AN AUTOMATED AND DIGITAL APPROACH TO MANUFACTURE COMPLEX, ONE-OFF COMPOSITE STRUCTURES

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ABSTRACT

CCAT-prime is a 6 m diameter telescope with a surface accuracy of 10 microns, operating at submillimetre to millimetre wavelengths and sited at 5600 m elevation on Cerro Chajnantor in the Atacama desert of northern Chile. The two main mirrors of the telescope are supported by large CFPR structures, designed to have near to zero thermal expansion and minimal deformation due to gravitational effects. These backup structures consist of a 6 x 7 m CFRP sandwich panel supported by a 1.5 m tall CFRP truss structure. Each of the two CFRP structures weights approximately 1500 kg and consists of 19,000 m^2 or 126 km of UD prepreg tape. The overall design and build responsibility lays with Vertex Antennentechnik GmbH of Duisburg, Germany, while Airborne Aerospace of Den Haag, the Netherlands, is responsible for the design and manufacturing of the mirror support structures

As the manufacturer of the CFRP support structures, Airborne decided that an automated manufacturing solution was needed to achieve the target manufacturing cost. However, because a large part of the structure is made up of a truss structure, it was found that laying up each strut in the trusswork individually by conventional Automated Tape Laying (ATL) would be inefficient. Therefore, Airborne combined this with a robotic Pick & Place process. The robot mounted ATL end effector is used to create a large base laminate . The laminate is then cut into smaller blanks using a robot mounted ultrasonic knife. Finally, the individual blanks are picked up and placed in the required position to make the truss structure using a robot mounted P&P end effector with vacuum grippers.

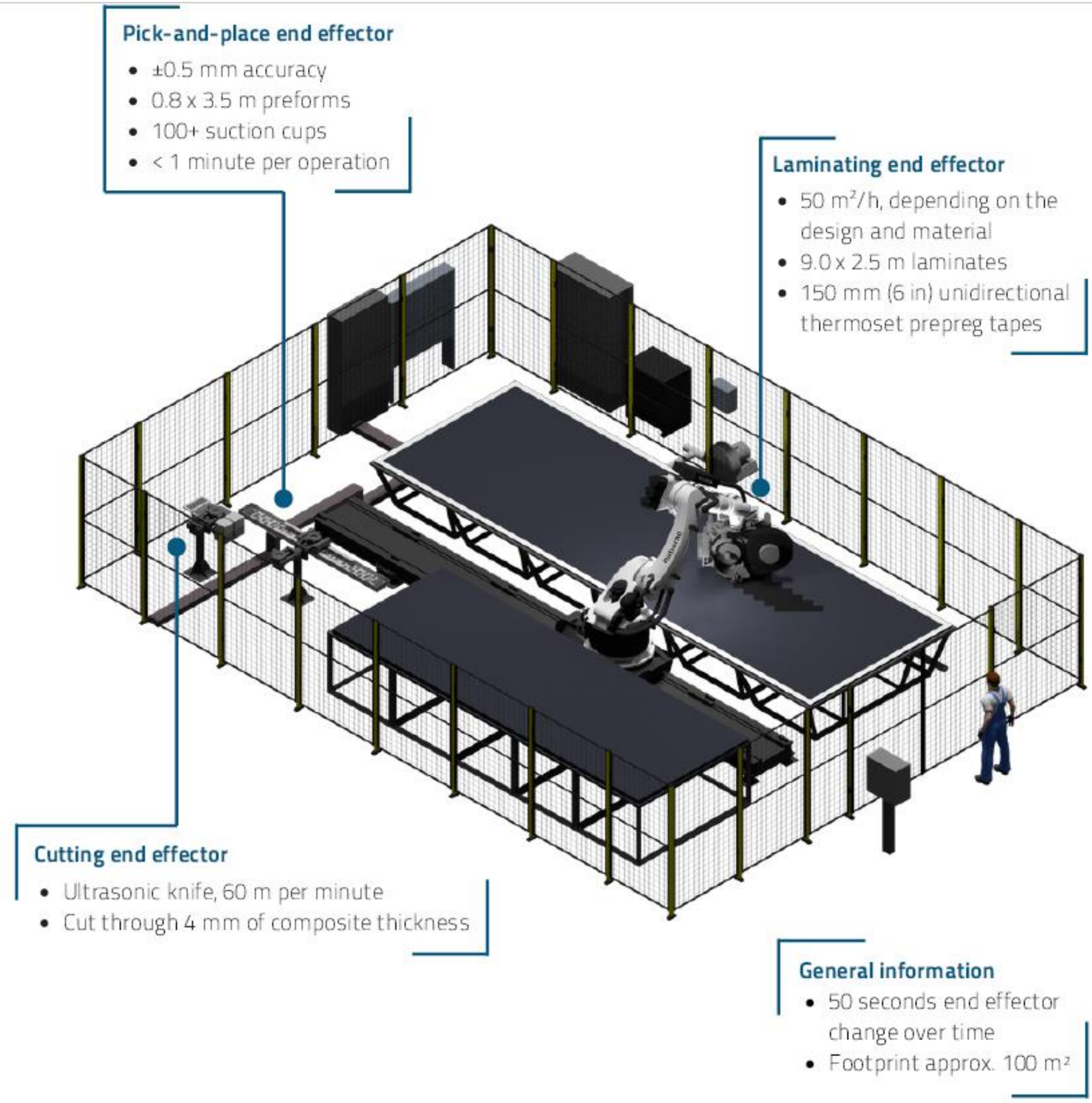
1. INTRODUCTION

1.1 Airborne Automated Laminating Cell (ALC)

Airborne has a long history of 25 years in composites, both in design and manufacturing as well as in developing and implementing automated production solutions. The composite know-how is embedded in system through its design and software, to enable easy and flexible manufacturing. Besides automated laminating, it also has solutions for automated honeycomb potting (sandwich), automated kitting, automated preforming using pick & weld, and systems for thermoplastic composite manufacturing.

The market for Automated Tape Laying (ATL) machines has traditionally been dominated by large gantry based systems used to manufacture large aircraft components. These systems requires a big capital investments, not only for machine hardware, but also for facility and infrastructure. The result is that these systems are only affordable for long running aircraft programs, and much less suited for smaller to medium sized products, as well as small series or one-off products. Because of this Airborne decide to developed a system based on affordable standard hardware, also allowing for quick reconfiguration when products change. Although based on standard components the system can easily be configured to suit a specific product, keeping the engineering costs down. This approach also makes it easy to increase production capacity by adding modules, without re-engineering the system.

At the centre of the ALC is one or more large industrial robot(s) placed on a linear track. Typically a single robot is used but the concept allows for multiple robots working in parallel, either on the same task or different tasks. The concept is based on a universal robot capable of performing different task by switching from one end-effector to the next. This also allows for one robot to have more than one of the same end-effector, providing redundancy as well as maximizing uptime by being able perform material replacement and maintenance offline.



Pick-and-place end effector

- ±0.5 mm accuracy
- 0.8 x 3.5 m preforms
- 100+ suction cups
- < 1 minute per operation

Laminating end effector

- 50 m²/h, depending on the design and material
- 9.0 x 2.5 m laminates
- 150 mm (6 in) unidirectional thermoset prepreg tapes

Cutting end effector

- Ultrasonic knife, 60 m per minute
- Cut through 4 mm of composite thickness

General information

- 50 seconds end effector change over time
- Footprint approx. 100 m²

Figure 1: Airborne Automated Laminating Cell

Although the concept is capable of a slightly single or double curved surface it is primarily focused on efficient manufacturing of 2D layups by automated tape laying. Typically a 150mm UD tape is placed on flat tool covered with a release film.

The next step in the process is typically to trim or cut the laminate to the desired net shape. This could be a single large contour, like the skin of rudder or flap, or it could be several smaller shapes like blanks for ribs or profiles. There are several ways to cut an uncured laminate but the most common practice is to use either an ultrasonic cutting knife or a rolling disc cutter. The choice usually depends on the type of material and geometry to be cut.

After cutting, the laminate(s) need to be offloaded from the layup table. For smaller laminates this could be done manually. However, for larger parts this will require several people to handle, which is inefficient when the rest of the production steps are designed to be operated by one person. Therefore it more efficient to use the same robot to also offload the cut laminate from the table. Depending on the part and the downstream process flow the laminate blanks can either be placed on a transport cart or directly on the cure tool. It is also possible to expand the ALC with an automatic hot-drape forming cell, to create ribs and profiles from the laminates. Another option is to use the same robot to also build up the final product, using smaller sub-laminates which are created by cutting shapes from a large ATL laminate. This allows for the automated manufacturing of large complex geometries, while retaining a high material efficiency.

1.2 CCAT-p

CCAT-prime (CCAT-p) will be a 6-meter diameter, 10-micron surface precision telescope operating at submillimetre to millimetre wavelengths and sited at 5600 meters elevation on Cerro Chajnantor in the Atacama Desert of northern Chile. The novel optical design will deliver a high throughput wide-field-of-view telescope so that large areas of the sky can be scanned rapidly. The high, dry site of the Atacama desert offers exceptional observing conditions. Deployment of CCAT-p on Cerro Chajnantor will provide operational experience at high very altitude, reducing risk for the future construction of a 25-meter class telescope at the high site.

The “crossed-Dragone” design establishes the CCAT-p telescope as a next-generation Cosmic Microwave Background (CMB) platform, capable of mapping the sky some 10 times faster than current CMB facilities. While other CMB efforts focus on wavelengths longer than one millimetre, the availability of simultaneous submillimetre imaging offered by CCAT-p will allow precise separation of dust emission from the CMB signal. With its large flat focal plane, CCAT-p will be ready to exploit the anticipated future advances in detector array technologies.

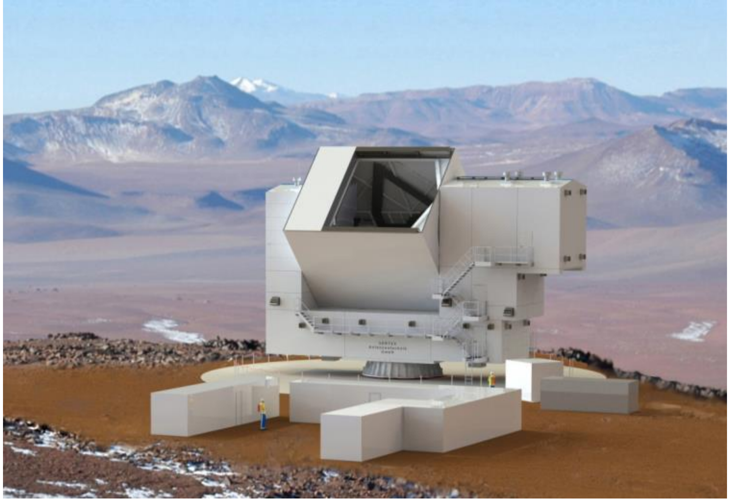


Figure 2:render of CCAT-p (courtesy of Vertex Antennentechnik GmbH)

The overall design and build responsibility lays with Vertex Antennentechnik GmbH of Duisburg, Germany, while Airborne Aerospace of Den Haag, the Netherlands, is responsible for the design and manufacturing of the mirror support structures. The collaboration between Vertex and Airborne goes back to 2006, when Airborne was selected to manufacture the South Pole Telescope (SPT) and later the 25 ALMA telescopes.

2. TELESCOPE DESIGN

2.1 Design and load cases

The telescope is based on a “crossed-Dragone” design with two mirrors in a near perpendicular configuration. The two mirrors consist of a number of very accurate aluminium tiles, supported by a carbon composite support structure that provides an extremely stable base for the mirrors. The two mirrors both have an area of approx. 6 x7m . The CCAT telescope is designed to operate at high altitude, in a cold and dry climate, under the following conditions:

- Temperature: -21°C to 9°C
- Elevation angle: 30° – 150° (from near horizontal to near vertical position)

Within these conditions the mirrors has to retain a surface accuracy of <10µm in order to guaranty the performance of the telescope.

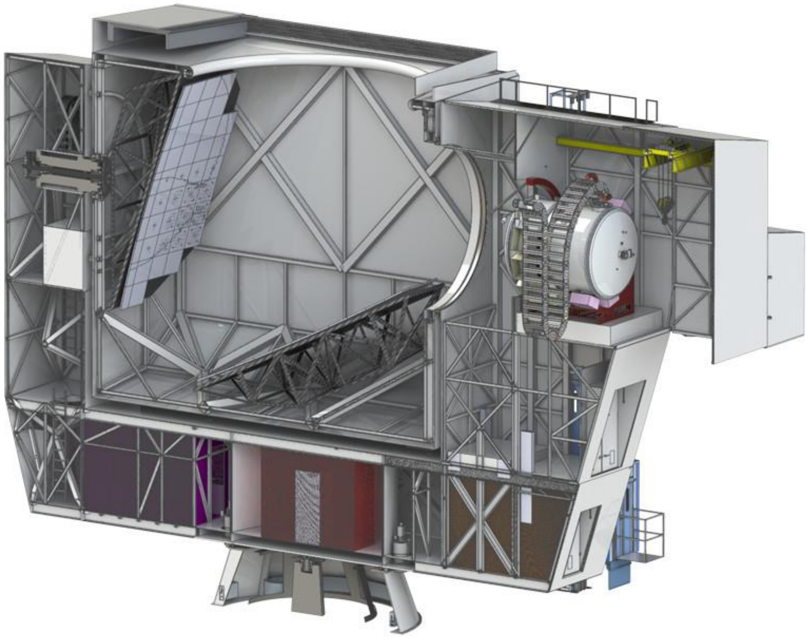


Figure 3: CCAT-p cross section (courtesy of Vertex Antennentechnik GmbH)

In order to meet these requirement it was necessary to design a mirror support structure with near to zero thermal expansions, while also having neglectable deformation due to gravity when rotating from horizontal to a vertical position. When translating these operational requirements into structural requirements the following target values was set:

- Mass target for mirror support structures: M1 ≈ 1600kg, M2 ≈ 1400kg
- Thermal expansion (CTE): 0.0 ppm/°C ±0.2 ppm/°C (in all directions)

Meeting all three of these requirements posed a major design challenge. In order to meet the CTE requirement, also with regards to uniformity, it was necessary to not only consider the in-plane properties but the full 3D behaviour of the structure. Small, local CTE variations could result in global deformation of the structure. In the end it was decided to use a hybrid structure, consisting of CFRP/Honeycomb sandwich top plate, with a monolithic laminate truss structure for support and attachment to the rest of the antenna construction.

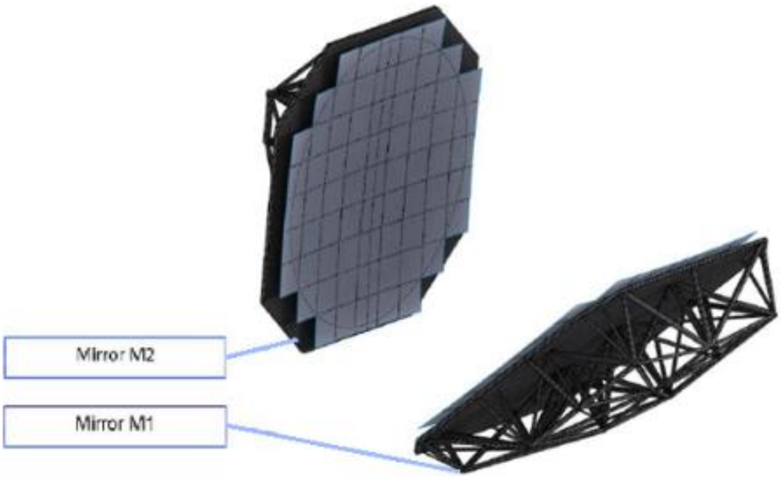


Figure 4: mirror support structure (courtesy of Vertex Antennentechnik GmbH)

In order to simplify the transport of the 7x6x1.5m composite structure it was decided to split the structures, making it possible to move them by trucks. However, this posed another challenge for the design, having to create a structure that can be assembled on-site while meeting both stiffness, CTE and accuracy requirements.

2.2 Materials

One of the major challenges was to select material and design the laminates for the antenna structures. Carbon fibres are known for their high specific strength and stiffness, as well as their low coefficient of thermal expansion (CTE). However, normal high strength carbon fibres does not have the properties in order to meet the requirements for the design of the mirror structures. In order to meet the requirement it became clear that higher performance fibres were needed. One option would be to use PAN based high modulus fibres, which has a much higher stiffness as well as a lower CTE. However, these HM fibres are also significantly more expensive, making it very difficult to meet the cost targets. A third alternative would be to use pitch base carbon fibres, which are known of their very high stiffness as well as a low CTE, while at the same time being more affordable than PAN based HM fibres. One drawback with pitch based fibres are their low elongation to break, making them quite difficult to process, without damaging the fibres.

After an extensive material testing program, including both mechanical and thermal testing as well as process testing, Airborne decide on using on using prepregs based on Pitch fibres.

After the initial material selection the program continued in order to detail and verify the specific material properties. Because of the strict mechanical and thermal properties requirements extensive work went into detailing material properties such as fibre areal weight and resin content.

In order to verify the material properties more than 700 mechanical samples were manufactured and tested. Furthermore, a number of samples were manufactured and tested in order to verify the CTE properties of base laminates as well as sandwich structures.

Another important aspect of the material testing program was the processing of the prepregs, especially in combination with Automated Tape laying. Typically pitch fibres has an E-modulus of >650GPa but only 0.3% - 0.4% strain to failure. This makes the fibres very prone to breaking if not handled carefully. A number of test was performed to verify that fibres and prepreg could be process by ATL, without breaking during placement. These tests showed that pitch fibre prepreg could be successfully placed using the ATL process, while retaining the same mechanical properties as those achieved with hand layup. However, testing showed although it was possible to place this material without damage to the fibres, the processing of this material was different to that of HS PAN fibres. Due to the more than 3 times higher stiffness of the pitch fibres compared to PAN fibres, the pitch prepregs were prone to pre-releasing from the backing paper, thereby causing problems during tape laying. In the end this problem was solved by changing the backing paper used for the prepreg, selecting a paper with a slightly more “grippy” coating.

2.3 Top Plate

The top plate is a CFRP/honeycomb sandwich, with a skin thickness >15 plies and a thick core. The 6x7m top plate is produced in 4 segments, allowing for autoclave cure of the sandwich panels and also simplifies transportation of the backup structure. In the top plate there are approx. 600 CFRP bushing mounted, which holds the adjusters for the mirror surface.

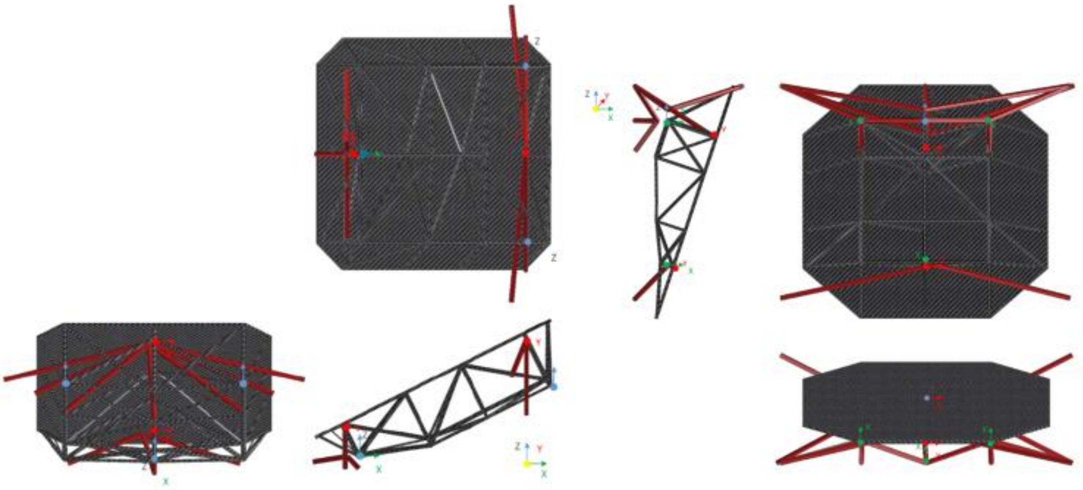
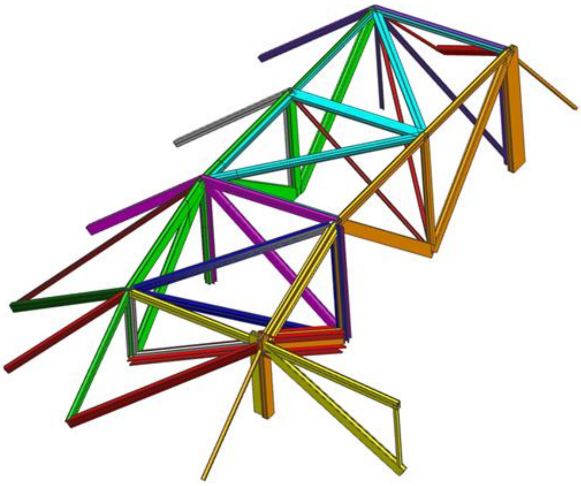


Figure 5: top plate and truss structure (courtesy of Vertex Antennentechnik GmbH)

2.4 Truss structure

The top plate is supported by a CFRP truss structure, also providing the connection with the rest of the telescope structure. The truss structure has to support the top plate while rotating from 30° to 150°, keeping the total mirror deformation <10µm. The truss structure also has to have a CTE similar to the top plate, in order to not influence the shape of the mirror during ambient temperature variations.



For the design of the truss a hollow box structure was selected consisting of full CFRP skins in combination with standard CFRP profiles. During the truss design all cross-sectional areas of the individual beams needed to be optimized to meet the performance requirements resulting in an unique design for all beams. This is needed to account for the complex, asymmetric loads on the mirror backup structure.

Figure 6: truss structure

3. MANUFACTURING

3.1 Manufacturing concept

With lessons learned from previous telescope projects, such as the South Pole Telescope and ALMA, it was a clear desire for the project to try and automate the composite manufacturing as much as possible. While the primary goal of the design was to meet the very stringent performance requirements, a secondary goal was to design a structure that could be manufactured taking advantage of automated manufacturing technologies. This resulted in a design based on flat or single curved elements, which can very efficiently be manufactured using ATL. Furthermore, using a large, flat base laminate as a starting point, it is possible to cut blanks that can be formed into profiles. These blanks can also be used as building blocks for a larger, more complex structure, also using the robot to place these elements in the correct position.

3.2 Work preparations

While designing the composite telescope structure it became clear that this would require a large number of unique laminates, as well an even larger number of cut blanks. It is estimated that the CCAT telescope will require about 120 ATL produced laminates, with several thousand cut blanks, using approx. 20.000m^2 of prepregs. Creating the layup programs for the ATL product is a relatively simple process. However, creating the robot programs to also cut and pick and place several thousand blanks was estimated to take around 2000 hours of programming. With this in mind it became clear that a new approach to work preparation and robot programming was needed. Because the ALC is not only used for ATL, but also cutting and pick place operations, it was logical to integrate all these functions under one software platform.

The ALC Manager is a software platform created by Airborne, which allows for end-to-end integration of the manufacturing process. The ALC Manager allows for direct import of CAD data, either in DXF for the shape geometry, or as a FiberSim XML file, containing information about geometry, material and layup information. The information imported can be of single product, or multiple products to be made from a single laminate. It is also possible to import information about a target geometry, to allow for building a product using robotic pick and place. The software also interact with the ALC during manufacturing, providing real time status of the production, as well as receiving data from sensors and inline inspection systems. This data input can be used to automatically create a quality inspection report at the end of a production run. The systems also has a barcode scanner, used to scan the information on the prepreg rolls, thereby ensuring full traceability of the materials used.

A typical work flow looks like this:

- Import product geometries and layup information
- In case of multiple product; nest the different shapes to ensure minimal material usage
- Create an ATL laminate around the nested products, and generate the ATL code for production
- Generate code for the cutting of the individual parts
- Generate pick and place code, to place and build up a product on a second table.
    - The sequence of blank placement is taken into consideration when generating P&P code, also when multiple ATL laminates are needed to produce large complex structure.

3.3 Automated Tape Laying (ATL)

The main process within the ALC is the automated tape laying. With this process the approx. 120 different laminates are produced, in sizes up to 6900x1900mm with a thickness of >15 layers. In the case of the top skin the product is laid up directly, while for the truss and c-profiles the ATL creates a base laminates from which shapes are cut.

The ATL works with a 150mm wide UD prepreg, either based on carbon pitch or PAN fibres. The tapes are placed with a nominal gap of 1mm, with a typical accuracy < +/- 1.0mm. The maximum production rate is in the range of ~ 50m^2/hour, however for the fragile pitch fibre prepregs the machine is running at a lower speed in order to prevent damage to the fibres.

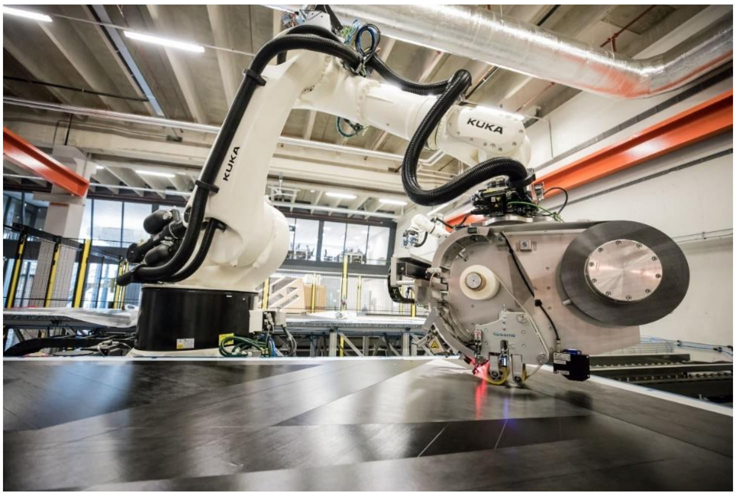


Figure 7: Airborne Automated Tape Laying

3.4 Laminate Cutting

In order to create blanks it is necessary to be able to cut them from a larger laminate. The ALC has two different methods of cutting the uncured laminates; it can either use a rolling disc cutter, or an ultrasonic knife, the choice in method depends on the product and the tooling used.

Typically the ultrasonic knife is faster, able to cut thicker laminates and more complex geometries.

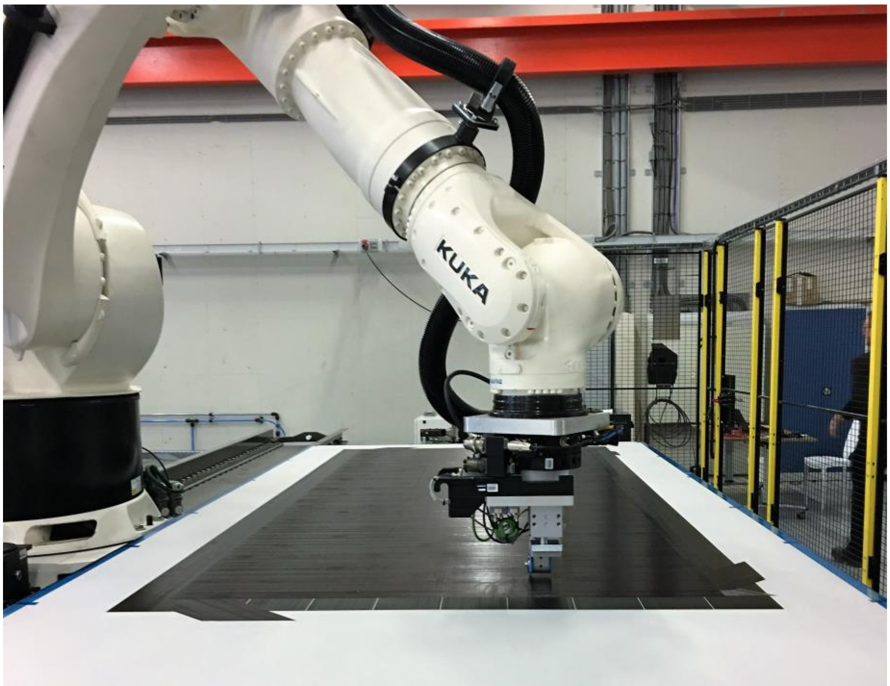


Figure 8: laminate cutting using disc cutter

3.5 Pick and Place

Using a quick tool changing system, the robot can automatically switch end effector within 1-2 minutes. In order to build up a product on the second table, the robot will switch to a pick & place end effector. The P&P end effector used for the CCAT project is 3000x400mm and has an array of individually controlled vacuum grippers. In order to pick a single product from a larger laminate it is important to only activate the suction cups that falls within the product. The selection of suction cups is done by the ALC Manager, which has an algorithm that determines the optimal picking strategy.

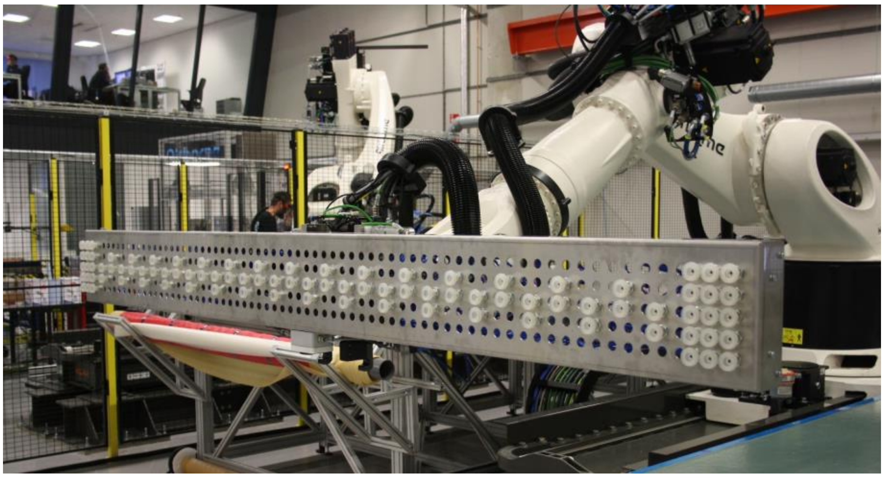


Figure 9: pick & place end effector

For the CCAT project the P&P process is used in two different ways. For the c-profile production the P&P is used to offload the layup table after cutting of the blanks. Because the c-profile blanks are nested in random way in the main laminate, it is difficult for the operator to find and recognize the different parts. Using the robot for offloading allows for simultaneous sorting of the different parts, making it much easier for the operators to correctly identify and label the blanks.

The main application for P&P within the CCAT project is to build the truss skins. The truss skins is built up of tens or up to hundreds of individual blanks, cut from one or more master laminate. This process makes it possible to build large, complex products in a nearly fully automated fashion. The enabling technology behind this process it the ALC manager which greatly simplifies the production planning and robot programming, reducing the work preparation effort from hours and days, down to minutes.

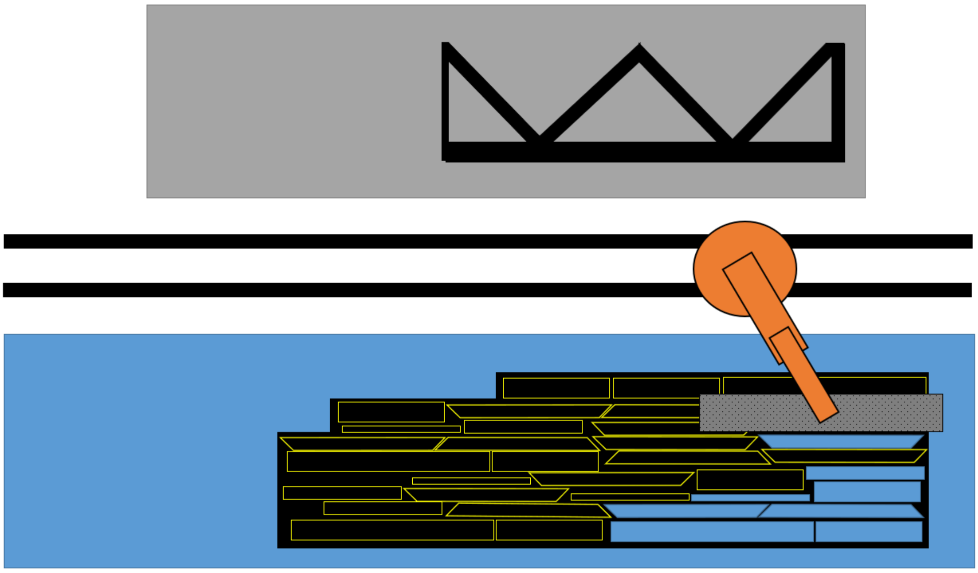


Figure 10: pick & place of truss structure

3.6 Manufacturing of c-profiles

Using c-profiles to create a hollow box for the truss structure allows the manufacturing of these parts standardized and partly automated. All c-profiles have the same layup and cross section, but are made to length, by cutting the prepreg blanks to near net shape. After the cutting, the blanks are hot-draped formed, using infrared heating and a reusable vacuum membrane. After forming the c-profile are vacuum bagged and cured in an oven cure (no over pressure). Using this process it is possible to efficiently manufacture more than 400 individual profiles, with a total length of 1200m, while achieving a dimensional tolerance +/-0.2mm of the cross section.

3.7 Quality Control

The ALC monitors and logs a large number of process parameters during production. Some of this information, such as preheating and compaction pressure, is monitored to ensure that the process stays within specifications. Other parameters like robot movement, speed and accelerations can be logged and later used to improve the performance of the system.

The ATL head also has an inline inspection system, using a laser line scanner to continuously measure the gaps between placed tapes. Typically a gap requirement of 0 to 2.5mm gap is used for the ATL process. When these values are exceeded, the inline inspection system triggers a warning, allowing for the operator to inspect the laminate and decide in any further action is needed. This information is also stored and is outputted in the equality report and the production run has finished. The gap information can also be stored in a database together with the data of the robot parameters. This information can later be used to investigate the correlation between robot movements and laydown accuracy, thereby improving the system.

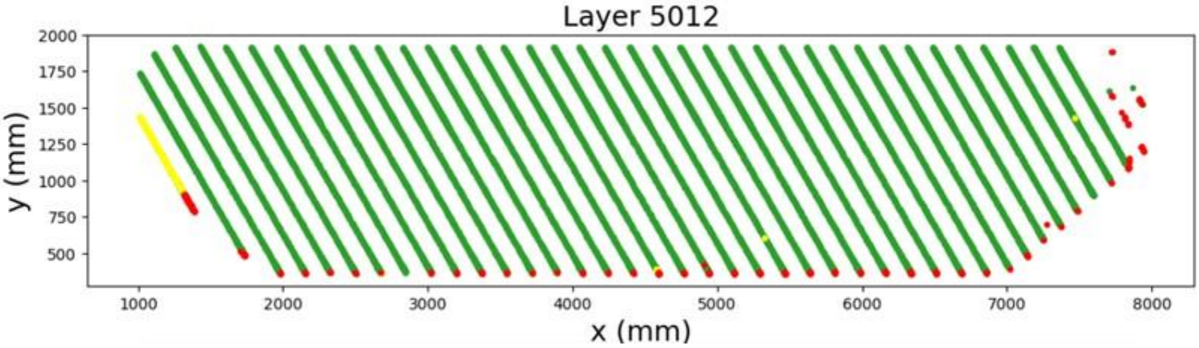


Figure 11: gap measurements green = in desired bandwidth, yellow/blue are still within spec but outside desired bandwidth, purple/red are outside spec (purple = too large gap, red = overlap)

The systems also allows manual input from operators, such as other defects, repairs and material change. All this information is collected and presented in a quality report after the completion of production.

4. CONCLUSIONS

The CCAT project has demonstrated the benefits of using automation in composite manufacturing, in particular taking advantage of the Airborne ALC. However, an equally important improvement has been achieved by taking a digital approach to the design and manufacturing process. The ALC Manager is estimated to have saved thousands of hours in work preparations and robot programming. By going directly from CAD design to robot code, not only cuts down the lead time, but it allows for a high degree of flexibility when it comes to production planning. The software allows for on-the-fly programming, which can be performed by the robot operators. By using the software platform in combination with inline quality inspection has also greatly reduced the need for manual quality inspection. This has made it possible to go from a 100% manual quality inspection, to only inspect based on warnings from the software.

The ALC is a highly flexible automated production platform which has many potential applications beyond the manufacturing of complex telescope structures. This system can also be integrated with downstream processes, such as press forming or other consolidation process, making a fully automated process, from prepreg to cured product feasible.

5. REFERENCES

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3. Stephen C. Parshley, Jörg Kronshage, James Blair, et. al.,*CCAT-prime: a novel telescope for submillimeter astronomy*, SPIE Astronomical Telescope + Instrumentation, 2018, Austin, Texas, USA; Proceedings Volume 10700, Ground-based and Airborne Telescopes VII; 107005X (2018)