Fiber Assignment by Continuous Tracking for Parametric Fiber Reinforced Polymer Reconstruction

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ABSTRACT

In this work, we propose an extension of the recently presented Parametric Reconstruction (PARE) algorithm[1] towards the direct reconstruction of straight and curved fibers in glass fiber-refinforced polymer (GFRP) samples. The fibers are traced based on the Fiber Assignment by Continuous Tracking by introducing a piece-wise linear model. We show how the algorithm can estimate fiber parameters from the X-ray projection data and give an outlook on its application in our existing fiber estimation framework.

Keywords: μCT, Materials Science, Glass Fiber reinforced Polymer, GFRP, Tomography, Modeling of Microstructures

1. INTRODUCTION

Glass fiber-reinforced polymers (GFRP) are versatile components which are used in a multitude of manufactured products. Analysis of the structure of GFRP enables researchers to develop new ways of implementing the GFRP technology into mechanical components. To that end, a good knowledge of the spatial statistics of the fibers in the polymer is important to determine the mechanical properties of the GFRP.

X-ray micro-computed tomography (μCT) is an imaging method that allows to study the internal structure of those composites in a nondestructive way, at high spatial resolution. The reconstructed images are processed to gain insight in the aforementioned spatial statistics, i.e. the direction distribution of the fibers contained in the material sample.[2] The reconstructed image quality, and with that the quality of the fiber parameter statistics, depends on several parameters, such as the number of projections and the acquisition geometry. Furthermore, traditional image processing methods to extract fiber statistics suffer from reconstruction artifacts and don't allow using the measured projection data directly to improve the estimates of the statistics. Therefore approaches to improve upon the quality of parameter estimation are an active research topic.[3,4]

We recently developed the Parametric Reconstruction (PARE) algorithm,[1] in which the GFRP sample is parametrized as a set of straight fibers embedded in a constant matrix. The algorithm was shown to perform well in estimating fiber parameters back from simulated data, even when only a limited number of 40 to 100 projections is available. Using a numerical optimization method in projection space, PARE is able to argely avoid error propagation. The assumption of a perfectly straight fiber, however, is often too strict, as fibers with high aspect ratios will usually bend in the volume. This requires the parametric model to be adjusted to allow for curvature.

In this paper, we introduce a tracing algorithm based on Fiber Assignment by Continuous Tracking (FACT)[5] to facilitate curved fiber estiamtion. FACAT is a commonly used tractography algorithm in diffusion-MRI. It traces a fiber according to the main eigenvector of a 3×3 structure tensor and enables the trace to follow any curvature. In the following, we shortly introduce on the existing parameter estimation algorithm, PARE,[1] followed by an explanation of the proposed tracing algorithm. We then show tracing results and conclude with an outlook on what we aim to achieve in future work.

2. METHODS

As the proposed method is heavily based on our existing method, PARE, we first explain the method in short, then elaborating on the addition of the proposed tracing.

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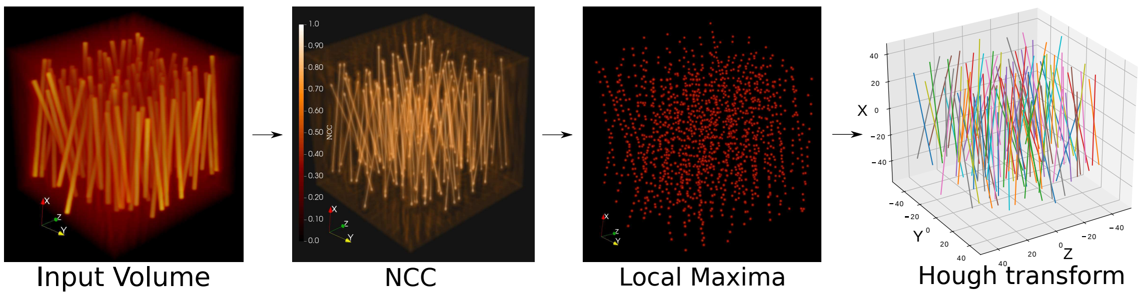


Figure 1: Flow diagram of the fiber detection step in PARE.

2.1 Parametric Reconstruction

PARE utilizes cylinders to model straight fibers in a resin matrix of the GFRP. The volume is first reconstructed from measured radiographs using the Simultaneous Iterative Reconstruction Technique (SIRT)[6] and then analyzed using a chain of image processing steps. First, the normalized cross correlation (NCC) is computed, after which the NCC's local maxima are extracted, and finally the center line of the cylinder is computed using the Hough transform.[7] The result of these processing steps is shown in Fig. 1.

The length of the fiber is determined by the Euclidean distance of the local maxima furthest from the center of points comprising the line.[1] The intermediate cylinder estimates resulting from the Hough transform are used to generate a voxel model of the fiber and the surrounding polymer matrix and the resulting volume is forward projected and compared to the measured radiographs. The vector, $\hat{\boldsymbol{\xi}}$, represents the fiber parameters that minimize the difference between simulated and measured radiographs. A fiber parameter vector $\boldsymbol{\xi} = (\boldsymbol{p}_x, \boldsymbol{p}_y, \boldsymbol{p}_z, \boldsymbol{a}_\theta,\ \boldsymbol{a}_\phi, \boldsymbol{l})$ is composed of $\boldsymbol{p}_x, \boldsymbol{p}_y, \boldsymbol{p}_z$ the components for centroid position coordinates , $\boldsymbol{a}_\theta, \boldsymbol{a}_\phi$ the spherical coordinates of the direction unit vector and $\boldsymbol{l}$ the fiber length for all N detected and estimated fibers. The radius of the fibers is assumed to be known. The minimization problem can be defined using these vectors as

$$\hat{\boldsymbol{\xi}} = \arg\min_{\boldsymbol{\xi}} ||\boldsymbol{W}\boldsymbol{x}(\boldsymbol{\xi}) - \boldsymbol{p}||^2, \tag{1}$$

Here $\boldsymbol{W}$ is the projection matrix describing the forward projection with a fixed geometry and $\boldsymbol{p}$ is the measured projection data.

2.2 Fiber tracing

While PARE performed well on simulated data, its application to real GFRP datasets revealed that several parts of the algorithm could be improved. One of these is the use of the Hough transform, as it only supports the detection of straight fibers. Another concern is the fact that the Hough transform can not differentiate between several shorter line segments and a single continuous one. This means that volumes containing pairs of fibers that are positioned in the shape of, e.g. a 'T', would possibly be split into three individual fibers, instead of detecting two. Therefore we replaced the Hough transform with our proposed tracing algorithm.

As an initial step of said algorithm we compute the local direction vectors of the reconstructed volume using its Hessian, as described by Wirjadi et al.[8] These vectors will serve the same purpose as the diffusion ellipsoid's direction axes in FACT.[5] We extract the centers of the fibers in the reconstructed volume using the NCC. From that, we derive the morphological skeleton of a thresholded NCC. All skeleton voxels are then subsampled by a factor of three in each dimension. On these subvoxels we locally perform another NCC. The subvoxel with the highest response becomes the refined voxel position of the point. These refined points are used to seed the tracing as follows:

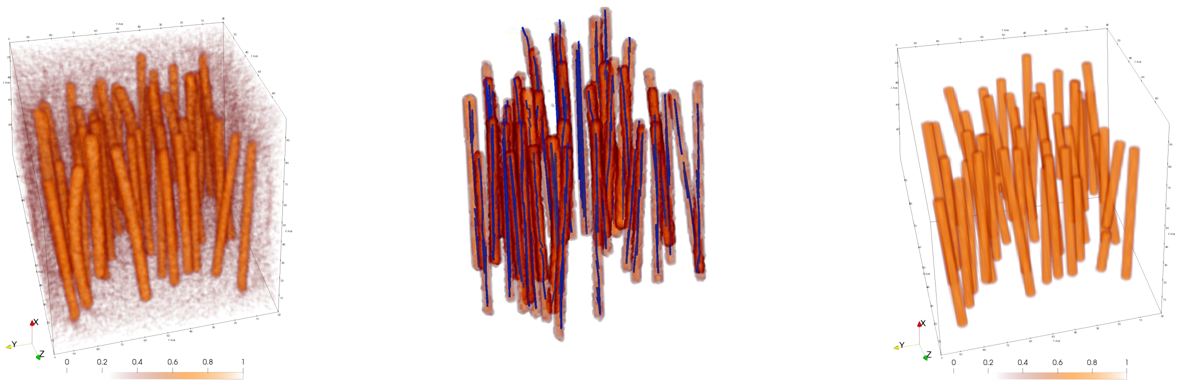
1. If there are seed points left, randomly select one of them, otherwise stop iterating;
2. A line segment with length $3r_\mathrm{f}$ is centered around the point. Its direction is chosen from the local direction vector field at that point, linearly interpolated. We then perform a cylinder fit using the mean squared error as a measure, similar to the cross correlation described by Rigort et al.[9]

3. Find the closest other seed point to the end point of the line segment.
4. This point will be the next point in the tracing if the two consecutive line segments meet the following criteria
   (a) The angle between the direction vectors of the two line segments is $< \theta_1$
   (b) The distance of the two closest points on the line segments is $< r_f$
   (c) The angle between the current line segment's direction vector and the connection line through the two closest points is $< \theta_2$.

   Here, r_f is the radius of the fibers and the angles $\theta_1 = 10°$, and $\theta_2 = 20°$.
5. If the conditions are met, remove all seed points from the list that would be located inside a cylinder with the line segment as its central axis and radius r_f. Then go to step 2. If the condition is not met, go to step 6;
6. Start the tracing from the same initial point chosen in step 1, but in the opposite direction, as it is done by Teßmann et al.[10] Flip all vectors in the tracing in the same way; If this is the second time going through this step, go to step 1;

The above loop stops, once the tracings in both directions have finished. The algorithm then returns a list of points that describe the trace of one fiber, as visualized in Fig. 3. We then compute a linear least square fit to obtain the line equation for the cylinder's central axis and use the extrema in the list (the end points of the line segments) to compute the length of the cylinder.

Once all the seedpoints have either been used for tracing or removed by step 5, we do a final clustering, where fiber traces that are intersecting or touching are combined into one fiber segment. This step uses the same criteria as in 4, but on the larger segments. The merging of the fibers is repeated until no more touching fiber segments are found. The result of the complete algorithm is a list of cylinders that describe the fibers in the volume. This is not accounting for the curvature in the fibers, though, as the optimization still assumes a straight cylindrical model.



(a) Reconstruction of the used phantom with added Poisson noise. For better visibility, some of the grayvalues are set to be partially transparent.

(b) Trace lines after processing the reconstruction from Fig. 2a using the proposed algorithm.

(c) Fiber volume without matrix rendered from the output of PARE after being applied to the reconstruction shown in Fig. 2a.

Figure 2: Result of fiber parameter estimation using the proposed tracing agorithm.

3. EXPERIMENTS

To test the tracing algorithm, we generated a phantom with 9 curved and 36 straight fibers. The curvature was modeled as a parabola in 3d space, generated by fitting a parabola to the two end points and a displaced center

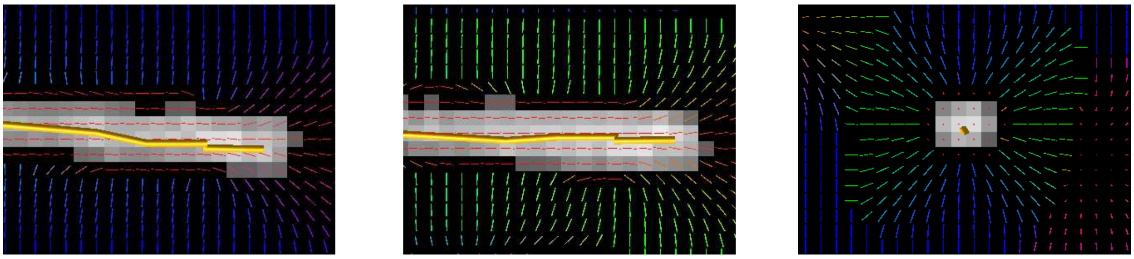


Figure 3: Slices through the vector field and zoomed in on the end of one fiber. In light gray the fiber voxels are shown, superimposed on that is the vector field. The color of the vectors corresponds to their x, y, z components encoded as RGB, respectively. Overlaid in yellow is the trace line rendered as a tube.

point of the central line segment of a cylinder. The straight fibers were modeled as outline in the experiments section of our work about PARE.[1] The phantom was simulated to have a resolution of 2.8µm isotropic voxel size and the fibers have a constant diameter of 5 voxels or 14µm. The radiographs were simulated using the ASTRA toolbox[11] and had Poisson distributed noise added to them, using 10000 photons as the unattenuated intensity for each detector pixel and the λ parameter as the measured intensity in the radiograph. We generated 100 projections with equidistantly spaced angles from 0 to 360°. We used the same cone beam geometry, as we used for our earlier experiments on PARE.[1] Those projections were then reconstructed using SIRT, before passing the data to the tracing algorithm.

4. RESULTS

We have tested the tracing algorithm on a simulated phantom containing 45 straight and curved fibers. The SIRT reconstructions of the phantom and the reconstructed fibers are shown in Fig. 2a. In Fig. 2c the result of the linear least square fitted fibers is shown. The estimated fibers are close to those present in the volume, with some being shorter than their counterparts in the reconstruction and one fiber being split in two. The latter is most likely a result of one small section of the fiber being removed for being too short too early, eliminating the connection between the two sections. A close up view of the used vector field and the tracing of one fiber following the vectors can be seen in Fig. 3. The length estimation of the fibers, of course, is limited to fibers that do not intersect the volume borders. The length of the fibers, which are not completely encased, cannot be estimated, as information is missing.

5. CONCLUSIONS AND FUTURE WORK

We showed a fiber tracing algorithm, based on FACT, that accomodates fiber curvature and estimates fiber parameters from simulated GFRP data. The algorithm can extract straight and slightly curved fibers from the volume. As a next step we aim to incorporate the curvature into the estimation model to get more accurate fiber estimates.

ACKNOWLEDGMENTS

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