INLINE INSPECTION TECHNOLOGIES FOR PROCESSING OF DRY FIBRE MATERIALS

Christian Eitzinger, Sebastian Zambal
Profactor GmbH
Im Stadtgut A2
4407 Steyr-Gleink, Austria

ABSTRACT

Quality control for dry material placement still requires manual inspection and thus leads to a substantial reduction in overall productivity. In this paper we describe recent developments in the field of automatic inspection systems, with a particular focus on methods that can be integrated into the production process. For dry material placement the measurement of fiber orientations and the inline detection of various types of defects turned out to be most important. Two different sensor technologies based on machine vision have been developed for this purpose and their properties have been analyzed. Additionally, emphasis was also put on the data management, especially how to acquire and process the large amounts of data, this also includes methods for making the data available for follow-up processing steps, such as part verification systems. Experimental results on a full-scale dry material placement machine will be presented.

1. INTRODUCTION

Automated placement of dry carbon and glass fiber material has made huge gains in efficiency and level of automation. Typical processes include dry fiber placement (DFP) [1], where multiple tows are placed in parallel and automatic dry material placement (ADMP®) [2] where large patches of material are placed. For all these processes manual inspection is still required, which is currently reducing the productivity of machines.

1.1 The ADMP® process

Automated dry material placement is a process, where wide patches of dry, multi-axial material are placed in a mold. The width of the material may range from about 10cm (4') up to 1.7m (70'), depending on the curvature and size of the part that is being produced. The material is placed by a lay-up head that is moving continuously along the part, while following the 3D shape of the mold. The main advantage of the process is that it can place large quantities of material with high precision and in comparably short time. It thus reaches a very high productivity. This level of productivity, however, is being reduced by the need to perform manual inspection after each layer. Various kinds of possible defects (see section 2.1) and contaminations may occur that need to be checked and re-worked if needed. Inspection needs to be done "in situ", while the machine is stopped. During this time the machine is not productive and considering the high efficiency, the need for such manual inspection has particularly negative impact on the overall productivity. To provide a solution, inline inspection methods have been developed that will be described in the next section.

1.2 Inspection technologies

Vision based methods are most suitable for inline inspection, because they are contactless and comparably fast. The approach is to analyze the pattern (texture) of the surface to detect any deviation from the normal appearance of the material. The main problem of vision-based methods, however, is the shiny and black (for carbon) surface structure of carbon and glass fibre materials. This makes the direct application of vision-based sensors challenging. The traditional way for machine vision applications for inspection of carbon fibres is to suppress the direction dependent reflections using diffuse light sources [3, 4]. For carbon fibres this is particularly challenging, because the black fibres need a lot of light to distinguish between different directions. The second step is to analyze the fibre directions using texture analysis. This has been tried in [5] and leads to reasonable results on specific materials, if the lighting is controlled and the field of view is small. For scanning of large areas with varying materials, the method is difficult to implement. Similarly, an alternative approach [6] uses a combined system of 3D profile scanners and a 2D camera system. Again texture analysis is used as the main tool to extract fibre orientations. As for the previous methods, the field of view is small and the analysis is highly dependent on the material that is used.

More recent developments use the particular reflection properties of carbon and glass fibre to determine fibre orientations and thus the texture of the material [7]. This approach is based on the idea of photometric stereo [8], where multiple images taken under illumination from different directions are combined. Classical photometric stereo uses a reflection model of the surface to perform 3D re-construction. In our case the very specific reflection properties of carbon and glass fibre material can be used to determine the fibre orientation in 3D.

A complementary inspection technology is based on 3D laser profile scanning. A laser with a specific lens is used to project a line on the surface, while a camera acquires the shape of this line. Through a proper calibration the 3D shape can be re-constructed by merging the single lines that are acquired while the machine is moving [9]. The data acquired by the sensor system represent depth information in the form of a 3D point cloud, but they do not allow the analysis of the surface pattern (such as fibre orientations). This method has been established as a standard for DFP processes, where most of the relevant defects can be detected based on 3D information.

2. INLINE INSPECTION METHODS

In the following section we first describe the possible defects in ADMP® processes. We do not so much focus on the particular tolerances and quality control rules that apply, but on their characteristic properties that are relevant for automatic detection. Based on this analysis we present two different detection methods that provide complementary information. The key aspect to be addressed is the large width of the material that needs to be inspected with comparably high resolution and at production speeds.

2.1 Defects classification

There is a set of typical defects that is widely known from DFP processes. Typical defects are gaps between tows, overlaps of tows, twisted tows, early/late cut of tows and foreign objects such as fuzzballs. For the ADMP® process some of these defects do not occur or are of lesser relevance, while there may be other types of deviations that need to be detected. Typical examples are shown in figure 1. In the following we provide a tabular overview of typical defects and their characterization.

Defect Type	Description	Detection
Angle deviations	Fibre orientation may change due to the draping of the material in the mold, depending on the curvature of the part.	Orientation
Late/early cut	The edges of the fabric need to be determined and their correct positioning relative to the mold.	3D Orientation
Overlap splices	Splices are allowed to a certain extent, but should not accumulate in a particular area.	3D
Gaps	Gaps may occur between different tows, e.g. when non-crimp fabric is used.	3D Orientation
Foreign objects	Any kind of contamination on top of the material has to be avoided. So called "fuzzballs" are the most relevant objects.	Orientation 3D
Missing stitches	The stitching yarn may be missing or broken and should be detected.	Orientation

Table 1. Defect types relevant for ADMP® and their characterization.

Table 1 shows the list of the most important types of defects and their characterization. The column "Detection" indicates through which image modality (3D shape or fibre orientation) the defects can be detected best. For "late/early cut" and "gaps" both detection methods could potentially be suitable, but there are certain restrictions when using texture. In both cases the edge of the material (the whole patch or a single tow) needs to be determined. This will be visible as a step in the 3D data and can thus be detected through profile scanners. Fibre orientation may also provide an indication about the edge of the material, provided that fibres in the layer below the material are not oriented in exactly the same direction as the top layer.

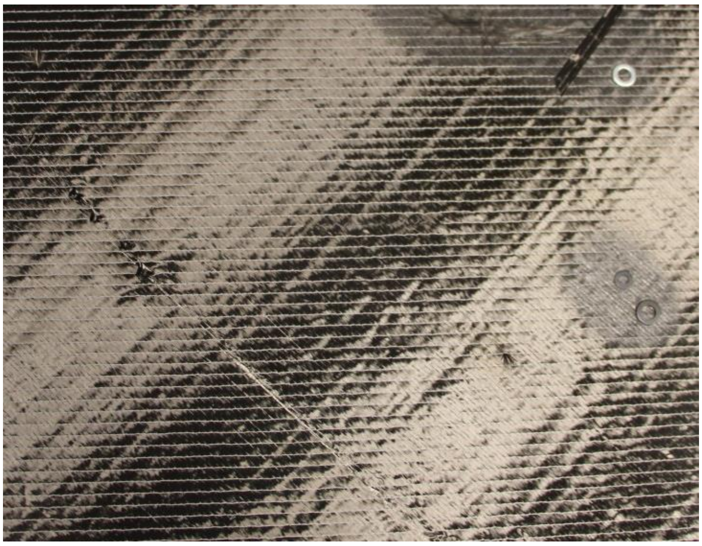

Figure 1. Various kinds of defects, such as gaps between tows, foreign objects, missing stitches, fiber distortions.

For foreign objects the situation is difficult to assess, because they have a very wide range of characteristics. Defects such as fuzzballs can easily be detected in both image modalities, while flat material (especially foils or paper) will only be detectable by measuring fiber orientation, because fiber orientations either cannot be determined for a foreign object or will deviate substantially from the expected direction. As is obvious from table 1, no single measurement system will provide a robust detection of all relevant defect types and thus a combination of methods is required.

2.2 Fibre Orientation Measurement

The concept for fast and accurate measurement of fibre orientations has been developed in [7]. The method is image-based and provides a fibre orientation measurement per image pixel at a rate of up to 1000 frames per second. The resolution of the image is typically 60µm per pixel, with a field of view of 50x50mm². The technology requires that a ring of LED light sources is arranged around the optical center of the sensor. The geometrical configuration of the LEDs relative to the fibre material and the camera is determined by the reflection model of the carbon fibers. This requires that the outer diameter of the sensor is about three times larger than its field of view. While this no problem for manual operation or robotic scanning systems, it poses a challenge for the wide material that is placed with the ADMP® process. A staggered arrangement of 10 sensors that covers – say – 500mm of width, would require three or more likely 4 rows of sensors, which would lead to a very large and impractical sensor system.

To resolve this problem a modular approach was developed, where the rings of LEDs overlap and the sensors are arranged in a single row in such a way that their fields of view fit seamlessly together. All the modules are identical and could, theoretically, be extended to arbitrary lengths by adding new modules, as shown in figure 2. The switching of the single LED light sources was arranged in such a way that they do not interfere with neighboring cameras. The sensor thus behaves like a single camera that can scan an arbitrary width of material. This makes the sensor also suitable to scan incoming material or to check carbon fibre fabric during production.

Figure 2. Each sensor module uses a ring of LEDs. The single rings overlap to allow an arrangement of the sensors in a single row. Switching of the LED modules is arranged so that sensors do not interfere with each other.

2.3 Depth Measurement

The acquisition of 3D depth data from the surface allows a more straightforward approach. The technology is based on laser profile scanning, where a laser projects a line onto the surface and a camera acquires images of this line for analysis. There are commercial cameras available that automatically perform the extraction of the profiles at high speeds and the required depth resolution (typically 0.1mm for this type of application) determines the corresponding field of view. In contrast to the above mentioned fiber orientation sensors, the field of view is much larger than the sensor and thus an arrangement in a single row is easily possible. The preferred angle of incidence of the laser line relative to the optical axis of the camera is usually 60°. In order to create a more compact setup one or two mirrors are used that guide the light into the right direction. In order to deal with specular reflection of carbon fibre it proved to be useful to include diffusive optical elements in the path of the laser beam. This leads to a significant improvement of the signal to noise ratio and makes the data acquisition much more robust.

3. INTEGRATION INTO THE PROCESS

This section describes the integration of the sensors into the lay-up head for the ADMP® process as shown in figure 3. It covers the main hardware aspects and explains the processing steps and the use of the data for part verification. Finally, initial experimental results are provided based on first scans done during the manufacturing process.

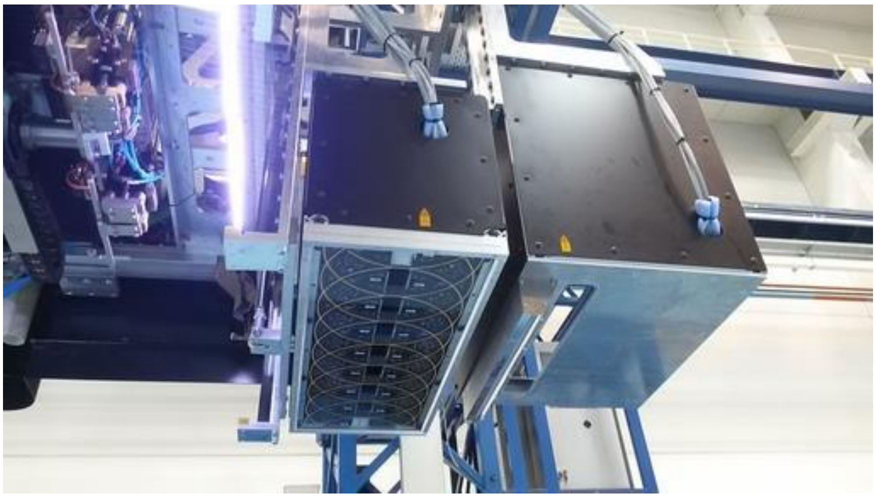

Figure 3. Integration of the sensors into the placement head. The fibre orientation sensor is in the center of the image with the characteristic LED light rings and the laser profile scanner is mounted to the right.

3.1 Data Acquisition and Processing

For the experimental evaluation a setup with a scanning width of 370mm was chosen. This required the integration of five cameras for fiber orientation measurement, by using the modular approach as described in section 2.2., and three laser profile scanners as described in section 2.3. The fibre orientation sensors (“FScan”) provide raw image data at a rate of 1166 frames per second (at scanning speed of 0.25 m/s), which corresponds to a rate of 239 MB/s. These raw data are converted into fiber orientation measurements per image pixel and used for defect detection. The current version of the defect detection uses local fiber orientation histograms to determine those regions where fiber orientation deviates from the expected values. This approach turned out to work well on unidirectional and multi-axial material. For detecting the stitching yarns (defect: “missing stitches”) a particular image modality, called diffuse reflection, is used. This allows the segmentation of the yarns.

The laser profile scanner (“LScan”) uses on-board processing so that the raw images are analyzed directly on the camera board and only the extracted laser profiles are transferred to the PC for further analysis. The defects that are to be found in these depth images usually corresponds to discontinuities in the 3D point cloud, so that an edge detector provides a good indication of potential defects. In particular it allows the identification of gaps between tows and of the edges of a ply.

For both sensors a hand-eye calibration is done in addition to the intrinsic calibration so that the defect locations extracted from the image can be transferred to the 3D CAD model of the part. This is done by acquiring position data from the lay-up machine in addition to the sensor data.

Once the defects have been identified and their location and boundaries are known, the data are used for two purposes: on the one hand they provide information to the machine operator where possible re-work may be required on the current layer and on the other hand the data are used for part verification. This process is based upon a so called Manufacturing Database [10] that collects design data about the part as well as actual manufacturing data. The Manufacturing Database uses a generic file format based on HDF5 that can be easily extended and provides a hierarchical structure. As far as the part verification is concerned the database stores the defects found in each layer and grows during the manufacturing process to generate a digital twin of the manufactured part. This enables the calculation of the effects that these defects will have on the mechanical strength of the part by using either analytical models or finite element methods. Finally, these results will enable a well justified decision about which defects will require re-work and which deviations can be left in the part.

3.2 Experimental Results

For the experiments the above mentioned, modular version of the fiber orientation sensor “FScan” was integrated into the machine together with the laser profile scanner “LScan”, each with a scanning width of 370mm. The material that was placed by the ADMP® machine was unidirectional non-crimp fabric with a width of 700mm. Consequently, two passes of the sensor were required to fully scan the placed material. The design of the test part was based on a section of an A350 wing lower cover, as shown in figure 4 below.

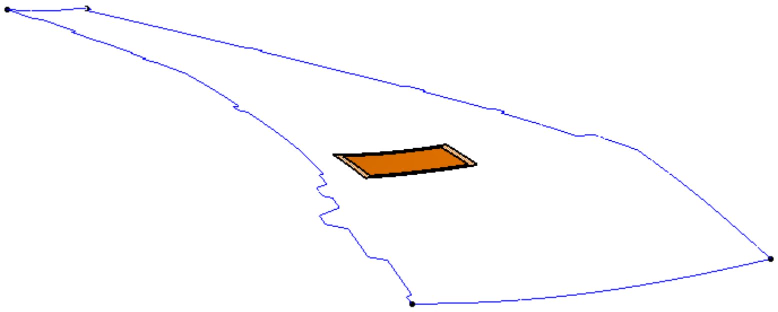

Figure 4. Section of the A350 wing lower cover that was selected for the experiments.

16 layers were placed to complete one part where 9 layers covered the complete area of the part and the remaining layers are so-called “pad-up” layers that make up a thicker region of the part. Lay-up and scanning of a single layer took between 4 and 10 minutes in the experimental setup, depending on the amount of material to be placed. Scanning of a full layer with the “FScan” takes roughly 1 minute, for the “LScan” 45 seconds. Raw data delivered by the sensor hardware is approximately 10 GB for the “FScan” and just 15 MB for the “LScan” per layer, this is due to the pre-processing of the laser profiles that takes place on the camera. Two industrial PCs were used to acquire the data and were able to process the incoming data in almost real-time, so that results were available with very small latency.

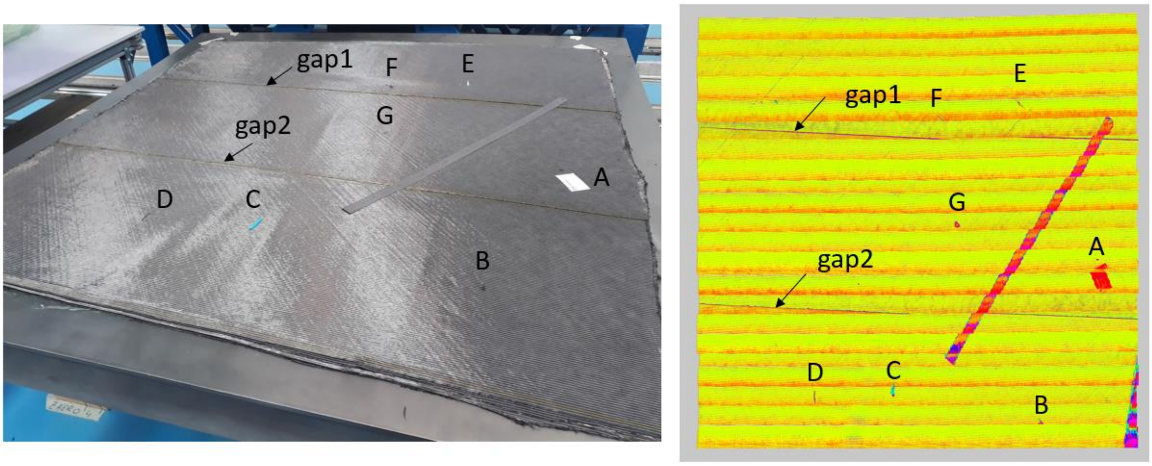

Figure 5. Defects and foreign objects on a sample part. Corresponding defect locations are marked with letters. The image on the right shows this part with color-coded fibre orientation.

The focus of these experiments was on the “signal to noise” ratio and to assess whether the data can be acquired with the proposed sensor design. Scanning results are shown in figures 5 and 6 below. Figure 5 shows a photograph of a sample surface (left). Foreign objects were added on top of the surface for testing. The figure shows color-coded fiber orientations on the right side. The acquired images are combined into a single view using position information as delivered by the lay-up machine. Foreign objects, fuzzballs, and gaps are clearly visible in terms of different fiber orientations (i.e. different color). Corresponding interesting regions are labelled with letters both in the photograph and in the scan.

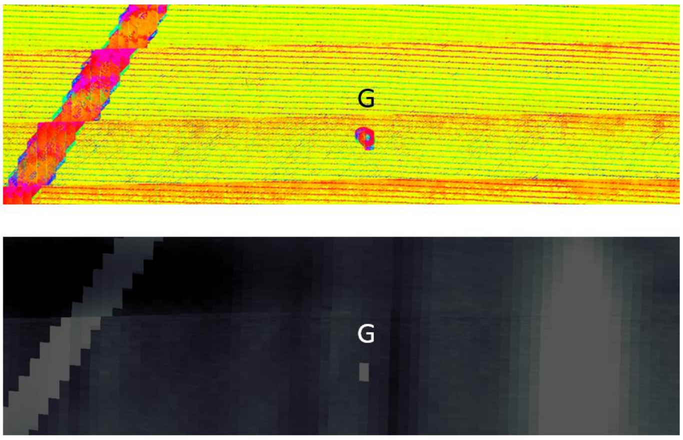

Figure 6: Foreign object on the sample part. The top image shows the fibre color-coded fibre orientation, while the bottom image shows the height map coming from the laser profile scanner.

Figure 6 shows a comparison of defect “G” for FScan (top) and LScan (bottom) sensors. FScan data again show color-coded fiber orientations. LScan data show local height deviations of the surface (dark indicates low regions, bright indicates high regions). The resolution of LScan data in scan direction is significantly lower than perpendicular to it. Defect “G” (a screw-nut) is clearly visible in both, FScan and LScan data. In combination with additional modalities of the FScan sensor (diffuse image, polar angle, etc.) a rich description of various defects and surface features is possible.

4. CONCLUSIONS

To fully use the potential of highly efficient dry material placement processes, such as ADMP®, automatic inline quality control methods are used. The range of defects that are to be detected requires depth information as well as an analysis of fiber orientations. An automatic inspection system needs to solve the problem of how to inspect the large width of the material in an efficient way. In this paper a fiber orientation sensor with a modular design approach was presented, that can be used to inspect material of large width and at high resolution. Through efficient processing the large quantities of data acquired during scanning can be processed in near real-time. Data about the defects can then be integrated into a digital model of the manufactured part, which allows an assessment of the impact that the defects will have on its mechanical strength. Experimental results showed that the sensor design leads to a good image quality, where all the relevant defects are clearly visible. For full-scale aircraft parts, the automatic inspection will lead to productivity gains of 10% to 15%.

5. ACKNOWLEDGEMENTS

Work presented in this paper has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 721362 (project "ZAero") and from the county of Upper Austria in the framework of the "DigiManu" project.

6. REFERENCES

1. Belhaj, M. Deléglise, M., Comas-Cardona, S., Demouveau, H., Binetruy, C., Duval, C. and Figueiredo, P. Dry fiber automated placement of carbon fibrous preforms. Composites Part B: Engineering. 50. 107–111. 10.1016/j.compositesb.2013.01.014. (2013).
2. https://www.compositesworld.com/products/danobat-launches-automation-solution-for-dry-material-manufacturing, 24th June, 2014; last accessed 05.05.2018
3. Schmitt R., Pfeifer T., Mersmann C., and Orth A. A method for the automated positioning and alignment of fibre-reinforced plastic structures based on machine vision. CIRP Annals Manufacturing Technology, 57(1):501 – 504, 2008.
4. Shi L. and Wu S.. Automatic fiber orientation detection for sewed carbon fibers. Tsinghua Science & Technology, 12(4):447 – 452, 2007
5. Miene A., Bildanalytische Qualitätssicherung in der Preform-Fertigung, 5. Sitzung der Arbeitsgruppe „Werkstoff- und Bauteilprüfung", Augsburg, 5th of March 2010
6. https://www.maschinenmarkt.vogel.de/sensor-spuert-fehler-in-cfk-leichtbauteilen-auf-a-354751/; 2012; last accessed 05.05.2018
7. Zambal S., Palfinger W., Eitzinger C., Robotic inspection of 3D CFRP surfaces, 3rd IEEE International Workshop on Metrology for AeroSpace, Florence (Italy), June 22-23, 2016
8. Woodham R.J., Photometric method for determining surface orientation from multiple images. Optical engineering, 19(1):139– 144, 1980
9. Cemenska, J., Rudberg, T., and Henscheid, M., Automated In-Process Inspection System for AFP Machines, SAE Int. J. Aerosp. 8(2):2015, doi:10.4271/2015-01-2608
10. Heinecke F. and Wille T.: From as-designed to as-built analysis using an multiscale approach and model update. EASN – 5th Int. Workshop on Aerostructures, 2 – 4 September 2015, Manchester, United-Kingdom