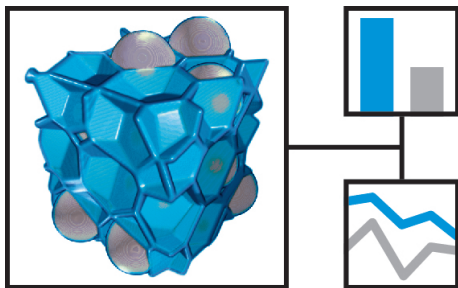


Quantitative analysis of non-woven microstructures based on microscopic images



MAVI fiber 2d

User manual

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Contents

1	Introduction	1
1.1	MAVfiber2d's purpose and scope	1
1.2	MAVfiber2d versions and licensing models	1
1.3	Framework	2
1.4	Central Workspace	3
1.5	View Navigator and Control	3
1.6	Fundamental concepts	5
1.7	Images in MAVfiber2d	5
1.7.1	Image attributes	5
1.7.2	Image types	6
1.8	MAVfiber2d's coordinate system	6
2	Mathematical background	6
2.1	Non-linear Diffusion filtering	7
2.2	Toggle mapping	7
2.3	Local fiber thickness and orientation by moments of inertia	8
3	Tutorial	9
4	Reference manual	11
4.1	Change Settings	11
4.2	Load Image	11

Contents

4.3	Set Meta Data	11
4.4	Color Conversion	11
4.5	Crop	11
4.6	Preprocess	13
4.7	Analyze	13
4.7.1	Area or length weighted distributions	13
4.7.2	Fiber thickness analysis	13
4.7.3	Fiber orientation analysis	15
4.8	Colorize	15
	Index	17

1 Introduction

1.1 MAVIfiber2d's purpose and scope

MAVIfiber2d is a software for processing and analysis of microscopic images as produced e.g. by scanning electron microscopy (SEM). It is a laboratory tool intended to complement any device for 2D image acquisition.

MAVIfiber2d is particularly suited for quantitative analysis of non-woven materials microstructures.

MAVIfiber2d characterizes the complex geometry of these microscopically heterogeneous structures quantitatively: It determines the thickness and orientation distributions, as well as the cloudiness of the imaged samples.

MAVIfiber2d's analysis core is complemented by fast visual control.

This handbook intends to

- give the non-expert user a starting point to get into **MAVIfiber2d** and
- give the experienced user detailed information on the algorithms used.

1.2 MAVIfiber2d versions and licensing models

Demo version A demo version of **MAVIfiber2d** is available via www.mavi-3d.de. The demo version is fully functional except saving and exporting images or analysis data being disabled. The image size you can work with is restricted to 256^2 pixels, however.

Full license **MAVIfiber2d**'s current licensing model is a single user floating license controlled by a USB dongle. To run a fully licensed **MAVIfiber2d**, you need this special dongle, the matching license file, and the **MAVIfiber2d** installer. Please contact mavi@itwm.fraunhofer.de to get information on how to obtain them.

MAVIfiber2d basic edition measures fiber thicknesses only.

MAVIfiber2d standard edition measures fiber thicknesses and fiber orientations.

MAVIfiber2d premium edition measures fiber thicknesses, fiber orientations, and cloudiness.

1.3 Framework

MAVifiber2d has a multi document interface, which allows for processing of multiple documents at the same time. The application main window provides menus, a toolbar, several docking windows and a statusbar surrounding a large central workspace, see Figure 1.

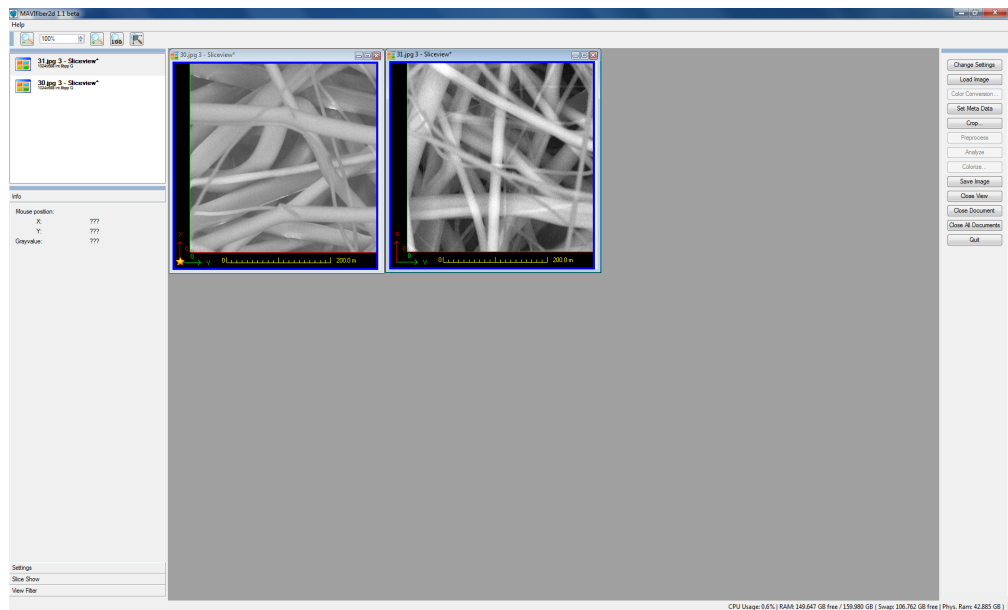


Figure 1: **MAVifiber2d**'s main window.

The toolbar on the right provides **MAVifiber2d**'s functionality, in the order of a typical analysis:

- (1) Change Settings
- (2) Load Image
- (3) Color Conversion
- (4) Set Meta Data
- (5) Crop
- (6) Preprocess
- (7) Analyze
- (8) Colorize
- (9) Save Image
- (10) Close View
- (11) Close Document
- (12) Close All Documents
- (13) Quit

A menu entry is active (i.e. can be chosen by clicking on it) only if the corresponding function can be applied to the selected image (that is, if the







image is of a valid gray value type).

The toolbar  offers control functionality for the current view window.

1.4 Central Workspace

The central workspace contains all view windows available in the application. Each view is associated with a specific document and displays its content. The foremost view of the workspace is assigned to the active document. All operations will be applied to this document. Activate a window by clicking on it or its symbol in the view navigator window.

Navigation in the view navigator window by cursor is not possible. Under Windows operating systems this can however easily be done using Ctrl and Tab keys.

The titlebar of a view window consists of the view icon on the left hand side, which provides a window menu when clicked, the name of the view window, and three control buttons on the right hand side. The window menu allows you to close, resize and move the window. The  and  buttons minimize and maximize the window, respectively, and the  button closes it. If the last view window of a document is closed, the document is closed too. When a window is maximized, the view icons and the control buttons are displayed on the left and right hand side of the menu bar . In this case, the  button turns into a  button which restores the original size of the window when clicked.

1.5 View Navigator and Control

At startup the **MAVifiber2d** framework has two windows docked on the left border of the workspace, a view navigator (Figure 2(b)) on the top and a view control window below. The windows can be moved around by using the mouse on the docking edge (Figure 2(a)). If the window is not docked to a side of the workspace, then it becomes a floating standalone window. By clicking on a docking window or on the menu bar with the right mouse button you obtain a control list of all available docking windows which allows to activate and deactivate them.

The view navigator window shows a list of all available views. A list entry consists of the view icon, the view label and an additional description provided by the view. The active entry is marked by a different background color. When an entry is selected, the assigned view becomes active and is moved to the foreground of the workspace.

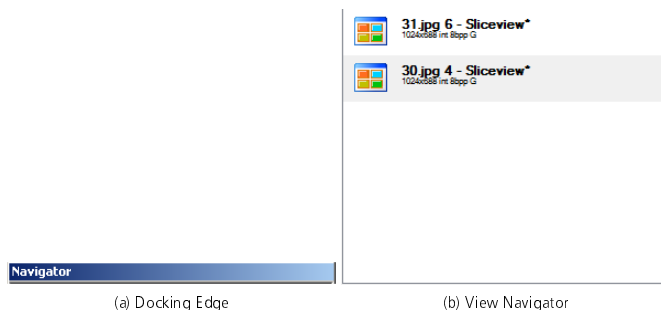




Figure 2: **MAVIfiber2d**'s framework: Docking Edge and View Navigator Window.

The toolbar  offers functionality to control or modify the view windows. You can zoom in to or out of the currently activated view by clicking on one of the  buttons.

The view control window contains several tabs containing further functions to control and modify the view windows. A tab can be activated simply by clicking on it. The Info tab contains the current mouse position within the image and the gray value of the corresponding pixel, see Figure 3(a). The Settings tab (Figure 3(b)) contains the functions

- Reset window:** undoes any translations, magnifications or changes of background color on the currently activated view window
- Set BG Color:** offers a choice of background colors via a color selection dialog
- Save current view:** saves the current view in the active view window including the view filter if applicable but not the zoom. Available file types are BMP, PNG and XPM. An additional dialog offers the possibility to decide whether a scale should be drawn.

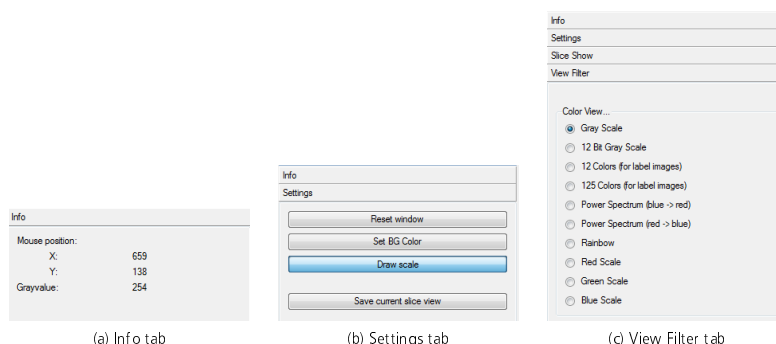


Figure 3: The tabs in the View Control Window.

1.6 Fundamental concepts

MAVIfiber2d analyzes fibers “segmentation free” in the following sense: Fibers are not separated (labelled). Instead, thickness and orientation are determined in each pixel in the fiber system. That is, the fiber thickness/orientation distribution in the “typical point in the fiber system” is measured. This results in an area weighted thickness or orientation distribution. Once the thickness is measured area weighted can be transformed in a length weighted distribution by simple reweighting. Details are explained in Section 4.7.1.

The fiber system to be analyzed is obtained by the pre-processing steps detailed in Sections 2.1 and 2.2.

1.7 Images in MAVIfiber2d

MAVIfiber2d is built on the idea of pixels being the vertices of a grid and holding information on the image content as gray values. More precisely, let $\mathbb{L} = (s_1, s_2)\mathbb{Z}^2$ be an orthogonal lattice with lattice spacings $s_1, s_2 > 0$.

MAVIfiber2d's analysis functions work for image data with different lattice spacings. However, the pre-processing is pixel based and thus does not correct for differing lattice spacings.

1.7.1 Image attributes

An image is not just described by its pixel's gray values. **MAVIfiber2d** stores the following image attributes in the image header:

Creator A string containing information about the image creator.

Description A string containing information about the content of the image.

History A string summarizing the transforms applied to the image.

Spacing A pair of floating point values describing the physical size of pixel spacings or edges in [m].

The image header entries will either be created when loading an image from a file containing the respective information or can be edited by the user via the **Set Meta Data** function. Before applying analysis functions, it should always be ensured that the image spacings are set correctly. If no spacing is set, the base unit for all measurements is [pixel].

1.7.2 Image types

MAVfiber2d deals with scalar images and COLOR images. For the latter, the RGB color space is the only choice.

image type	description	range
MONO	just 2 components – foreground and background	0 (background), 1 (foreground)
GRAY8	8 bit integer gray values	[0, 255]
GRAY16	16 bit integer gray values	[0, 65.535]
GRAY32	32 bit integer gray values	[0, 4.294.967.295]
GRAYF	floating point gray values (single IEEE754 precision)	approx. $[1.17e^{-38}, 3.40e^{+38}]$
COLOR	triple of 8 bit integer gray values	$[0, 255]^3$

Table 1: **MAVfiber2d**'s image types

1.8 MAVfiber2d's coordinate system

MAVfiber2d's x-axis is the vertical one, its y-axis the horizontal one. The origin (0,0) is interpreted to be the lower left corner of the rectangle representing the observation window.

When importing image data **MAVfiber2d** assumes the data to be X local if not explicitly stated otherwise by the original image format. That is, the data is read with the X coordinate running the fastest and the Y coordinate the slowest resulting in e. g. pixel (1, 0) being read before pixel (0, 1).

2 Mathematical background

This section summarizes the pre-processing as well as the local analysis methods for both thickness and orientation. The former follow [1], the latter [3]. The main pre-processing ingredients are a non-linear diffusion filter for smoothing and edge enhancement and a morphological toggle mapping for improved contrast. This combination turned out to be particularly suitable for SEM

images. The local thickness and orientation analysis exploits the idea to approximate a fiber locally in pixel x by the ellipse of inertia centered at x .

2.1 Non-linear Diffusion filtering

Diffusion filtering adaptively simplifies the image exploiting the heat conduction equation [10]. Its simplest case is just convolution with a Gaussian filter known to smooth and thus blur the edges of objects, too. Non-linear diffusion filtering [8, 5] enables preservation and even selective enhancement of edges:

Let the input image be denoted by $f : \Omega \mapsto \mathbb{R}$, $\Omega \subseteq \mathbb{R}^2$ and write K_σ for a Gaussian kernel of standard deviation σ . The filtered image u is derived by solving the non-linear isotropic heat conduction equation

$$\begin{aligned} \partial_t u &= \operatorname{div}(g(|\nabla u_\sigma|^2) \nabla u) \\ \partial_\nu u &= 0 \quad \text{for all } x \in \partial\Omega \\ u(\cdot, 0) &= f \end{aligned} \tag{1}$$

where $u_\sigma := K_\sigma * u$ and ν is the normed outer normal vector. The artificially introduced time $t > 0$ controls how strongly the image is smoothed. In **MAVfiber2d**, $t = 100$ is fixed. $\sigma = 1$?

As diffusivity, we use

$$g(s^2) := \frac{1}{1 + \frac{s^2}{\lambda^2}} \tag{2}$$

from [8]. The contrast parameter $\lambda > 0$ steers edge preservation: Edges with gradient norm $|\nabla u|$ significantly higher than λ are not only preserved but even enhanced. The effect of the choice of λ is shown in Figure 8.

2.2 Toggle mapping

In order to enhance the fiber edges further and to increase homogeneity within the fibers, the so called toggle mapping [9, 7] or morphological shock filter is applied. It toggles between erosion and dilation depending on which the original pixel value is closer to. Denote by $S \subset \mathbb{R}^3$ a structuring element and by ϵ_S and δ_S erosion and dilation w.r.t. S centered in the current pixel x . The toggle filter is then defined by

$$\sigma_S(f)(x) = \begin{cases} \epsilon_S(f)(x), & \text{if } f(x) - \epsilon_S(f)(x) < \delta_S(f)(x) - f(x) \\ \delta_S(f)(x), & \text{if } \delta_S(f)(x) - f(x) < f(x) - \epsilon_S(f)(x) \\ f(x), & \text{else} \end{cases} .$$

In **MAVfiber2d**, the structuring element is a square of side length three pixels.

2.3 Local fiber thickness and orientation by moments of inertia

For each pixel $x \in \mathbb{L}$, a quasi-distance is determined based on the gray value difference after iterative dilations and erosions with the chosen structuring element S . The quasi-distance is just the size of the structuring element yielding the largest difference. Write ϵ_S^m and δ_S^m for an m -fold erosion and dilation with structuring element S , respectively. For a given range $M \subset \mathbb{N}^+$ the classical quasi-distance according to [4] is defined as follows:

$$d_q(x, S) = \operatorname{argmax}_{m \in M} (\epsilon_S^m(x) - \epsilon_S^{m+1}(x), \delta_S^{m+1}(x) - \delta_S^m(x)) . \quad (3)$$

Here, a modified version is used. A threshold t controls, when a gray value difference is regarded as significant:

$$d_q^t(x, S) = \operatorname{argmax}_{m \in M, m \leq m_{\min}(t)} (\epsilon_S^m(x) - \epsilon_S^{m+1}(x), \delta_S^{m+1}(x) - \delta_S^m(x)) \quad (4)$$

with $m_{\min}(t) = \operatorname{argmin}_{m \in M} (\epsilon_S^{m+1}(x) - \epsilon_S^m(x) \geq t \vee \delta_S^m(x) - \delta_S^{m+1}(x) \geq t)$.

Now determine for each pixel $x \in I$ the quasi-distance based on line shaped structuring elements in the coordinate and the diagonal directions. That is, all directions given by the 8-neighborhood are considered. From the oriented quasi-distances $d_q : I \times N_8 \rightarrow \mathbb{R}^+$, the centered fiber edge points in those directions are deduced $e : I \times N_8 \rightarrow I$ with $e(x, v) = \frac{1}{2}(d_q(x, v) + d_q(x, -v))v$. Subsequently, the moments $m_1(x), m_2(x) \in \mathbb{R}$ and the main axis of inertia are calculated from the edge points in pixel x . The local fiber direction $\theta(x)$ is deduced from the main axis of inertia $\theta' \in [0, \pi)$:

$$\theta(x) = \frac{1}{2} \arctan \left(\sqrt[3]{\tan(2(\theta'(x) - i\frac{\pi}{4}))} \right) + i\frac{\pi}{4}, \quad (5)$$

with $i\frac{\pi}{4} \leq \theta'(x) < (i+1)\frac{\pi}{4}$, $i \in \mathbb{N}$.

The corrected moments of inertia then yield the fiber thickness T in pixel x :

$$T(x) = \sqrt{m_2(x)/g(\theta(x))} \quad (6)$$

with

$$g(\theta(x)) = \begin{cases} \frac{2 - \sqrt{3 \cos^2(4(\pi/2 - \theta(x))) - 1}}{\sin^2(4(\pi/2 - \theta(x)))} & , \text{ for } \sin^2(4(\pi/2 - \theta(x))) \neq 0 \\ \frac{3}{4} & , \text{ else} \end{cases}$$

For each pixel and each direction from the 8-neighborhood, the quasi-distance additionally yields the information whether it was reached by a dilation or an erosion. This information is used to classify the pixel as foreground (fiber system) or background (pore space). A pixel belongs to the foreground, if it is a

foreground pixel according to the quasi-distance in at least 6 out of the 8 considered directions.

Further details can be found in [2]. The thickness measurement has been validated by comparison with interactive measurements in [1], and based on synthetic SEM images in [6].

3 Tutorial

This section offers a step-by-step tutorial for the three analysis tasks solved by the premium edition of MAVIfiber2d.

Thickness and orientation analysis without crossing correction, steps illustrated in Figure 4:

- (1) Change Settings:
 - Preprocessing: PDE contrast parameter: 1
 - Edge strength: 1
 - Thickness weighting: area
 - Thickness histogram bin width: 1
- (2) Load Image: input the original image (a). It is a gray value image and no scale or other meta data are coded into the image. Thus Color Conversion and Crop can be omitted.
- (3) Set Meta Data
- (4) Preprocess (b)
- (5) Analyze: Crossing threshold: 255, Output: Estimated thickness image and estimated orientation image (c,d)

Note that with this choice of the crossing threshold, the fiber crossings are not removed. Decreasing the Crossing threshold value removes fiber crossings, see Figure 5.

Thickness and orientation analysis with crossing correction, results shown in Figure 5:

- (1) Change Settings: Preprocessing: PDE contrast parameter: 1, Analyse fibers: Crossing threshold: 100
- (2) Load Image: input the original image
- (3) Set Meta Data
- (4) Preprocess

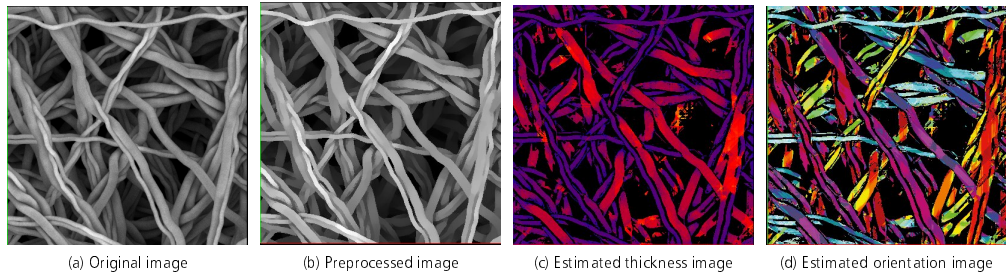


Figure 4: Processing steps for thickness and orientation analysis.

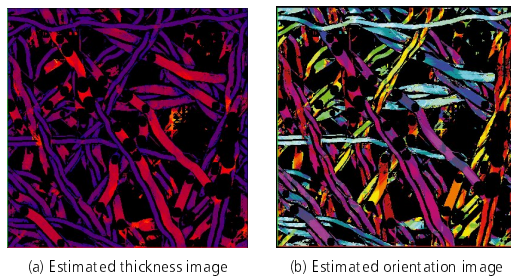


Figure 5: Thickness and orientation analysis results with crossing correction.

- (5) Analyze: Output: Estimated thickness image and estimated orientation image (a,b)

4 Reference manual

4.1 Change Settings

Set the preprocessing and analysis parameters. Should not be changed while analyzing a set of images for which analysis results should be comparable.

- Contrast for diffusion filtering, used by Preprocess
- Edge strength for fiber analysis, used by Analyze
- Crossing threshold, used by Analyze
- Weighting strategy, used by Analyze
- Histogram bin width for the thickness, used by Analyze
- Names for output thickness and orientation histograms, used by Analyze
- Color maps for thickness and orientation maps produced by Analyze

The histogram bin width has to be at least as large as the pixel spacing to be specified via Set Meta Data. Note that setting no color map, e. g. leaving the corresponding entry field empty results in gray value images.

4.2 Load Image

Choose the input image. COLOR images have to be converted into a GRAY8 image.

4.3 Set Meta Data

Set the meta data. In particular, set the pixel spacing. If the spacing is not given, all analysis results will be based on the unit [pixel].

Technically, this means, that the spacings are set to 1 m. Note that the histogram bin width for the thickness analysis then has to be at least 1 m, too.

4.4 Color Conversion

Offers a variety of choices for converting COLOR images in RGB, HSV or HSL color spaces into a GRAY8 image.

4.5 Crop

MAVIfiber2d assumes the complete window to be filled with the fiber structure to be analyzed. Thus scales, legends or other meta data have to be

Crop

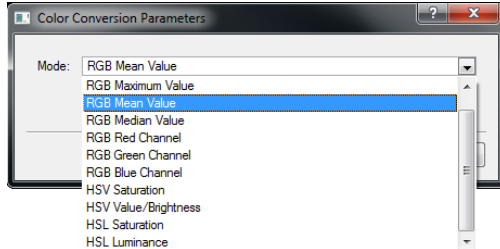


Figure 6: Color Conversion dialog box.

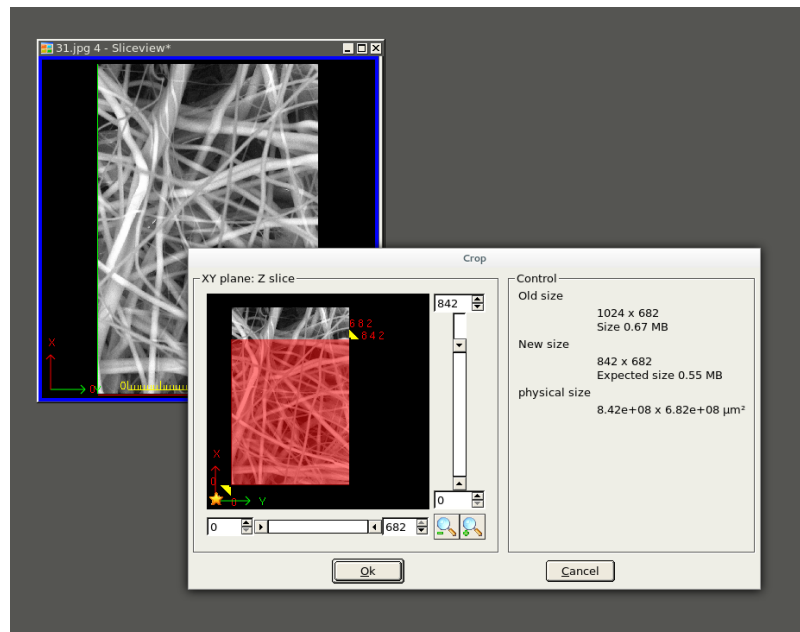


Figure 7: Interactive cropping dialog window.

cropped. This can be achieved by either pulling the sliders or entering the desired new dimensions. The crop result is shown as red overlay.

4.6 Preprocess

This function applies the diffusion and the toggle filtering as described in Sections 2.1 and 2.2 above. The result shows the fibers that will be analyzed. Gray values within fibers should be homogeneous, relevant edges should be preserved.

If the Contrast parameter (Equation (2)) is chosen too high it will detect artificial fibers in the background and join fibers. If it is too low, fibers will break. In cases where λ can not be chosen perfectly, a compromise has to be found depending on the aim of the analysis:

For thickness analysis: rather preserve fiber parts of real thickness, losing some fraction of fiber is OK.

For orientation analysis: preserve fiber cores, losing fiber thickness is OK.

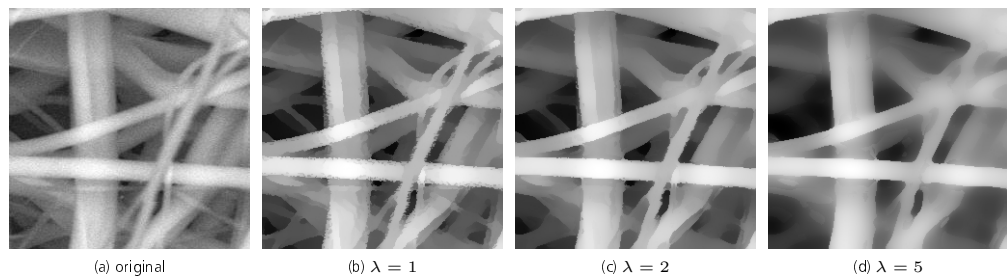


Figure 8: Effect of the choice of the contrast parameter λ from Equation (2).

4.7 Analyze

4.7.1 Area or length weighted distributions

The thickness analysis yields a local thickness in every pixel in the foreground or the fiber system, respectively. Collecting these informations from every pixel with equal weights, results in an area weighted distribution. The length-weighted thickness distribution is achieved by simply weighting the thickness value $T(x)$ in pixel x by $1/T$.

Analogously, a length weighted orientation distribution can be deduced from the thickness map and the area weighted orientation distribution.

4.7.2 Fiber thickness analysis

The theoretical background is given in Section 2.3 above. The threshold t from Equation (4) controlling the quasi-distance is set by the parameter Edge strength. Discretization effects start to kick in at thicknesses of 6-7 pixels.

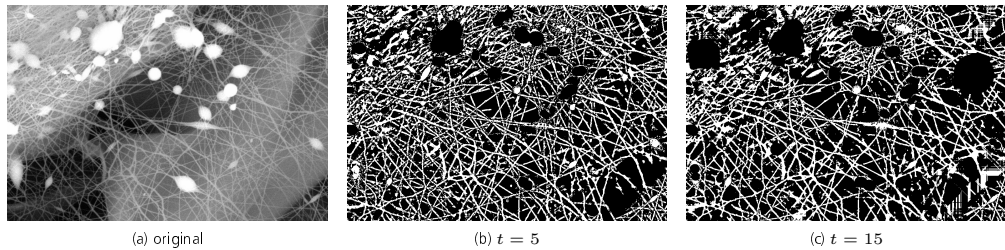


Figure 9: Effect of the choice of the edge strength parameter t from Equation (4).

Crossing areas can bias the measured thickness distribution towards higher values. Thus, thick areas can be removed from the fiber system using the Crossing threshold $t_c \in [0, 255]$. Areas thicker than t_c are regarded as crossings and therefore removed. More precisely, let f denote the binary image with the fiber system as foreground and $EDT(f, x)$ the Euclidean distance to the nearest background pixel in f for foreground pixel x . If $EDT(f, x) > t_c/255 \max_{y \in f} EDT(f, y)$ then the circle with radius $EDT(f, x)$ centered in x is set to background.

Output The thickness analysis data can be exported as csv file.

A thickness map image can be saved either as GRAYF or COLOR. In the former, the float pixel values are the measured fiber diameters. The latter is eligible only if a color map has been chosen before.

The MONO image of the measured fiber system is shown for a visual sanity check. Possible problems like breaking of fibers or erroneous removal of crossings can be detected that way.

The thickness distribution is exported as csv file. Its header contains the following information:

Thickness-Analysis

Acception-Threshold: number of directions

Crossing-Threshold: $t_c \in [0, 255]$ from Section 4.7.2

Contrast-Parameter: λ from Equation (2)

Resolution: pixel edge length

Histogram-Width: bin width for thickness histogram

Maximal-Probability-Range: lower and upper bound of histogram bin containing the maximum of the distribution

Modal-Range: lower and upper bound of histogram bin containing the medium of the distribution

Mean: mean and standard deviation of the distribution

Trimmed-Mean: mean and standard deviation of the distribution, ignoring values lower than the 5%-quantile and greater than 95%-quantile of the distribution

Subsequently, the results are given in five columns:

diameter-upper-limit: upper bound of bin

absolute-quantity: fiber area or length contributing to thickness values in that bin

relative-quantity: fraction of total fiber area or length contributing to thickness values in that bin

cumulative-distribution: normalized sum of current bin and all predecessors

density: histogram entry normalized such that integral yields 1.

4.7.3 Fiber orientation analysis

The theoretical background is given in Section 4.7.2 above. The local fiber orientation is the orientation of the main axis of inertia as given in Equation (5).

Output The orientation analysis data is written as a csv containing just two columns – the angle to the x -axis in degrees and the corresponding area or length, respectively, see 4.7.1.

Moreover, an orientation map is given, color coding the orientations according to the color map chosen in Change Settings. If no color map was chosen, the result is a gray value image of type GRAYF whose gray values for the fiber pixels are the measured angles to the x -axis in radians. Background pixels get a negative value.

4.8 Colorize

If thickness or orientation maps are shown as gray value images, then Colorize allows to choose a color scheme for them after Analyze.

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Index

coordinate system, 6

gray value
types, 6

history, 5

image, 5
attributes, 5
COLOR, 6
creator, 5
description, 5
GRAY16, 6
GRAY32, 6
GRAY8, 6
header, 5
MONO, 6
type, 6

interface, 2

lattice spacing, 5

main window, 2

pixel, 5
gray value, 6
pixel spacing, 5

spacing, 5