A non-parametric approach for 3D texture synthesis

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3D-Imaging of Materials and Systems – Hourtin, September 2010.
Introduction
What is it about?

We dispose of a 2D observation of a 3D structure...

Can we get a digital representation of the 3D structure?
Introduction
What is it about?

A **stereology** question:
Starting from **one single 2D observation**, i.e. the exemplar, is it possible to **synthesize a volumetric texture** that perceptually and statistically conforms to the original?

The answer is... **yes, provided that** : 
- **The exemplar texture is homogeneous**, 
- **The 3D texture anisotropies are known:** 
  - Isotropic textures 
  - Wire-like textures 
  - Lamellar textures (in sheets).
Introduction
Dense carbons and HRTEM

Dense pre-graphitic carbons used as reinforcements in composite materials for aerospace applications

- Anisotropic material composed of sheets (i.e. layers),
- The observation plane is orthogonal to the sheets,
- Orthotropy: any 2D section that is orthogonal to the sheets has similar statistical properties.

→ 2D/3D synthesis is possible
Introduction
The global project: building a virtual material

(1) Synthesis of 3D HRTEM-like images
(2) Simulated annealing under image field
(4) Comparison Exp/Sim
(3) HRTEM image simulation
(5) Calculation of properties

*PyroMaN – ANR Project*, 2010-2012
Pyrocarbon matrices at the nanometric scale: characterization, modeling, properties.
Outline

Introduction

About 2D example-based texture synthesis
  Parametric vs. Non Parametric Approaches
  Wei & Levoy’s algorithm
An original 2D/3D extension
Results
Conclusions & prospects
2D example-based texture synthesis

*Parametric vs. non-parametric*

- **Parametric approaches:**
  - **Principle:**
    - to learn some target statistics from the input sample
    - to synthesize a 2D texture that reproduces such statistics.
  - A classical method in 2D: Portilla & Simoncelli’s multiresolution analysis/synthesis algorithm.
    
  - A 2D/3D extension exists...
2D example-based texture synthesis

**Parametric vs. non-parametric**

- **Non Parametric approaches:**
  - **Principle:**
    Sample the exemplar to synthesize the output texture.
  - **Direct sampling of the exemplar**
  - **Sampling from the probability distribution of the exemplar**
    (known thanks to non parametric learning)
2D example-based texture synthesis

*Wei & Levoy’s algorithm*


- **Principles**
  - A non parametric method
  - **Locality and stationarity**: presumption of a stationary Markov random field (MRF)
  - **Pixel by pixel synthesis** in the lexicographic order using a causal neighborhood.
  - A multi resolution version
2D example-based texture synthesis

*Wei & Levoy’s algorithm*

- **Algorithm description**

  **Input:** the exemplar image
  **Output:** the synthetic image

  **Begin**

  Random initialisation of the output
  For each output pixel in a lexicographic order
    Extract the neighbourhood of the current pixel
    Search the most similar input neighbourhood
    Update the output with the value of the input pixel
  End for

  **End**
2D example-based texture synthesis

*Wei & Levoy’s algorithm*

- Choosing the neighbourhood system
  - Causal neighbourhood ⇔ causal scan
  - Neighbourhood size:
    - Must be greater than the largest texture patterns.
    - Directly affects the computational efficiency.
  - Multi resolution neighbourhood:
    - Causal in the current level $L$
    - Non causal in the upper level $L+1$ (already synthesized)
2D example-based texture synthesis

*Wei & Levoy’s algorithm*

- **Acceleration by TSVQ** (Tree Structure Vector Quantization)
  - Learning before synthesis:
    - Use of a recursive point partitioning algorithm
    - Dynamic generation of a binary search tree
  - Efficient ‘nearest point’ queries by searching the binary tree

![Diagram showing comparison between full search and TSVQ for nearest point queries.](image-url)
2D example-based texture synthesis

*Wei & Levoy’s algorithm*

- **Acceleration by TSVQ** (Tree Structure Vector Quantization)

  **Input**: the exemplar image  
  **Output**: the synthetic image

  **Begin**
  - TSVQ learning from the input image
  - Random initialisation of the output image
  - For each output pixel in a lexicographic order
    - Extraction of the neighbourhood of the current pixel
    - TSVQ-based search of the most similar input neighbourhood
    - Update of the output with the value of the input pixel
  **End for**

  **End**
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About 2D example-based texture synthesis
**An original 2D/3D extension**
*Using the orthotropy assumption*
The 2D/3D synthesis algorithm
Dealing with neighborhoods

Results
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An original 2D/3D extension

*Using the orthotropy assumption*

- The property of orthotropy
  Any 2D view orthogonal to the sheets has the same statistical properties (hence visual appearance)
  ⇔ Image spatial statistics does not depend on $\theta$.

- 2D/3D extension of Wei & Levoy’s algorithm
  The volumetric texture is synthesized one voxel at a time by maintaining 2D coherence with nearby pixels within two orthogonal views ($\theta=0$ and $\theta=\pi/2$).
A new 2D/3D extension

The 2D/3D synthesis algorithm

- Algorithm description

```
Begin
    TSVQ learning from the input image
    Random initialisation of the output block
    For every slice of the block
        For each pixel in the lexicographic order
            Extraction of 2 neighbourhoods (front and side view)
            TSVQ-based search of 2 input pixels
            Update of the output with a mix of the input pixels
    End for
End for
End
```

Sample texture → Random 3D block → Front and right views → Exit 3D block
An original 2D/3D extension

*Dealing with neighborhoods*

- **Extracting two neighborhoods**
  For each voxel, two 2D *multi-resolution* neighborhoods are extracted: one for the front view, another for the side view.

- **Double TSVQ-based search**
  One search for each view
  → two values found.
An original 2D/3D extension

*Dealing with neighborhoods*

- Combining TSVQ search results
  
The two values are combined using the following rule:

\[
val = \frac{\alpha_f \cdot val_f + \alpha_s \cdot val_s}{\alpha_f + \alpha_s}
\]

where \( \frac{1}{\alpha_{f,s}} = [\min_{w \in W_{\text{input}}} (dist(w_f,s, w))]^\beta \)

According to Kopf et al. (2007):
- this solution minimizes an energy function (dissimilarity between output and input).
- Optimal value \( \beta = 1.2 \)

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Results

[128 x 128] \xrightarrow{\text{neighborhood} = 5, \text{iterations} = 2, \text{stages} = 5} [256 x 256 x 256]

Weak anisotropy
Original sample
2D/3D Synthesis

Results

[128 x 128] → neighborhood = 5 → stages = 3 → iterations = 3 → [256 x 256 x 256]

Strong anisotropy
Original sample
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Conclusions

- From a perceptual point of view: promising results which confirm the relevance of the approach.
- The algorithm tends to produce textures that are more regular than those observed in the input image.
- Mixed performances
  In spite of TSVQ acceleration (complexity $N \log N$), the approach is still computationally demanding.
Prospects

- Quantify the quality of the synthesized images using...
  - grey level & orientation statistics
  - structural features (fringe length, tortuosity,...)

- Develop new non parametric strategies...
  - Non causal non lexicographic scan of the output image
  - Sampling from neighborhood probability distribution
  - Parallel strategies

- Use synthesized blocks for atomistic simulations (in progress...)