INLINE QUALITY CONTROL FOR THERMOPLASTIC AUTOMATED FIBER PLACEMENT BY 3D PROFILOMETRY

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ABSTRACT

Thermoplastic Automated Fiber Placement (T-AFP) is a promising technology for the manufacturing of complex aerospace parts. In contrast to tapelaying of duromere prepregs T-AFP has the potential of in-situ consolidating the laminate as well as the opportunity for a dust-free assembly based on thermoplastic welding. Subsequent rework is challenging in this single-stage process due to the direct consolidation onto the substrate. In result inline quality control gains even more importance. Starting from AIPS 0302019 at DLR’s Center of Lightweight Production Technology in Augsburg we investigated the feasibility of a fully automated inspection system based upon a high-performance light sheet sensor that is capable of detecting most crucial defect types such as gaps and overlaps inline, allowing an early correction by the user or by a control system. We found that especially overlaps between tracks in lower plies have the potential of introducing extreme undulations at higher plies. In order to assure a constant minimum gap between placed tracks in production, measuring overlaps as well as gaps has been our focus. Since steering effects and other influences are complex all received data is associated with machine data and stored in a data management system for further algorithmic and AI-based evaluation.

1. INTRODUCTION

1.1 Thermoplastic Automated Fiber Placement

Thermoplastic structural parts for aerospace applications allow welded joints and a dust free assembly of pre-equipped system units. Today only relatively small and often geometrically simple thermoplastic parts are in service, because consolidation is a crucial step. While press consolidation gives best results it is complex, involving heavy machinery and costly tools which limit the part size. Autoclave consolidation, which is second best concerning part quality, is costly and implies plenty of auxiliary material that has to comply with the consolidation temperature. Out of autoclave vacuum bag consolidation often suffers from insufficient consolidation pressures and auxiliary materials degeneration under oxygen atmosphere at higher process temperatures is an issue. Thermoplastic Automated Fiber Placement (T-AFP) is a relatively new process route for high performance aerospace part generation and offers the opportunity of in-situ consolidation, making the a.m. additional consolidation unnecessary. Figure 1 illustrates the process and shows our setup.

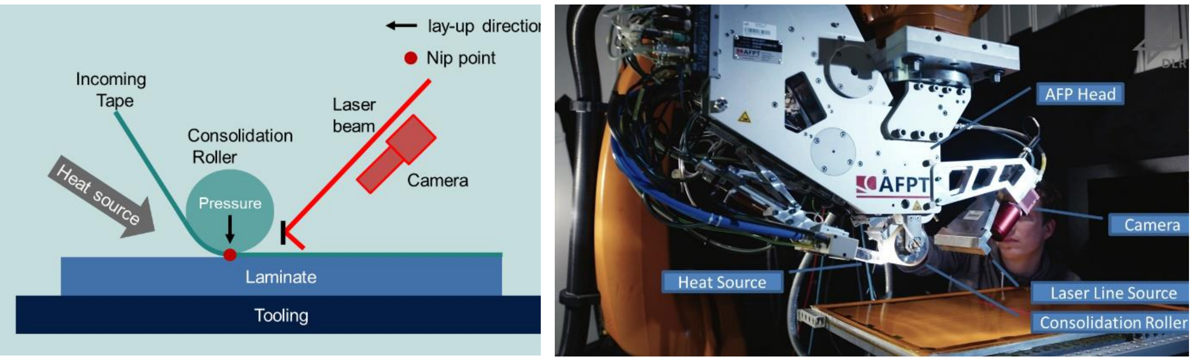

Figure 1: Setup of T-AFP cell with profilometer attached

The tape is heated to the process temperature in the range of up to 400 °C by optical radiation (flash lamp or laser) and subsequently compacted and cooled down by a consolidation roller [1]. Finally, a 3D profilometer is measuring the tape geometry. As long as the process works properly the instant consolidation is advantageous, but if errors occur there is no chance of easily correcting them afterwards. Especially under this condition automated real-time inline inspection may help to avoid critical defects and open the way for a closed loop process and shorter production times with reduced scrap rate.

2. EXPERIMENTATION

2.1 Defect types and measurement method

According to [2] defects in T-AFP may be divided into the categories imprecise positioning, improper bonding, foreign anomalies and tow anomalies. All defect types can be measured with light sheet profilometry (Figure 2) and amongst the evaluation methods are analytical approaches, image analysis by computer vision, machine learning and even deep learning [3,4,5,6], depending on the exact requirements and the availability of data. Analytical approaches offer maximum performance and optimum traceability but are limited in flexibility, computer vision needs medium data sets and allows a flexible detection of well-known defects at medium traceability but method development needs a skilled expert who is also a programmer, machine- or deep-learning requires huge annotated data sets and high processing power for learning and good processing power for evaluation (inference), offers maximum flexibility but next to no traceability. Since high quality data are essential for method development we focused on a computer-vision assisted analytical approach with data management integration in order to allow machine or deep learning on huge, well annotated datasets. The sensor was a AT C5 sensor which captures 2048 pixels wide profiles with 12 bits resolution. The real-world depth (z) resolution depends on incidence angle and optics and is in our case 1,76 microns, while the lateral (y) resolution is 39,4 microns. The resolution in layup direction is given by the max. scanning speed of the system and was set to 100 microns in our case.

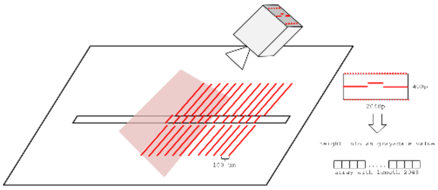

Figure 2: Laser light sheet triangulation

2.2 Data Acquisition and Management

On the use case of a LH_2-Tank structure we investigated how to acquire, annotate and store the data. Figure 3 shows our manufacturing orientated storage model.

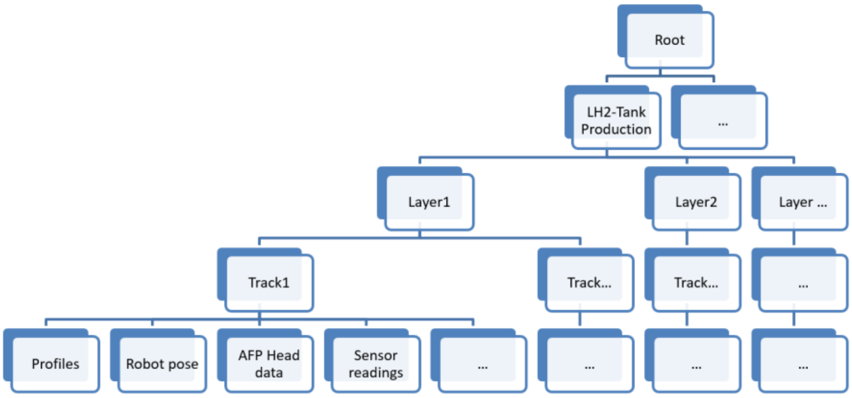

Figure 3: Data storage model

Starting from root the main node "LH2-Tank production" is followed by layer (ply)-nodes which are followed by track nodes (parent-child relation). The track nodes contain references to the measured profiles, robot pose data, AFP head data and miscellaneous sensor readings. The nodes also contain information about the manufacturing sequence (predecessor-successor relation), so the part hierarchy is reflected as well as the manufacturing hierarchy.

Figure 4 shows the IIoT (Industrial Internet of Things)-Layout: The data sources Robot, AFP Head and Profilometer are connected to three dedicated databases for meta data (the hierarchy and data reference), time series data (like data streams from sensors) and chunk data (3D-Scans of tracks). Communication protocols are OPC-UA and HTTP (REST).

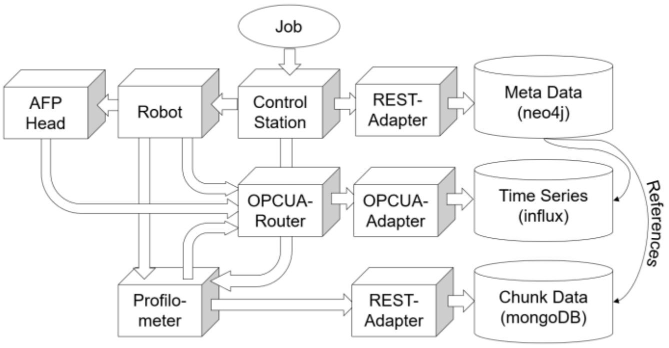

Figure 4: IIoT-layout

The robot is offline-programmed by CG-Tech's VERICUT-software which creates robot programs in the same layer-track hierarchy as shown in Figure 3. Control station, robot, AFP-head and profilometer have OPC-UA servers attached. Server-Server communication is enabled by OPC-Routers when necessary. The robot exposes layer and track numbers relating to the VERICUT-programs. The control station runs a data reference generator, which recognizes track and layer changes and creates the meta data node structure accordingly. Time series data are streamed into the time series data base and can be correlated with the nodes by a start and a stop reference, which are generated on track change. A chunk data node-id is also exposed by the data reference generator according to the actual track. On track end the profilometer grabs this id and uploads the collected data to the right place in the chunk data base in background. The communication between robot and the profilometer measurement system is done by TCP-IP XML communication, which in contrast to OPC-UA offered better defined handshakes at the time the system was created. The profilometer camera is hardware triggered by robot I/O and the robot transmits a UDP packet containing the pose for every camera shot. This way every profile can be transferred into a point cloud afterwards by using the pose, the robot TCP (tool centre point, here lying in the compaction roller’s nip point) and distance from nip-point to the laser line.

2.3 Test part manufacturing

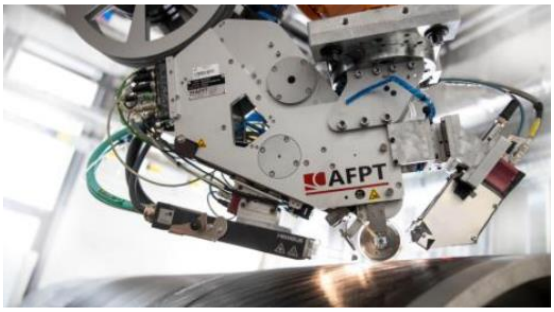

Figure 5: Test part manufacturing

Several plane plates with fiber orientation 0/90/0/90/ 90/0/90/0 were built and measured. For test purposes gaps and overlaps were introduced intentionally in selected layers. The system was also used for manufacturing a prototypical tank structure, allowing test measurements on a real 3D geometry. Heat source was a flash lamp by Heraeus, that heats up the tape to the desired ≈400°C. Additionally to the mounted band pass filter the camera had to be equipped with a light-trap housing coated with actar-black by ACM coatings in order to minimize scattered light (Figure 5).

3. RESULTS

3.1 Test plates

Test plates with overlap and gaps were measured. The nominal tape width of 38.1 mm (3 x ½” tapes) was found to spread up to 41.1 mm during layup, so this was assumed as effective tape width and the layup was adjusted accordingly. Since the layup quality is subject to ongoing improvements and flat samples are tendentially hard to produce the measurements proved to be very noisy (Figure 7 to Figure 10) and the detection process was therefore far from stable. Nevertheless, correct classifications always formed the majority of the observed results, so from a statistical view the identification of sufficiently persistent errors, e.g. longer gaps or overlaps, is perfectly possible. Figure 6 shows results for a small portion of the first ply of the overlap plate. Gaps are drawn in blue, overlaps in red.

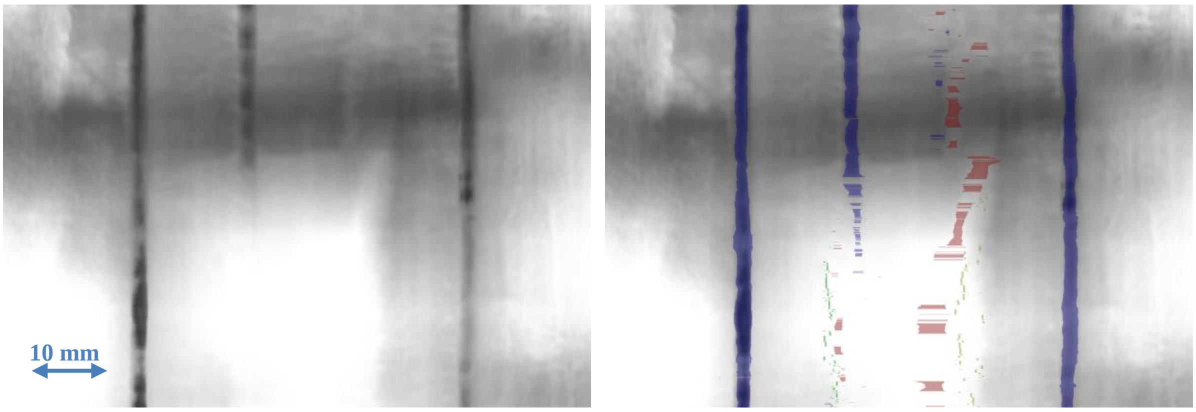

Figure 6: First ply of gap plate, automated evaluation on the right side

The scan was performed after all tracks of the ply were done, giving gaps at both sides. Generally, the surface is highly uneven what makes a correct detection difficult. The intentional effective gap of 1 mm to the left and the right side can be clearly identified and was measured to 1,7 and 1,2 mm FWHM (full width at half maximum). Volatile additional gaps or overlaps between the tows were observed and measured in our sample as 1,5 mm FWHM each (Figure

7). In contrast to this encouraging results, measuring gaps in higher layers proved to be quite challenging, since the layup involves 90 degree changes between subsequent layers, and the reflection of the laser line depends highly on the fiber orientation, giving a very bad signal to noise ratio for the 90° material. The gap presence was cross-checked with a profile taken by a Keyence VHX-5000 digital microscope and the issue is definitely with the inline profilometer. Previous measurements on a calibration plate had shown good results, also 45° shift of the underlying ply never was an issue, but in this special case the gaps were completely masked out, what is not acceptable. A loose nut in the camera optics focus was found to be the reason for blurry images and had lowered the image quality just enough to make gap detection impossible in this special situation. Thorough monitoring of the equipment and regular scanning of a test sample is therefore highly recommendable.

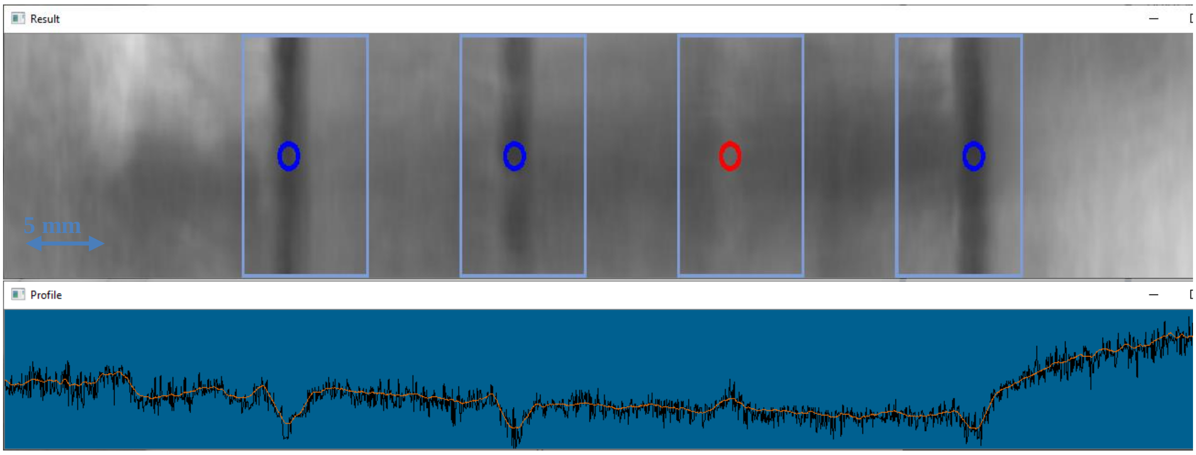

Figure 7: First ply of gap plate (height profile and sample cross section)

Figure 8 and Figure 9 show the observed results for ply 1 of the overlap plate. Again, the scan was performed after all tracks of the ply were done, resulting in overlaps at both sides. Here, even more unevenness is observed and detection results are less stable. The intentional effective overlap of 4 mm to the left and the right side was measured to 1.9 and 2.4 mm FWHM with additional overlaps between the tows of 1.9 and 3.1 mm FWHM. As observed for the gap plate there are volatile overlaps and even sometimes gaps between the tows that contribute to the overall surface roughness. Still the majority of the classifications at the left and right side of the tracks is correct, but with less significance than for the gap plate.

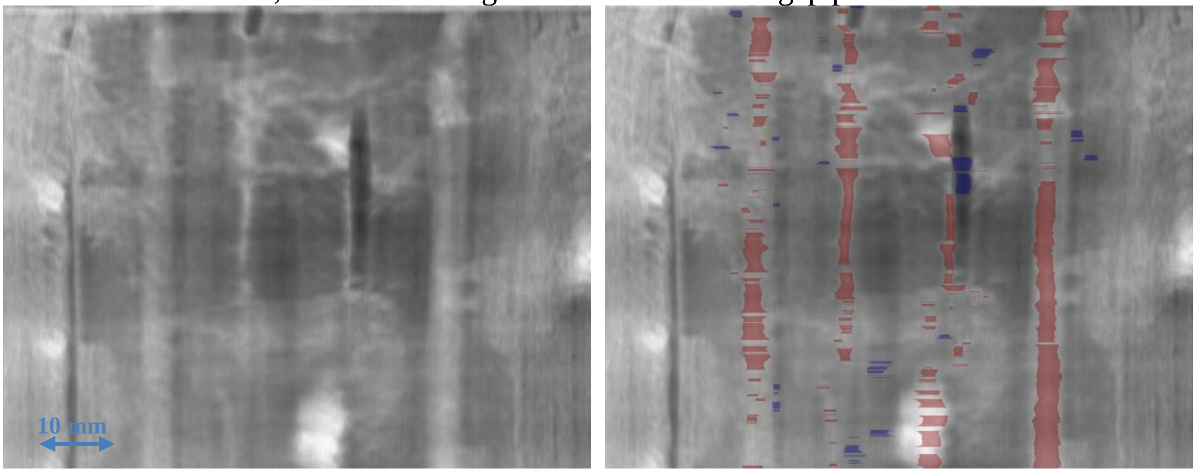

Figure 8: First ply of overlap plate, automated evaluation on the right side

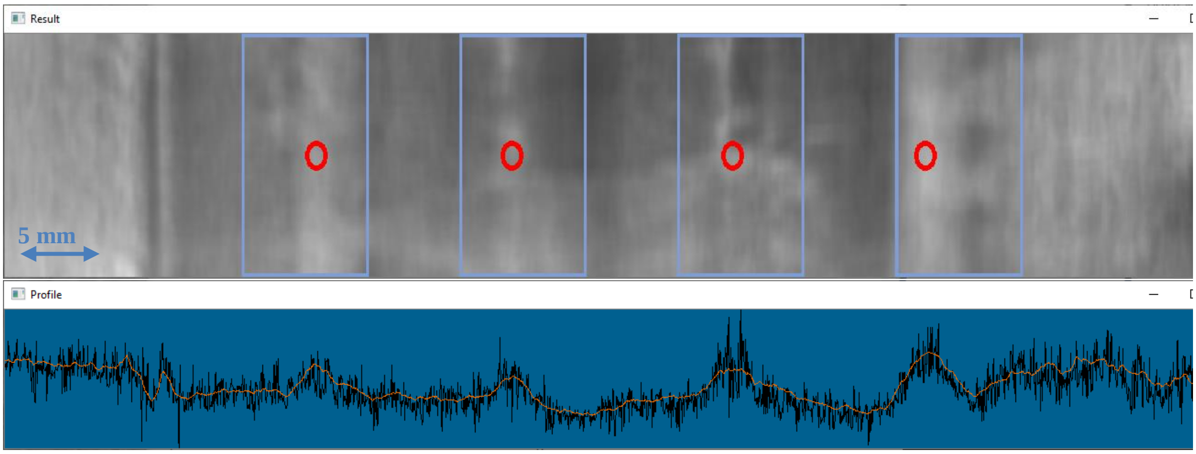

Figure 9: Figure 6: First ply of overlap plate (height profile and sample cross section)

Moving on to higher plies the problems concerning surface roughness increase. Figure 10 shows the very same part of the gap plate with increasing ply number (the gray wedge to the right is the height-scale). Interestingly ply 2 shows no sign of the gaps observed in ply 1, and also no significant sign of the 1 mm gaps that should be observed. Plies 4 and 5 are without gap, while ply 7 introduces a 2 mm gap. It seems as if gaps tend to disappear or just can't be clearly measured if the surface gets too rough. Additional to the median filters used in the detection software further image enhancement and noise reduction as proposed in [7] may help to make the detection more reliable. Unfortunately, the a.m. change in reflectivity if the underlying layer has a difference of 90° in fiber orientation masked out the gaps in this experiment except of the first ply.

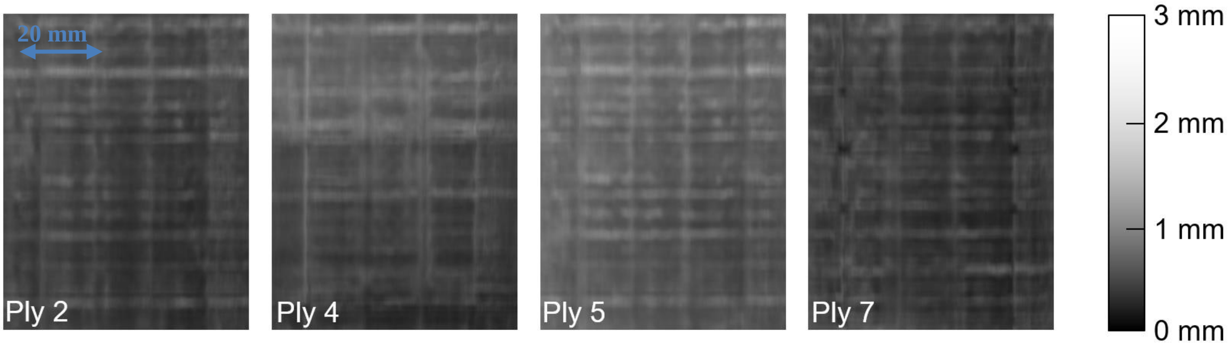

Figure 10: Selected plies of gap-plate

Figure 11 illustrates the behavior for the overlap plates. In contrast to the gap plates overlaps propagate through several (minimum 3) plies (plies 1, 2, 6, 7 and 8 were fabricated with 4 mm overlap) and seem to increase the overall surface roughness. Again, further image augmentation may increase the evaluation reliability.

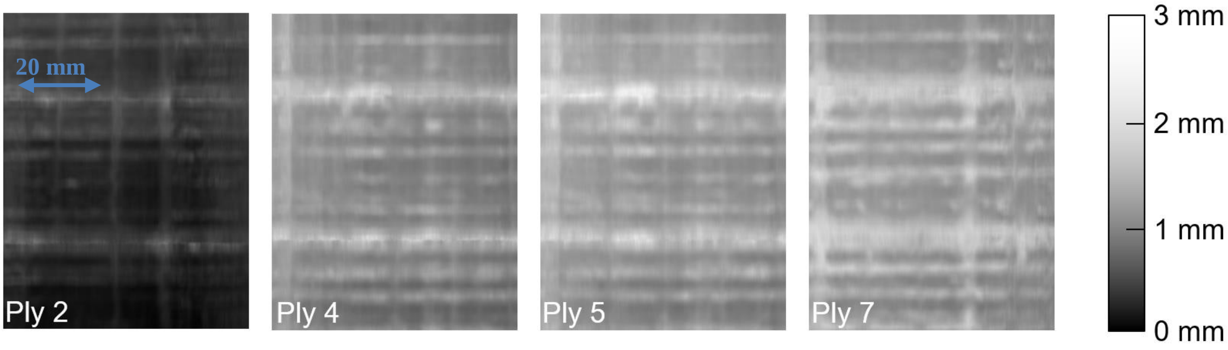

Figure 11: Selected plies of overlap-plate

3.2 Tank structure

Moving from plates to cylindrical parts one has to leave the pure 2D representation. Still there is a huge influence from underlying plies but fortunately the overall surface roughness becomes more regular allowing improved detection quality (Figure 12). Evaluation is still done in the 2D depthmap image, since pointclouds are uneasy to cope with. Having done the evaluation, both the points and the defects are mapped to 3D. In the future we intend to allow geometric aggregation in order to identify spatial regions with high flaw densities. Again, gaps are drawn in blue, overlaps in red. The yellow line shows the edge of the currently placed track.

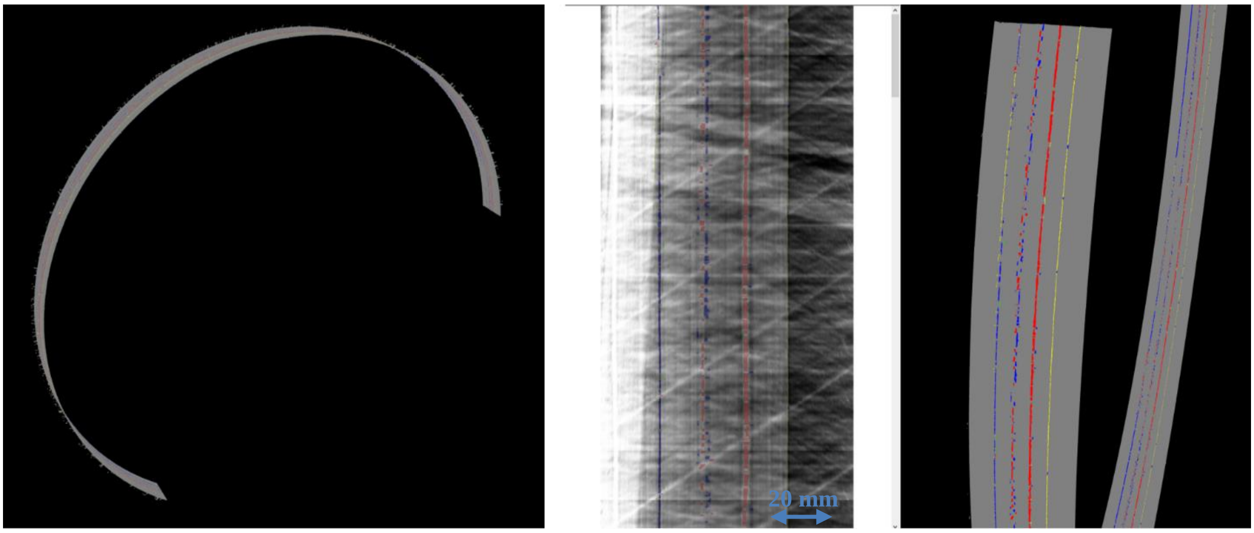

Figure 12: 3D cut-out of a point cloud measured with the TPS sensor at a cylindrical part (left). Cut-out of 2D evaluation (middle) and corresponding 3D visualization (right)

4. CONCLUSIONS

Our experiments showed that a 3D-Profilometer (like it is used for duromere prepreg AFP) is capable of measuring all occurring defect types encountered in T-AFP and that there are further types of defects that have to be considered. Automated evaluation was proved to be partially possible, i.e. for gaps, overlaps and steps. The detection of gaps showed to be highly sensitive to the combination of material properties, camera settings and optics and remains a challenge with a 90 degree change in the fiber orientation between subsequent layers. The coverage of all defect types in analogy with AIPS 0302019 seems to be in reach with enough effort by specialists in the field of computer vision and artificial intelligence. For this purpose, high quality and well annotated data is needed, and the described automated data annotation and storage system is a very important starting point towards a future inspection norm for T-AFP. As process and materials evolve the surface quality will increase and detection problems will decrease, opening the way to a reliable inline quality control.

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6. DISCLAIMER

The results, opinions, conclusions, etc. presented in this work are those of the author(s) only and do not necessarily represent the position of the JU; the JU is not responsible for any use made of the information contained herein.

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