Photometric stereo on carbon fiber surfaces

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Abstract
The production of carbon fiber-reinforced plastic (CFRP) is currently changing from a highly manual and expensive to an automated process. However for automated production of CFRP parts new sensor systems for quality control are required.
In this article we present a photometric stereo inspection system that is able to automatically evaluate critical quality criteria of carbon fiber fabrics. Based on the sensor output we propose a specific segmentation method, tailored towards the typical properties of woven carbon fiber fabrics that partitions the fabric into single segments for feature calculation and classification. Finally we show that the proposed system is able to detect a multitude of defects in a real-time system.

1. Introduction
Carbon fiber sheets, woven carbon fiber fabrics, raw carbon fiber-reinforced plastic (CFRP) and clearcoat painted CFRP all have the same unusual reflection properties because of the microscopic shape and good reflectivity of the carbon fibers. The traditional way for machine vision applications for inspection of carbon fibers is to suppress the direction dependent reflections using diffuse light sources [4, 5]. Here we introduce a novel way of inspecting carbon fiber surfaces using photometric stereo.

Photometric Stereo (PS) methods derive the orientation and reflectance values for a 3D surface from multiple images captured from the same point of view under different illumination directions. The recovered surface normals are then integrated to reconstruct an objects’ surface. When compared to conventional stereo vision, PS has the advantage that it does not require a solution of the correspondence problem and thus allows a per pixel surface reconstruction. However it only measures the orientation and not the position of the surface. PS must not be confused with shape from shading that deals with the recovery of shape from a gradual variation of the shading in a single image [8]. In the classic PS formulation introduced by Woodham [7] the author assumes a Lambertian object which is viewed under \( \geq 3 \) different light conditions assuming point light sources [3] and non-Lambertian reflectance models [6]. In particular the dealing with specular surfaces is challenging as the light sources must be spacious to be reflected to the camera for all possible surface orientations. Ikeuchi for instance used a Lambertian surface as an indirect light source [3].

PS has been applied successfully to a wide range of objects with different surface geometry and reflectance properties. Carbon fiber surfaces however have very special reflectivity properties that require a different method. We propose Fiber Reflection Analysis (FRA) that is based on a basic

*This work was funded by the Austrian Research Agency (FFG) under grant no. 498817, project Profit. It reflects only the authors’ view.
model for carbon fiber surfaces but allows to compute not only fiber orientations but also reflectivity properties of the surface.

FRA generates characteristic 4-channel images that can be used for visualization and manual evaluation. To enable automated evaluation and defect detection we propose Fiber Line Segmentation which is a robust and efficient method to extract the individual segments from fabrics. The features computed for these segments serve as major input for the final classification stage.

2. Fiber Reflection Analysis

A good optical approximation for a carbon fiber is an infinitesimal cylindrical perfect mirror. A ray reaching a point on a carbon fiber surface (CFS) is typically reflected by the microscopic cylindric surfaces of several parallel fibers. Following the law of reflection the reflected rays form a cone around the direction of the fibers.

![Figure 1. Fiber angle calculation. The camera \( c \) looks down to a surface point \( O \). The light source positions \( l_1 \) and \( l_2 \) are used to calculate the fiber orientation \( \mathbf{f} \).](image1)

![Figure 2. Camera (1) and light source setup. Each light sources on the ring (2) can be activated separately. The light incidence angle is around 45°.](image2)

![Figure 3. The portal-sensor as described in Section 5 consisting of a CMOS camera and a high power LED (\( \lambda = 400 - 700\,\text{nm} \)) ring.](image3)

To design a suitable light source we analyzed the ray of one pixel in inverse direction starting at the camera as shown in Figure 1. For simplicity the origin \( O \) is placed at the observed surface point. The camera \( c \) looks vertically down to a CFS. The ray of one pixel reaches the surface at the Origin \( O \) with a fiber orientation \( \mathbf{f} \). All the light sources on the inverse reflection cone are mapped to the single pixel of the camera. The simplest rotation-symmetric light source is a horizontal circle as shown in Figure 2. If there are intersections of the light circle and the ray cone \( l_1 \) and \( l_2 \) the orientation of the fiber \( \mathbf{f} \) can be calculated using the law of reflection:

\[
\mathbf{s}_i \propto \frac{\mathbf{c}}{||\mathbf{c}||} + \frac{\mathbf{l}_i}{||\mathbf{l}_i||}, \quad i = 1, 2
\]

\[
\mathbf{f} = \mathbf{s}_1 \times \mathbf{s}_2
\]
To be able to find the position of \( l_i \), multiple images are taken with different parts of the circle lighted. For each pixel of the image the positions \( l_i \) can be found using the gray values of the different images. Figures 4(b) and 4(c) show the signals of one pixel for point and segment light sources. However, for a real shape from shading approach the light sources must be smooth and overlapping.

Figure 4. Schematic reflectivity diagrams of carbon fiber surfaces (CFSs). The radial/vertical components (a-1) show the intensity of the observed light in a setup as shown in Figure 2. The diffuse part (a-2) is usually very small for CFSs but significantly larger for sewing threads and debris. The two specular peaks (a-3) are often very narrow and can not be detected reliably with point light sources (b). A discrete measurement can be done with segments (c). For a real shape from shading measurement of the peak positions (a-4) the light source segments must be smooth and overlapping.

3. Fiber line segmentation

The image modalities delivered by the photometric analysis stage of the sensor need to be partitioned into individual segments to facilitate feature computation. The shape of the segments is determined by the weaving pattern of the carbon fiber fabric currently under investigation. Figure 5 illustrates the diversity of segment shapes that can be found on carbon fiber fabrics.

The major difference to standard image segmentation approaches is that each pixel \( \varphi_{x,y}, 0 \leq \varphi_{x,y} \leq \pi \) of the orientation image \( I_{\varphi}(x, y) \) provides information about the fiber orientation. Standard image segmentation approaches such as region growing \([2]\) rely on the intensity difference between a candidate pixel \( p_c \) and the region to decide whether \( p_c \) should be added to the region. These methods work well
for a subset of fabrics (Figure 5 b, c) but fail for others (e.g. Figure 5 a, d, e show three fabrics where the border between adjacent segments cannot be fully determined by comparing pixel intensities). Also segmentation methods that are based on the detection of discontinuities between image regions fail for some fabric patterns (Figure 5 a).

To account for the specific requirements of orientation image segmentation, we propose Fiber Line Segmentation (FLS) for robust and fast segmentation of carbon fiber fabrics. First we detail the idea of FLS for a single segment. Next we describe how FLS deals with phenomena such as segment holes, measurement noise or misaligned fibers. Finally we discuss an optimization to reduce the computational load of segmentation in order to enable real time carbon fiber fabric inspection.

The idea of FLS is illustrated in Figure 6. The core segmentation method operates on the orientation image $I_\phi(x,y)$ only. Let us assume that we have to find the contour $C_i$ of a single segment $S_i$. FLS starts from a seed point $p_{0,0}$, located inside $C_i$. The fiber orientation at $p_{0,0}$, denoted by $\phi(p_{0,0}) =$
$I_\varphi(p_{0,0})$ determines the location of the next point $p_{0,1}$ that belongs to the fiber line $l_0$ by $p_{0,i+1} = p_{0,i} + [\cos(\varphi(p_{0,i})), \sin(\varphi(p_{0,i}))]^T$. New points are added to $l_0$ as long as $|\varphi(p_{0,i}) - \varphi(p_{0,i+1})|$ is smaller than a preset threshold. The same method is applied to the other “half” of the fiber line starting at $p_{0,0}$ again $p_{0,i-1} = p_{0,i} - [\cos(\varphi(p_{0,i})), \sin(\varphi(p_{0,i}))]^T$. The end points of $l_0$ are denoted by $p_{0,a}$ and $p_{0,b}$ respectively as illustrated in Figure 6 b).

The seed point $p_{1,0}$ for the extraction of the next fiber line $l_1$ is obtained by adding the vector $\vec{n}_0$, the normal vector of $[p_{0,b} - p_{0,a}]^T$, to the point $p_{0,\lfloor(a+b)/2\rfloor}$ as illustrated in Figure 6 c). The seed point $p_{1,0}$ is obtained by subtracting $\vec{n}_0$. Fiber lines are extracted this way as long as valid fiber lines can be found. A fiber line $l_i$ is valid if the maximum Euclidean distance $\max(||p_{i,a} - p_{i-1,a}||, ||p_{i,b} - p_{i-1,b}||) < t_{d(a,b)}$, the length of $l_i$ is larger than $t_l$ and the orientation difference to $l_{i-1}$ is below $t_\varphi$, where $t_{d(a,b)}$, $t_l$ and $t_\varphi$ denote preset thresholds.

After all valid fiber lines are found, the contour $C_i$ is built from the points belonging to the outermost lines and all points $p_{i,a}$ and $p_{i,b}$.

In the following we discuss a selection of practical FLS implementation aspects.

**Fiber orientation deviations:** The orientation image $I_\varphi(x,y)$ can contain inaccurate information for two reasons. There appear holes due to resin on the carbon fiber surface (Figure 7 a). To avoid that the presence of a hole “splits” one segment into two separate ones (Figure 7 b) we allow a preset number of consecutive fiber line points to lie within a hole (Figure 7 c).

For some fabrics, the fibers are not parallel to the visible segment border (Figure 7 d) due to minor measurement inaccuracies. Thus FLS would yield segments with “missing triangular areas”. We apply a growing step (Figure 7 e) that enlarges the contours of all segments in parallel to correct for this phenomenon.

**Seed point selection:** We generate each seed point (denoted as $p_{0,0}$ in Figure 6) on a regular square grid such that at least one point is located within each segment $S_i$. Seed points which are located on segment borders or in image regions that are not suited for segmentation are removed based on measures of azimuth noise and edges, polar angle, and diffuse reflection.

**Segmentation of a whole fabric image:** Given the list of selected seed points we start the extraction of the first segment contour $C_1$ with the first seed point $s_1$. Given that $C_1$ is valid (i.e. the segment area is above a threshold, and the aspect ratio of the segment is within a certain range) it is added to a label mask that holds 0 (no segment found) or the segment ID for each image location $(x, y)$. This mask is utilized to remove seed points that are within a previously found contour and to avoid that an image
point is assigned to multiple segments during FLS. The segmentation continues as long as unvisited seed points are available.

*Treatment of cyclic orientation data:* As FLS operates on an orientation image \( I_\phi(x, y) \) the cyclic nature of the data has to be considered for pixel comparisons (e.g. to determine the end of a segment fiber line). Whenever a new fiber line point is computed \( p_{i+1} = p_i + \begin{bmatrix} \cos(\phi(p_i)) \\ \sin(\phi(p_i)) \end{bmatrix} \) we have to correct for transitions between \( 0^\circ \) and \( 180^\circ \).

*Optimizing runtime:* A substantial segmentation speedup can be achieved by increasing the step size, both between the fiber line points as well as between the fiber lines. In case of an invalid line point or fiber line the step is reduced to 1 again to use the full image resolution close to the segment borders. For a step = 4 we obtain a speedup of up to 3 which corresponds to a segmentation time of 110 ms for an image with approximately 200 segments of size \( 832 \times 400 \) pixels.

4. Feature extraction and classification

Given the segment contours we are able to extract a set of characteristic and interpretable measures which can be divided into first and second order features. The first order features represent properties of a single segment such as mean and standard deviation of polar, specular, diffuse and orientation information, width, height and segment area. For the second order features the segment neighborhood is considered to derive the distance (to detect gaps between carbon fiber tows) and the relative orientation differences between adjacent segments. These features are closely related to critical surface properties and thus directly used for threshold-based classification with the thresholds being adjusted by domain experts according to the process requirements.

5. Results and Outlook

After developing the theoretical fundamentals of FRA using laboratory equipment we built two types of industrial sensors. These sensors work with gigabit ethernet CMOS cameras and 96 microcontroller triggered high power LEDs. The raw image data is sent to a PC which does FRA, segmentation and classification in real time with up to 50 million pixels processed per second. In the following we describe the sensors’ industrial application including qualitative results of the subsequent CFS analysis.

The *robot-sensor* is used to monitor the work of a free-form 3D CFRP sewing robot. The goal is to detect deformations of the fabrics caused by the sewing process. The sensor (field of view: \( 40 \times 40 \text{mm}^2 \)) makes 10 measurement (consisting of eight raw images) per second. An example measurement is displayed in Figure 8. FRA is used as input of a pixel-based classification to distinguish the carbon layers and the sewing thread. During the production process our software receives online quality parameters from the robot master PC over a network connection and returns the detected deformations in real time. The evaluation does not need any segmentation or pattern recognition and is therefore applicable to arbitrary layered or woven fabrics and different materials.

In a second industrial application the *portal-sensor* (Figure 3) is used for automated inspection of woven carbon fabrics before cutting. The sensor (maximum field of view: \( 60 \times 60 \text{mm}^2 \)) is mounted on a two-axis cutter table and can do a complete scan of the fabrics or just a zig-zag random inspection. The maximum speed of the sensor is 1 m/s with a scan width of 50 mm, so it takes about 20-25
Figure 8. Example for a single measurement of the *robot-sensor* (260 × 580 pixels each). The full field of view is 40/40mm, only a section of 14/30mm is displayed here. A sewing thread running from left to right in the middle of the image has just deformed the carbon fibers. (a) one of 8 raw images $s_i(\vec{x})$ taken with different lighting directions, (b,c) calculated diffuse and specular reflectivity $d_i(\vec{x})$ and $s_i(\vec{x})$ as explained in Figure 4(a) and Equation (3), (d) combined visualization showing the azimuth fiber orientation $\varphi_i(\vec{x})$ (black stream lines), the two carbon layers (red/green) and the sewing threads (white), (e) detected unexpected fiber orientations (red/green).

Figure 9. Example for a single measurement of the *portal-sensor* (500 × 500 pixels). The field of view is 35/35mm. In the middle of the image there is a strong deformation of the vertical rovings. Figure a) shows the polar image $\theta_i(\vec{x})$ as defined in Equation (3) with segment contours found with FLS. The segments are classified into faulty (red), okay (green) and border-segments (blue) which cannot be classified. Figure b) shows a 3D-view of the same measurement. The z-coordinate is enlarged by a factor of four for better visualization.

seconds for a complete inspection of one square meter. The sensor continuously acquires small frames (900 × 100 pixel) with a high frame rate (up to 1000fps), the raw images of each light direction are then stitched together to eight separate scans before processing them with FRA. The results are segmented using FLS. Figure 9 shows a single measurement. The FLS parameters can be easily configured for
new weaving patterns. The PC evaluates the data in realtime and displays the positions of defects on a screen. A threshold-based classification finds faulty segments using the contours, mean and variance of the reflectivity vector $R$ inside the segments. The system was tested with an industrial end-user to detect many different faults like deformations, gaps, damaged rovings, weaving faults and free fiber pieces. In a (yet offline) last step the 3D surface of each segment can be reconstructed using the polar angle image as shown in Figure 9(b). The calculated height and bending of the segments is usually related to the tension of the fibers and important for the appearance of clear-coat painted CFRPs.

For future work we plan to extend the set of surface features (Section 4) with a collection of “Blob” features [1] such as compactness or roundness. Another goal is to use FLS with pattern recognition methods for materials where FRA cannot be applied such as wire meshes.

Another major piece of future work will be a quantitative evaluation of the sensor for surface inspection tasks. First, we plan to assess the measurement (e.g. fiber orientation) accuracy for a range of materials such as carbon fiber sheets, woven carbon fiber fabrics, raw and clear-coat painted CFRP. A quantitative evaluation of the classification results itself depends on the availability of ground truth data which is difficult to obtain for the variety of CFRP surface phenomena.

References


