AI-based identification of binder and fibers in 3D images of nonwoven

Interpore 2019
Valencia, May 8th 2019

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Hans Hagen, TU Kaiserslautern
In everything that follows,

Our intention is to make the technologies available to you, the audience

- to speed up your modelling of processes and materials
- to help you design new materials and processes
- to understand the outcomes of real experiments

In the best sense of reproducible research

- By keeping software versions and input data with the results
- Including the post-processing options used

While making a living for ourselves

If you find you’d like to know more after this presentation, come to our booth in the exhibition
WHAT WOULD WE LIKE TO ACHIEVE?
WHY LABEL INDIVIDUAL OBJECTS IN SCANS?

- Obtain grammage total, per material or per class of objects
- Output of objects as triangulation (.stl), CAD (.dxf), etc.
- Find number of contact points per objects
- Determine shape & dimensions of individual objects
- Compute object orientation distributions
- Etc. etc.
HOW DO WE LABEL CT SCANS?

- **Now**: segment 3D scan; then label it using Artificial Intelligence
- **Soon**: label scan (gray values) directly with Artificial Intelligence
HOW DO WE DO IT?

- **Now**: segment 3D scan; then label it using Artificial Intelligence
- **Soon**: label scan (gray values) directly with Artificial Intelligence

- AI requires training data / ground truth
- Segmented training data can be created with GeoDict today
- Gray value images can be created with methods from Monday’s presentation by Andreas Weber
- Those will be used to train the next generation neural networks in GeoDict
GEODict® Module Overview
A rich source for AI training data
SEGMENTATION OF A SCAN

From stack of gray value slices

To 3-D empty / solid image
Training Data: Use GeoDict’s unique fiber modelling capabilities:

- Modeled 10 Digital siblings (512x512x256 Voxels) as training data
- Varied fiber curvature, orientation, length and diameter
- Corresponded to ~1 billion solid voxels as training data points
Training Data: Then make the models look like binarized scans!

- All fibers in the models get the same gray value, just as in the segmented 3D scans.
Solution: Use GeoDict’s unique material modelling capabilities

- modeled 18 Digital siblings (512x512x256 Voxels) as training data
- varied porosity, binder parameters as estimated for 4 different (Toray GDL) samples
- corresponds to ~800 million solid voxels as training data points
**ADDING BINDER: CONTACT ANGLE 0°**

<table>
<thead>
<tr>
<th>Material Information:</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID 00: Air [invis.]</td>
</tr>
<tr>
<td>ID 01: Solid</td>
</tr>
<tr>
<td>ID 02: Binder, Contact Angle = 00.0°</td>
</tr>
</tbody>
</table>

![Diagram showing geometric pattern with red circles and black outlines]
ADDING BINDER: CONTACT ANGLE 10°
ADDING BINDER: CONTACT ANGLE 20°
ADDING BINDER: CONTACT ANGLE 30°
ISOTROPIC BINDER (ANISOTROPY FACTOR 1)
Anisotropic Binder (Anisotropy Factor 2)
ANSOTROPIC BINDER (ANISOTROPY FACTOR 3)
ANSOTROPIC BINDER (ANISOTROPY FACTOR 4)
**Neural Network (N.N.) Training & Usage Phases**

**Training:**
- N.N. learns edge weights from input and output
  - **input:** Digital Twin data: binarized version
  - **output:** Digital Twin data: labeled binder and fibers version

**Usage:**
- N.N. predicts labeled output from input and edge weights
  - **input:** 3D scan data: binarized
  - **output:** 3D scan data: labeled binder and fibers
TORAY PAPER TGP-H-030, 05% WET PROOFING
TORAY PAPER TGP-H-030, 10% WET PROOFING
TORAY PAPER TGP-H-030, 30% WET PROOFING
TORAY PAPER TGP-H-030, 50% WET PROOFING
BINDER IDENTIFICATION IN GAS DIFFUSION LAYER

Crossection in X-Direction:

Idea: Maybe create 3-D Digital Twins from 2-D images using AI in the future?
Direct comparison of ground truth Digital Twin to n.n. result

- Blue/gray/white: correctly identified fiber/binder/pore
- Total binder volume percentages: True 13.1%, predicted 11.5%

Red error: 8% of binder falsely classified as fiber

Yellow error: 3.6% of fibers falsely classified as binder
EXAMPLES OF COMPUTABLE QUANTITIES

- Grammage / volume percentages: total, binder only or fibers only
- Binder distribution in through-plane and in-plane directions
- Size-distribution of binder points
- Total number of binder blobs/components
- Output of binder or fibers as triangulation (.stl), CAD (.dxf), etc.
- Number of contact points per fiber
- Length of individual fibers
- Curvature distribution along individual fibers
In production, binder is applied to the top of the fiber and, then, intrudes into deeper layers.

After labelling binder voxels, we can compute the distribution of binder in through direction (right).
IN-PLANE MATERIAL DISTRIBUTION (MATDict)  GEODict

Both materials  Binder only  Fibers only

Scale: White: 0% volume fraction, Red: 7.2% volume fraction
Neural Network (N.N.) Training & Usage Phases

Training: N.N. learns edge weights from input and output
- input: Digital Twin data: binarized version
- output: Digital Twin data: labeled fibers version

Usage: N.N. predicts labeled output from input using weights
- input: 3D scan data: binarized
- output: 3D scan data: labeled fibers
CT SCAN OF FIBER REINFORCED COMPOSITE

Input: segmented µCT scan

Output: labeled fibers
CT SCAN OF NONWOVEN

Input: segmented µCT-Scan

Output: labeled fibers

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More Examples of Computable Quantities:

- Grammage / volume percentages: total, binder separate or fibers separate
- Binder distribution in through-plane and in-plane directions
- Size-distribution of binder points
- Total number of binder blobs/components
- Output of binder or fibers as triangulation (.stl), CAD (.dxf), etc.
- Number of contact points per fiber
- Length of individual fibers
- Curvature distribution along individual fibers
- Fiber orientation distribution
DETECTION OF 14995 BOND POINT

Input: labeled individual fibers
Output: labeled individual bonds
**Orientation Analysis**

Input: segmented CT scan

Output: orientation plots
Next three slides show manually created statistical (digital) twins

This is right now one of the bottle necks: n.n. need models close to the real data

One of the future works is to use generative adversary networks g.a.n. to create the models

Another future work is the creation of gray value images from models that include the typical artefacts like rings and noise to use as left side in the training and usage phases of FiberFind-AI.
CT-scan vs Digital Twin
generated in GeoDict

µCT-scan

Digital Twin
CT-scan vs Digital Twin
GENERATED IN GEODict

µCT-scan

Digital Twin
CT-scan vs Digital Twin
generated in GeoDict

μCT-scan

Digital Twin
## Analysis of 2 largest samples so far

- **Carded nonwoven samples**
- **Scanned and stitched together by Bruker microCT**
- **Analyzed by Math2Market on workstation with 1TB of memory**

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Resolution</th>
<th>Physical dimensions</th>
<th>Domain sizes in voxels</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.4µm</td>
<td>43.9 x 11.6 x 4.1 mm</td>
<td>18,310 x 4,816 x 1,704 = 150 Giga Vox</td>
</tr>
<tr>
<td>B</td>
<td>2.7µm</td>
<td>42.2 x 10.9 x 4.8 mm</td>
<td>15,619 x 4,032 x 1,796 = 113 Giga Vox</td>
</tr>
</tbody>
</table>
SAMPLE A – SEM VIEW

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Physical dimensions</th>
<th>Voxel dimensions</th>
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<tr>
<td>2.4µm</td>
<td>43.9 x 11.6 x 4.1 mm³</td>
<td>18,310 x 4,816 x 1,704</td>
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Density Map (Cloudiness)
**FIBER ORIENTATIONS – SAMPLE A**

<table>
<thead>
<tr>
<th>XY</th>
<th>XZ</th>
<th>YZ</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Graphs" /></td>
<td><img src="image2" alt="Graphs" /></td>
<td><img src="image3" alt="Graphs" /></td>
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<tr>
<td><img src="image4" alt="Graphs" /></td>
<td><img src="image5" alt="Graphs" /></td>
<td><img src="image6" alt="Graphs" /></td>
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<td><img src="image7" alt="Graphs" /></td>
<td><img src="image8" alt="Graphs" /></td>
<td><img src="image9" alt="Graphs" /></td>
</tr>
<tr>
<td><img src="image10" alt="Graphs" /></td>
<td><img src="image11" alt="Graphs" /></td>
<td><img src="image12" alt="Graphs" /></td>
</tr>
</tbody>
</table>

View of a section of the surface in the direction of the X axis.
**Fiber Orientations – Sample B**

<table>
<thead>
<tr>
<th>XY</th>
<th>XZ</th>
<th>YZ</th>
<th>View of a section of the surface in the direction of the X axis.</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="XY View" /></td>
<td><img src="image2.png" alt="XZ View" /></td>
<td><img src="image3.png" alt="YZ View" /></td>
<td><img src="image4.png" alt="Surface View" /></td>
</tr>
</tbody>
</table>

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FiberFind was used on the complete sample. Process is explained on a smaller cutout.

The artificial intelligence separates the solid voxels in the image data into individual fibers. Each fiber becomes an independent, modifiable object which can be treated independently.

Geometric information, such as fiber length, fiber segment orientation and fiber diameter, can be read directly from the object.
CONCLUSIONS

- Neural networks separate binder and fibers and identify individual fibers
  - based on learning shapes
- N.N. can label multi-material scans where materials can not be separated by thresholding or classical image processing
- N.N. require training data consisting of segmented and labeled scans
  - These can be created easily using material models from GeoDict
    - Models continuously improve, e.g. by improving the binder model
- We continue to improve the capabilities by
  - Increasing the fidelity
  - Speeding up the computations
  - Extending the capabilities to other types of materials
  - Placing the capability to train N.N.s in your hands