Estimating 3D Fibre Orientation in Volume Images

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Background

- The fibre orientation is an important structural property of fibre-based materials. It determines for example mechanical properties and the tendency of the paper to curl and twist.
- The fibre orientation is not measured online in paper manufacturing. Instead, indirect (light spreading) and direct two-dimensional (sheet splitting) measurement methods are used.

Method

1. Calculate a local structure tensor in the neighbourhood of each voxel using six phase-invariant quadrature filters.
2. Smooth the tensor field component wise to obtain better estimates and remove local errors. The fibre orientation is assumed to vary slower than the small-scale variations and noise that are suppressed.
3. Calculate the eigenvalues and eigenvectors of each tensor.
4. Sort the eigenvalues by size (descending order).
5. The fibre orientation is estimated as the orientation of the eigenvector with the slowest signal variation (with the smallest eigenvalue).
6. A corresponding certainty measurement, c_2, is calculated for each orientation estimate using the eigenvalues.

Features of the proposed method

- ✓ The method can be used directly in grayscale (intensity) images without initial segmentation of fibre and void.
- ✓ All orientations in 3D can be estimated with good accuracy using only six phase-invariant quadrature filters.
- ✓ A certainty measurement is available for each orientation estimate and weighting the orientation estimates by the certainty estimates improves the results.
- ✓ The orientation estimates can be averaged for local image regions (like the layers of a sheet) or the whole sample.
- ✓ The orientation anisotropy can be calculated both for local image regions and the whole sample.

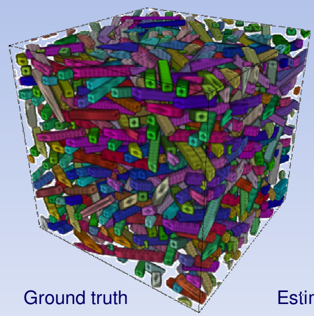
Try it yourself

Tear different paper materials parallel to the edges of the sheet. In one direction it will be harder to get a clean cut. This is due to the fibre orientation anisotropy. It is easier to tear in the machine direction.

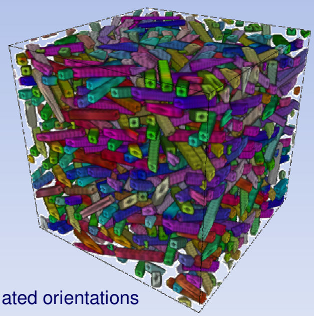
Experiments and results

Synthetic data

- Volume images with straight tubular fibres of known orientations were generated.
- The estimation error, E_n, was approximately 3.8 degrees in all test images. By weighting the orientation estimates with the certainty value c_2 the error could be reduced to approximately 3.0 degrees.
- Anisotropy estimates are shown in Table 1 and volume renderings of the ground truth and estimated orientations for a part of sample V_1 are shown below.



Ground truth



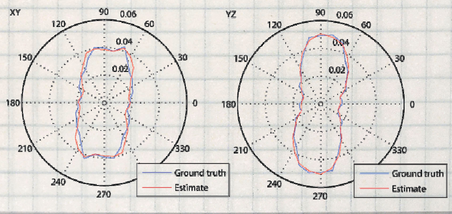
Estimated orientations

$$c_2 = \frac{\lambda_2 - \lambda_3}{\lambda_1} \qquad A = \sum_I w_I \mathbf{e_3} \mathbf{e_3}^T$$

$$E_n = \frac{\sum_I w_I c_2 \arccos(|\mathbf{v_{gt}} \cdot \mathbf{e_3}|)}{\sum_I w_I c_2}$$

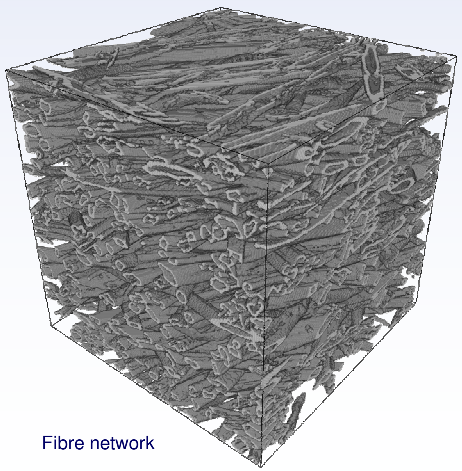
Table 1. Anisotropy estimation.

	Ground truth		Estimated anisotropy	
	r_1/r_2	r_2/r_3	r_1/r_2	r_2/r_3
V_1	1.0329	2.2618	1.0149	2.2475
V_2	1.6502	2.3094	1.5572	2.3444
V_3	1.0609	1.0159	1.0475	1.0135
V_4	1.8047	1.6483	1.8370	1.6974
V_5	2.2747	1.0580	2.1827	1.0601
V_6	3.6232	1.0466	3.4115	1.0535

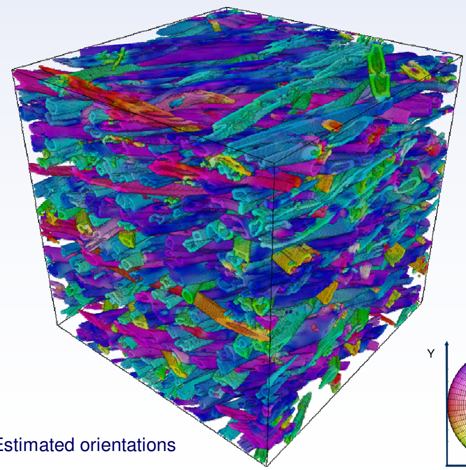


Real data

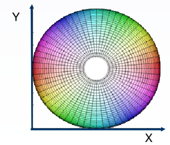
- The method was applied to X-ray microtomography volume images of fibre reinforced composites and paper with good results.



Fibre network



Estimated orientations



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