Advanced Fiber Evaluation Workflows

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Abstract
The presentation will highlight three different uses cases for tackling with fibrous materials using Avizo software.

The first two approaches handle resolved fibers in high magnification images. The first method demonstrates how to compute so called local orientations, where the fiber volume is subdivided into blocks of equal size. Each of such blocks will then be transferred into Fourier space in order to compute an orientation of the block’s content.

In the second case we will present our recent XFiber extension for tracing the centerline of cylindrical fibers by applying a template matching approach followed by a specific line tracing algorithm. Extracting each individual fiber centreline, this approach enables fiber counting, but also extraction of statistics such as fiber length, orientation or curvature.

The third approach will consider woven composites imaged at lower magnification, where individual fibers cannot be distinguished but the oriented texture of the yarns is visible. We will detail an advanced workflow for classifying the yarns based on their orientation.

Keywords: Fiber, Reconstruction, Orientation Map, Visualization

1 Methods

In the first part of this paper we describe different methods related to fiber detection and local orientation estimation. Such approaches and their application are heavily driven by the underlying image quality. The image quality may allow for detecting individual fibers but also fiber orientation evaluations of images with low contrast and/or resolution are possible.

1.1 Local Orientation

The local orientation information in a 3D image is computed using principal component analysis techniques. In particular, it estimates the main local orientation. The image is divided into cubic quadrants. The dimension of each block must be of the power of 2. The cubes may overlap. Then the Fourier transform is computed on each block to extract the amplitude.

The inertia matrix $M$ is computed on each Fourier transform. The matrix is symmetric, thus, the Jacobi iterative method can be used to extract the eigenvalues and the eigenvectors. The main fiber orientation is given by the eigenvector associated with the lowest eigenvalue.

The confidence of the estimated main orientation is calculated as follows:

$$\frac{Val_1 + Val_2 - Val_3}{Val_1 + Val_2 + Val_3}$$

with $Val_1$ being the maximum eigenvalue, $Val_2$ being the second and $Val_3$ the minimum of eigenvalues.

With this formula, the confidence is between 0.33 and 1, then, normalization adapts the range between 0 and 1 [1].

1.2 Cylinder Correlation
When doing cylinder correlation the normalized cross correlation of an image with a parametric solid or hollow cylinder template is computed. The template is defined by length, outer diameter and inner diameter for hollow cylindrical objects, as in Figure 1:

![Definition of the cylinder template](image1)

The possible cylinder orientations are sampled according to an adjustable angular sampling rate. A sampling rate of 5° usually gives good enough results in this approach. For each orientation, the parametric cylinder is converted into a voxel representation to generate a template. The normalized cross correlation of the voxel template with the image at each voxel position for all orientations is computed, using an efficient GPU-based implementation. The result is stored as two fields. The first field contains the maximum cross correlation for each voxel. The second field contains the orientation of the template that yields the maximum correlation. A detailed description of the general algorithm for computing the normalized cross correlation is described in [2].

![Illustration of the template matching based fiber tracing](image2)

In the second step of this approach the lines are traced. The line tracing is based on the correlation and orientation fields. All correlation values above a given minimum are sorted in descending order. A new line is started at the point with highest correlation score. A parametric search cone, centered on the current centerline point and oriented along the local orientation given by the template matching step, is used to perform the tracing, as illustrated in Figure 3. Tracing stops if the correlation value of all candidate points weighted by the deviation from a straight line is less than a given minimum correlation continuation quality. Then, a mask around the traced fiber is applied to avoid starting a new fiber too close from the detected one. The detection and tracing process is illustrated in Figure 2. A detailed description of the algorithm can be found in [3].
1.3 Yarn Segmentation

For yarn segmentation we consider woven composites imaged at lower magnification, where individual fibers cannot be distinguished but the oriented texture of the yarns is visible. The current approach is limited to cloth displaying 2 major orientation, orthogonal to each other.

In a first step an orientation texture map is computed by combining morphological operations like opening and closing together with a linear element according to the two main yarn orientations (Y and Z axis in this case).

This texture map gives a high value (positive, resp. negative) when the texture is oriented along Z (resp. Y).

By jointly thresholding the intensity and texture maps, robust markers can be obtained for the resin and respectively weft and binder yarns. A watershed algorithm is then used to grow these markers and classify the entire volume.

2 Results

The second part of this paper highlights a number of uses cases where the approaches of the first part have successfully been applied.

2.1 Mapping orientations in glass fiber composite at high resolution

The first case is a 50% glass fiber reinforced polymer based on a combination of semi crystalline Polyamide with partially aromatic copolyamide, shown in Figure 4. Data courtesy by Grivory GV-5H (EMS-GRIVORY):
The result of the local orientation computation is illustrated in Figure 5, using a cylinder oriented in the estimated major orientation for each block:
Figure 5: Slice through, and estimated local orientation using block-wise FFT analysis

The result of the Cylinder correlation and tracing approach applied on the same dataset is shown in Figure 6. Each individual fiber has been reconstructed, and is displayed with a directionally encoded coloring. The different oriented layers can clearly be identified. Local distribution of fibre orientations can be derived from this detection, and used to extract local maps of the major orientation, or tensors describing the local dispersion of the orientations.

Figure 6: Individual fiber extraction. Fibers are colorized by their local orientation. Statistics such as a local orientation field can be extracted and probed.
2.2 Defect detection in CFRP at high resolution

In the following use case a CFRP bike frame has been investigated at 0.27µm voxel resolution (data courtesy of Rigaku Corporation). The information about each individual fiber from the cylinder correlation has been used to better detect and understand the defects. As one can see in the lower left image of **Figure 7**, the actual defect is much bigger than the obvious void within the resin. The fiber density has been used to identify the true size of the defect. In the lower right image fibers are highlighted according to their contribution and connection to void or defects. Fibers colored in red are more heavily involved in defects than fibers colored in green or blue. Fibers not contributing at all to defects have been made fully transparent. With this approach defects can be detected without any thresholding. The upper left image of **Figure 7** shows the raw dataset with volume rendering. The coloring of the upper right image of **Figure 7** shows the different orientation layers:

![Figure 7 Different visual representations of fibers. Upper row visualize fiber layers. Lower row show color coded fiber to defect contribution from blue (low) over green (medium) to red (high) contribution.](image)

2.3 Classification of yarns in woven composite at low resolution

The final use case illustrates the yarn segmentation approach. The data shows woven glass-fibre reinforced composite where the images show the fibrous texture rather than individually resolved fibres, as shown in **Figure 8**. The yarns are well aligned along the cube axes (y and z in this case).
After applying the morphological operations together with some denoising the orientation maps can be combined (Figure 9):

The final result shown in Figure 10 is obtained after thresholding the orientation and intensity maps and applying watershed segmentation:
A more detailed description of the above dataset is available in [4]

2 Conclusion

Different methods provided by Avizo for analyzing fibrous materials at either low, medium or high magnification have been presented. The described methods have been illustrated in different use cases. The presented methods should cover most of current material research topics in the field of fiber characterisation.

References