Online preventive non-destructive evaluation for automated fibre placement

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(FIRST PAGE OF ARTICLE)

ABSTRACT

The strict quality requirements for aerospace composite structures give rise to costly quality control procedures. In automated fibre placement (AFP) these procedures rely heavily on manual inspection leading to long machine downtime periods and a slower production process overall. A preventive non-destructive evaluation technique of the composite laminate quality based on an online geometric analysis of the fibre using a laser profile sensor has been developed. This sensor has been mounted on a KUKA KR210 R2700 Extra 10-axis robot and software integration was performed using Robot Operating System (ROS). The robot is equipped with interchangeable end-effectors including an automated fibre placement end-effector, developed at TU Delft. The robot mounted laser profile sensor, in combination with robot positional data, was used to create a 3D model of the fibre. This model can be used in two ways. In real-time it can be used to perform an online assessment of the laminate quality including layup geometry, positioning with respect to a reference location, and detection of in-plane buckling defects. Furthermore the full geometric model obtained can be used to validate mathematical or numerical simulations of the fibre placement process and investigate the effects of process variables on the quality of laminate placement and defect creation. In an industrial process this evaluation method can provide full traceability of the part-product quality. The data can both be used during the qualification of a newly designed laminate, but also for quality assurance during series production.

INTRODUCTION

The use of fibre composite materials can provide significant improvements to the specific strength and stiffness of (aircraft) structures when compared to conventional metal alloy structures [1]. Over the years the use of high-performance polymer-matrix fibre composites has grown steadily. However due to the high costs of structures made from these materials, the take-up of aircraft components made of composites was slower than anticipated [2]. Cost modelling has identified using automation of material deposition, at much higher rates than current machines are capable of, as one step towards the reduction of the cost of carbon fibre reinforced structures [3]. This

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motivation, together with the ability of producing (near) net shaped components and a freedom in laminate design has driven the development of the automated fibre placement process.

Strict requirements on the quality of aerospace components, together with the large number of variables which influence the production of composite materials, give rise to stringent quality assurance procedures during all manufacturing steps. The first step usually consist of a quality check on the incoming raw materials and assuring correct storage. During manufacturing various quality control measures are in place to ensure that all parameters (e.g. temperature, humidity and compaction pressure) stay within the specified ranges. Finally, finished components are inspected using destructive and non-destructive tests to verify strength, stiffness and shape requirements [4].

Automation in quality assurance processes can be found in the continuous monitoring of important process parameters (e.g. temperature) or final component inspection (e.g. automated ultrasonic inspection). During ply layup with a fibre placement machine, quality assurance consists primarily of visual inspection. To prevent defects from occurring during layup and developing over subsequent production steps, the layup process is temporarily halted to visually inspect if anomalies such as, gaps/overlaps, incorrect positioning or in-plane buckling has occurred. It is estimated that this leads to 30% to 60% machine downtime due to inspection and rework [5]. This makes quality assurance in AFP an important cost driver.

Previous research in the AeroNDT laboratory has shown that the important features that indicate the quality of a composite layup can be detected using a laser profile sensor. This sensor creates a high quality geometric model of the layup geometry, and from this model the presence of defects such as unremoved (backing) foils, incorrect number of plies and incorrect fibre orientation could be determined [6].

In the current research, the above mentioned measurement concept, which has been proven in an optical laboratory, has been transferred to a manufacturing laboratory and real-time, automated data analysis has been developed. The laser profile sensor was combined with an industrial robot that is used for AFP, to obtain composite tape measurement data. In the next section the experimental setup and the method of data acquisition are introduced.

EXPERIMENTAL SETUP AND DATA ACQUISITION

The work presented in this research has been performed at the Delft Aerospace Structures and Materials Laboratory (DASML) of the Delft University of Technology (DUT). Within this laboratory a newly acquired KUKA automation cell (shown in figure 1) is used to perform research into the development and optimization of several automated composite manufacturing techniques (e.g. AFP and filament winding). The automation cell consists of a KUKA KR210R2700 Extra robot arm that is mounted on a linear track. A horizontal external positioner and two additional drive motors provide a total of 10 controllable axes using the KUKA KR C4 controller. The robot can accommodate a payload of 210 kg and has a pose repeatability of 0.06 mm.

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Figure 1. Overview of the KUKA automation cell with AFP end-effector

Based on the knowledge gained with laser profile sensors in the AeroNDT laboratory, the Micro Epsilon scanCONTROL 2950-25 laser displacement sensor was selected for the acquisition of the measurement data. This sensor uses triangulation [7] to provide a height profile of the measurement object along a laser line of approx. 25 mm wide. It provides height measurements of up to 1280 points along this line with an accuracy of up to 2 µm in the height direction at a maximum frequency of 2000 Hz [8]. By mounting this 2D (line) sensor onto a robotic arm, 3D measurements of a fibre sample could be obtained.

Robot operating system (ROS) [9] has been used as a framework in which the data for this research is acquired. ROS is an open source, flexible framework for developing robot software and has been used because it provides many tools for easy software integration, data sharing over multiple machines and data analysis. Communication with the KUKA robot has been established using a ROS driver [10] that implements an Ethernet connection to the KR C4 robot controller using KUKA.RobotSensorInterface (RSI) [11]. Using this the actual robot axes positions (of the 6 primary axes) were obtained at 50 Hz, which is a frequency that is determined by KUKA`s RSI software. For the communication with the sensor, software that was provided by the manufacturer has been modified to enable integration into ROS [12]. This software provided the laser profile measurements up to 100 Hz. Higher sensor readout frequencies are achievable (up to 2000 Hz), this however has a limiting effect on the size of the measuring field that can be obtained.

The data acquisition within ROS is based on a model of the experimental setup (see figure 2). At 50 times per second the drive motor position of each robot axis was obtained, this drives a chain of quaternion transformations that starts at the robot base (global coordinate frame) and ends at the tool center point (TCP). A known bracket geometry and geometric information of the sensor provides the transformations from TCP to the sensor frame in which the height measurements were provided.

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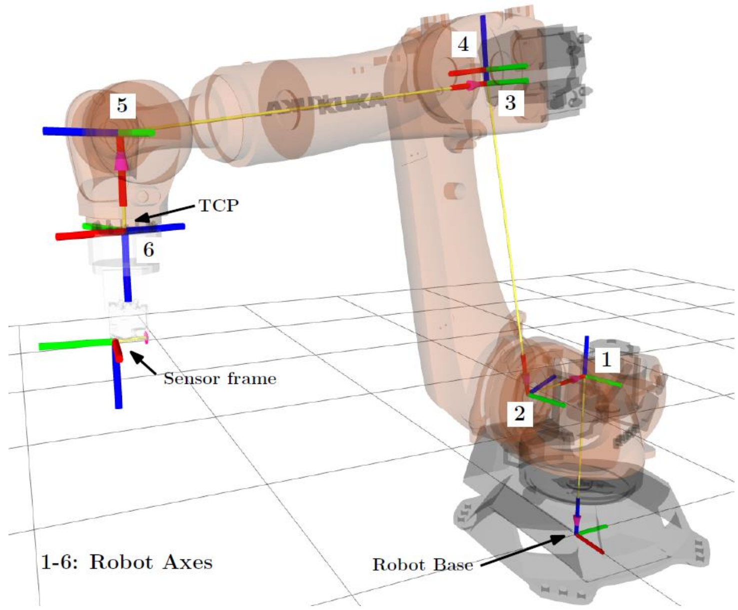

Figure 2. Model of the experimental setup

By combining the data from the robot and sensor, a laser profile measurement in a global coordinate frame is obtained. During the experiments the robot was programmed to follow an already placed fibre sample that has a width of 25.4 mm and approximate thickness of 18 µm. Figure 3 shows a section of the measurement (approximately 200 laser profiles) that is recorded over 2 seconds. The automated data analysis that is developed for this kind of data is introduced in the next section.

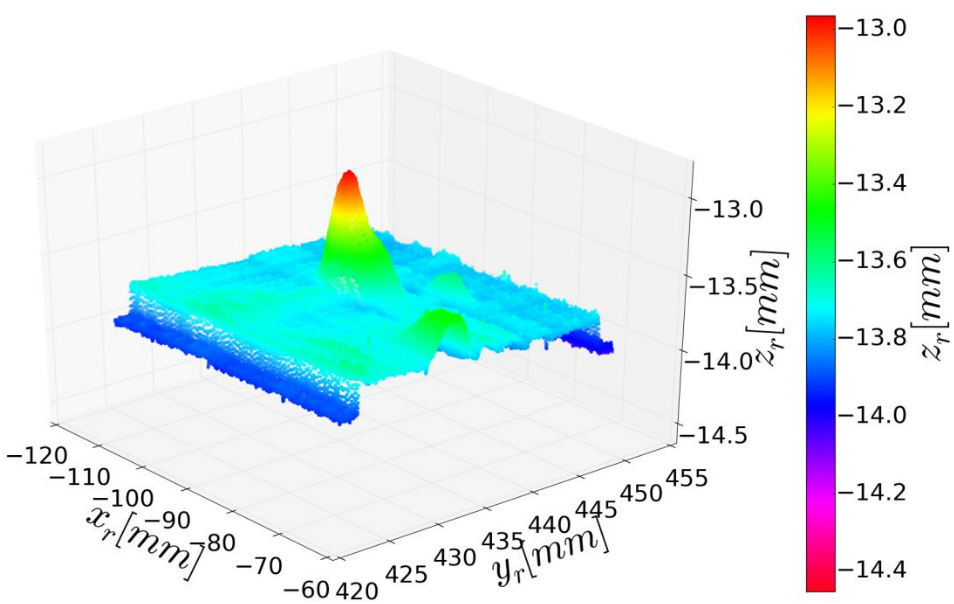

Figure 3. Section of data acquired with the experimental setup

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AUTOMATED DATA ANALYSIS

The automated data analysis performed in this project was aimed at obtaining the fibre edge location, edge curvature, fibre width and height in real-time using the (type of) data as shown in figure 3. To achieve this, algorithms from the open source image processing library OpenCV [13] have been used.

The initial data is acquired in a 3D point cloud format, this means that, after filtering and outlier removal, the point clouds were first converted to an image format where each z-coordinate was normalized to an 8-bit value (0 to 255). This provided a greyscale representation of the data. This representation is shown in figure 4. It can be noted that at this point the spatial relationship between the pixels is (temporarily) lost. However at a later point this information could be recovered by mapping each pixel onto the original data point.

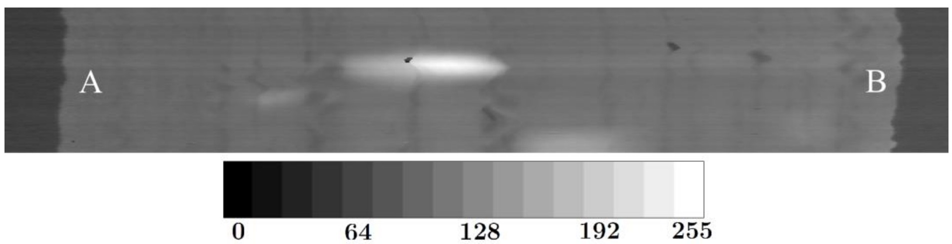

Figure 4. Greyscale image representation of measurement section

All goals for the data analysis could be met by fully segmenting the image. For each pixel it has been determined if it corresponds to: 1) the background, 2) an edge (indicated with an A and B in fig. 4) or 3) the fibre. The main method used was segmentation using marker-based watershed [14]. Marker-based watershed has been selected because it is a fast, well tested algorithm that provides closed contours by design and is widely applicable because it is a general method. By choosing marker-based watershed over normal watershed problems of over-segmentation are mitigated.

Marker-based watershed needs some preliminary information about the image. Therefore first an initial segmentation into two regions has been made using thresholding with Otsu`s method [15]. This is a method for the automated determination of the best thresholding value. The algorithm will find the pixel threshold value that yields the minimum weighted within-class variance in pixel values. Together with subsequent processing steps this yielded the preliminary marker distribution in figure 5. This image shows the three regions: background (blue), edge (red) and fibre (green). Within the edge regions the actual fibre edges are located. On these regions the watershed algorithm has been applied.

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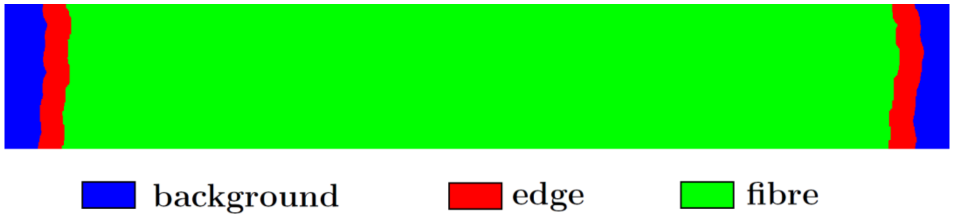

Figure 5. Preliminary marker distribution

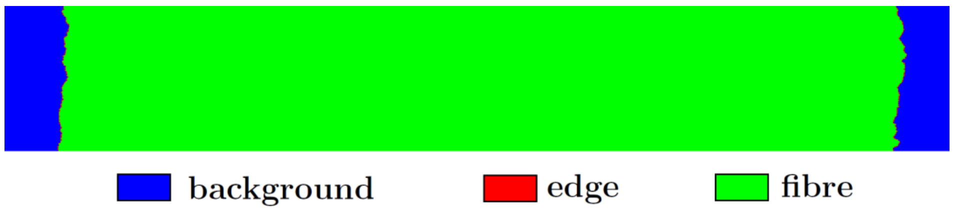

Figure 6. Final marker distribution

The marker-based watershed algorithm operates analogues to catchment basins that are found in nature. The greyscale image in figure 4 can be considered a topographic surface. By flooding this surface from the local minima, and preventing the merging of different basins, the image is partitioned into regions with similar greyscale values. Due to local irregularities and noise in an image, default watershed algorithms tend to yield an over-segmented image. Marker-based watershed algorithms use initial information to prevent over-segmentation.

A fully segmented image provides segment information on each pixel. The final marker distribution is shown in figure 6. This information was mapped back onto the original point cloud to yield a segmented point cloud. Using this segmented point cloud the fibre width, thickness and edge curvatures were determined.

The width follows from a local Euclidian distance calculation and an mean of this distance over all edge points. Assuming that edge points are ordered in pairs of left (L) and right (R) edge points, and considering N-pairs, the mean width is calculated by equation 1.

$$\overline{w} = \frac{\sum_{i=1}^{N}\left(\sqrt{\left(x_L^i - x_R^i\right)^2 + \left(y_L^i - y_R^i\right)^2 + \left(z_L^i - z_R^i\right)^2}\right)}{N} \quad (1)$$

To determine the thickness of the fibre an area based approach has been used that evaluates the mean z-coordinate of all fibre and background points separately, and takes the difference between these two values. This approach can yield a higher thickness then the actual value due to out of plane buckles. For now this situation is recognized using a simple check, in future work such occurrences can be researched further and additional processing needs to be added.

Finally the edge curvature has been determined by first performing a least squares cubic polynomial fit. The fitting algorithm that was used minimizes the squared errors between the original data and the cubic fit. The results of the fitting of two separate functions to the top and bottom edge of a curved fibre sample are shown

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in figure 7. These cubic polynomials can be differentiated twice in order to calculate the curvature at any point along the edge using equation 2.

$$\kappa = \frac{\frac{d^2y}{dx^2}}{\left[1+\left(\frac{dy}{dx}\right)^2\right]^{\frac{3}{2}}} \qquad (2)$$

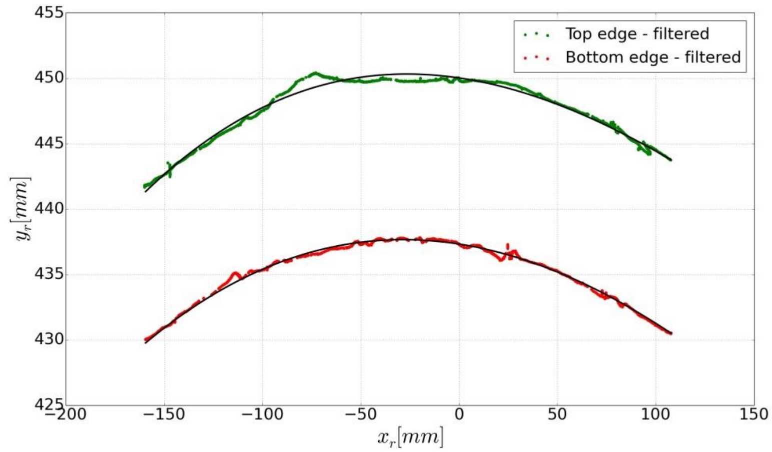

Figure 7. Fibre edge interpolation

The algorithms and analysis shown in the previous paragraphs have been implemented in Python programs that are incorporated into ROS. This yields a system that will continuously monitor the scanned data that is provided by the sensor and robot arm combination, and will perform the complete analysis on data that is gathered over 2 seconds. The results of these calculations are then distributed again and can be used for subsequent processing or visualization.

DISCUSSION

It has been shown that using a laser profile sensor in combination with a robot arm provides a high quality geometric model of a carbon fibre sample. By analyzing this geometric model using algorithms from OpenCV a real-time system is achieved that can detect the fibre and provide its location in space, determine its width and thickness and analyze the edge curvatures. The current system can also be used to further develop the analysis techniques and include other types of defects and/or laminate features.

An analysis of the accuracy of the system has shown that the absolute positional accuracy is mainly influenced by the absolute positioning accuracy of the robot arm. While no solid data on the absolute accuracy of the KUKA robot arm is reported in literature or by the manufacturer, it is estimated by looking at comparable machines that the error in the absolute position can be up to approx. 500 µm. This means that when comparing the absolute position of a fibre in the global reference frame to the desired position large deviations are expected. It must however be noted that, when integrating the laser profile sensor onto a fibre placement end-effector, not

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only the measurements are subjected to this uncertainty but also the placement of the fibre itself. When it comes to features that are measurable within one laser profile measurement, the width and height, an uncertainty of approx. 30 µm is found. This uncertainty is several times higher than the theoretical accuracy of the sensor (2 µm). The main causes for this are mechanical vibrations that occur when performing measurements with a moving sensor.

Current quality requirements on laminates for aerospace applications are set with visual inspection methods in mind, this means that deviations in geometry and defects can occur over relatively large areas when compared to the minimum detectability of the proposed system. So to achieve a similar accuracy in detection as a visual method would, a less accurate sensor could be used.

If a sensor of high quality would be implemented in an industrial process, then an unprecedented model of the actually produced part is obtained. This kind of insight could lead to stricter requirements on allowable defects, which in turn could influence the safety margins that are related to manufacturing induced defects.

CONCLUSION

The experiments and analysis performed in this research have shown that preventive non-destructive evaluation based on laser displacement sensing can be used to monitor the production quality of composite laminates during automated fibre placement. A prototype system has been developed that has shown that the fibre can be detected to an acceptable level of accuracy. Furthermore from the geometrical model of the fibre key characteristics such as, layup geometry, positioning with respect to a reference location, and in-plane buckling defects can be detected. An accuracy analysis has shown that while mechanical vibrations and inaccuracies in robot positioning do influence the measurement results, they do not inhibit a successful detection and analysis of the fibre.

Good results were obtained using image processing techniques for the segmentation of the sample geometry into background, edge and fibre regions. For correctly placed fibre samples the thickness, width and edge curvature can be calculated. When large flaws in the placement of the fibre exist, the segmentation can fail. This failure is recognized by the system and presented to the user.

Future research is aimed at incorporating the detection and analysis of more fibre features and/or flaws and possible letting the robotic system take corrective actions. And using the current system to provide a full geometric model of the placed fibre to support the validation of mathematical or numerical simulations of the fibre placement process. With the system in place the creation of manufacturing induced defects can be tracked, linked to their effects in subsequent production steps and finally their influence on the properties of the test sample.

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