materials used are the same as used for manual layup, implementation effort, even into already running programs are expected to be limited.

2 AUTOMATION VERSUS MANUAL LAYUP

Current state-of-the-art equipment and automation solutions for composites manufacturing show significant improvements of manual labour cost and also manufacturing lead-time compared to traditional manual layup. On top of that, automation also realizes a more constant high part quality. It is not stated here that automated manufacturing processes realize higher part quality than manual layup of parts, as a very skilled operator can reach very high part qualities as well. However, any well implemented automated manufacturing processes will perform always within the targeted specification as it performs exactly the same actions, independent of which operator is involved and far less dependent on the skill-level. Meaning part quality is far more constant, and fully monitored by sensorial data. This independency of skilled manual labour, independent of the day in the week, any distractions or the physical location (worldwide), is also an important advantage of implementing more automation into composite manufacturing processes. Especially as skilled manual labour is expected to become scarcer in future also.

Another advantage of limiting manual labour is that the handling of and exposure to hazardous bismaleimide (BMI) and epoxy resins becomes less of a health risk to the workforce involved. Similarly, for large layup structures, complicated layup procedures can require suspending people to lay the fibers from above these structures or overstretching to reach difficult locations. Having the automated manufacturing setup do most of the “dirty work” removes risks for manufacturing personal without compromising the specific advantages of these not so healthy materials and difficult part geometries.

Regarding repairs there are no additional drawbacks to parts manufactured automatically, so this is considered to be at least equal to parts manufactured by manual layup and the challenges are the same. There might be a slight improvement due to the high repeatability of automated parts.

Automating composite manufacturing allows the integration with new possibilities originated from Industry 4.0. A fairly new and even more powerful concept is the integration with so called “Digital twins” allowing outside monitoring and control possibilities converting the production into more “smart” solutions for near future.

2.1 Quality Assurance

As outlined above, part quality will easily be more consistent due to the improved repeatability of the automated manufacturing process and improved independency of the human-factor. As vision equipment still struggles with black on black measurements (to identify ply boundaries) some intermediate solutions are currently most common. In some cases laser projection is used to show theoretical positions and pictures are captured and stored. This technique is similar to manual inspections, except for the fact that in those cases the manual operator interprets the result and physically signs off on the approved result. As a semi-automatic solution this can be done in a similar way for automated processes, as is also done and demonstrated in the automated preform cell in the ACM-PP at NLR. An Assembly Guidance vision system communicates with the surrounding equipment in the automated preform cell, knowing exactly which ply is put down by the robot and projecting the corresponding ply boundary and fiber orientation. The result is captured automatically again by a photo camera and stored automatically in folder specifically for that part. If, due to any outside disturbance, the communication between the vision camera and other equipment is interrupted or malfunctioning, the robot system will hold and signal an operator. In this way, there is assurance that every ply is captured and stored correctly. The inspections are very fast and can be done within the current cycle time of 10 seconds between plies, so the inspections do not slow down the automated layup process. The inspection of the captured result is not done real-time. Due to the high repeatability, checking the result is close to being a formality and has never led to rejected preforms so far. For this reason, the interpretations of the inspections are done remotely, after the complete automated layup is finished. This can be performed again by a (qualified) operator or QA officer, depending on the needs.

Systems currently coming to market – such as that used in the previously mentioned Flexdraper program and some commercially available inspections systems, as for instance Apodius – can not only capture layup quality graphically, but also perform real measurements and compare those with specifications and/or CAD data. This again limits the amount and or level of skilled manual labour necessary compared to a manual layup process making it more independent of the human factor as well.

Regardless the method chosen, inspections necessary for QA are more consistent due to the improved independency of the human factor. As automated processes are highly repeatable, the main focus of inspections of automated processes should be concentrated on limiting down-time of equipment instead of trying to mimic procedures necessary to control manual layup. In contrast to a human being, a machine or robot arm will always do the same thing.

2.2 Cost

According to cost calculations done and described for the three programs above, the use of automation over manual labour show potential recurring cost saving of 40-50 % compared to the baseline parts. Robotic pick & place activities also show a significant reduction of lead time compared to manual layup. Due to the independency of skilled manual labour during manufacturing, the high repeatability of the automated setup and sensorial information used either to control the manufacturing process or to signal an operator when anomalies occur, scrap rates will go down also.

For automatic pick & place solutions standard industrial robots can be used. The pick & place tool itself is mainly built with standard industrial available components but some of the hardware need some specific tailoring for different parts sizes, shapes and materials. For this reason no standard plug-and-play pick & place production systems are available yet. But as all necessary equipment and dedicated tooling necessary for automated pick & place is relatively simple and industrially available, the automated preforming technologies using pick & place, is very affordable. Due to limited setup cost and programming effort for robot pick & place, this process is already competitive for smaller sized parts or low volume production.

These advantages and a better buy to fly ratio by reducing scrap, make composite components and platforms more affordable. Savings on cost of automatically manufactured composite part also tips a new balance between repair and replacement. This decreases the amount of difficult repairs and probably improves service times as depending on design, location and application. Replacements can be much faster, meaning a higher operational employability and guaranteed part properties similar to new.

3 OBSOLESCENCE ISSUES

The influence of new automated composite manufacturing technologies regarding obsolescence issues of parts, tooling and manufacturing technologies for military logistics and operations is dual. The availability of spare parts can be guaranteed for a long time as it’s less depended on skilled manual labour. On the other hand does it mean that manufacturing equipment should be kept operational for a long time? As mentioned, tooling and equipment is standard and industrially available, but the setup is mostly dedicated for a certain product range. If dedicated tooling is documented and programming is stored, the availability of manufacturing technologies and tooling is similar to other automated manufacturing techniques, like, for instance, AFP or CNC machining. An advantage of automated composite manufacturing is the high repeatable part quality which is also independent of the production location or skilled labour. Interchangeability due to more constant part quality is better guaranteed and beneficial for maintenance and repairs. Also shortened lead times and considerable reduction of part cost are beneficial for military operations.

4 CONCLUSIONS

Large potential cost savings over 40% and lead-time reduction of automated composite manufacturing technologies based on pick & place and pick & drape have been outlined based on an actual aerospace part. Compared to baseline aluminium parts there is also significant weight saving potential while still reducing component cost.

Interesting is that some of these developments stay very close to already defined manufacturing protocols and specifications. As also the materials used are the same as used for manual layup, implementation effort, even into already running programs are expected to be limited.

Savings on cost of automatically manufactured composite part also tips a new balance between repair and replacement. It decreases the amount of difficult repairs and probably improves service times as depending on design, location and application. Replacements can be much faster meaning a higher operational employability and guaranteed part properties similar to new.

The overall effect of these new automated composite manufacturing processes regarding availability of spare parts, manufacturing technologies and tooling for a long time is at least similar and can be argued to be better than composite parts currently manually manufactured. Automated composite manufacturing based on pick & place limit the amount and/or level of skilled manual labour necessary compared to a manual layup process making it more independent of the human factor as well. This independency of skilled manual labour, which is expected to become scarcer in future also, is an advantage compared to current more manual manufacturing processes.

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