Structure, key points

1. Introduction

* The limitation of 3D CT. The importance and motivation of 2D to 3D porous media reconstruction.
* Key issues / targets in porous media reconstruction:
  + Basic: natural connectivity in 3 directions.
  + Long range connectivity
  + Fine shape / boundary features
  + Spatial heterogeneity
  + Accurate multi-scale structure and cross-scale connectivity
* The development and limitations of existing reconstruction techniques:
  + Object based / process based
  + statistics based
    - Spatial probabilistic models often based on two point statistics (e.g. simulated annealing)
  + Image based
    - Pixel based MPS (e.g. SNESIM, PAM)
    - Patch based MPS (e.g. CCSIM)
    - Texture synthesis (optimization based)

E-M

Global optimization that iteratively minimize the differences between the local patterns and their corresponding nearest (i.e. the most similar) patterns in training images.

* + Parallelization
* In this paper, we present an image-based framework for 2D to 3D pore architecture reconstruction inspired by the field of solid texture synthesis [], hereafter PAR. Different from [], a distance map transformation [] is applied to the binary training image that greatly enriches the spatial information, which enables a more accurate pattern similarity search especially for non-uniform regions. In addition, we find out two key reasons for losing connectivity and blurring issue for E-M optimization based micro-structure reconstruction: the typically used principle components analysis (PCA) technique for accelerating similarity search, and the averaging in E-step. We solve this by applying an approximate nearest search, k-coherence search [], which limits the search space regardless of TI size, together with a discrete solver [] that avoids blurring by always copying the original value from TI.

Comparisons show that our algorithm can preserve morphological and petro-physical properties from 2D training images of not only homogeneous structures such as Berea sandstone, but also complex ones including heterogeneous, anisotropic as well as bi-modal (multi-scale) structures, which is rarely achieved by state-of-the-art microstructure reconstruction algorithms.

The non-sequential process within each iteration of the algorithm is suitable for implementing parallelization through CPUs easily (also capable through GPU), thus the computation efficiency of PAR also outperforms or at least is comparable to previous reconstruction algorithms.

* This paper is organized as follows. In section 2 the original method based on Kopf [] is described. Section 3 presents details of our contributions, including enriching spatial information of TI using distance map transformation, and solving the connectivity loss and blurring issues. In section 4 three test cases of porous media are reconstructed and analyzed by means of human vision, morphological and petro-physical properties. The conclusion is given in section 5.

1. Basic global optimization method

Overview

M-step

E-step

Multi-resolution

1. Our proposed methodology

Distance map transformation

Pattern size and computation efficiency / pattern reproduction

Connectivity loss and blurring

PCA

Averaging in E-step

K-coherence search

Discrete solver

Index histogram

Position histogram

Parallelization

Multi-core CPU parallelization

Static workload schedule provides best cache usage and least communication cost

Minimum data synchronization

While not implemented in this work,

1. Results and discussion
   1. Evaluation Criteria
      1. MPC
      2. Minkowski functions: porosity, specific surface area, Euler number
      3. Pore network statistics: pore network PSD, shape factor distribution, coordination number, Euler connectivity function
      4. Predicted flow properties (single phase permeability, two phase flow rel. perm.)
   2. 3D actual data and training images

Berea, Grosmont, Cross-scale. Reconstruction results

* 1. Comparison with state-of-the-art algorithms? (visual and speed)

1. Conclusion

We conclude our contributions as:

* E-M style
* Specifically, we studied and discovered two key techniques that greatly improves the capability and:
  + Enrich the information in binary training image by distance map transformation.
  + Discovered that the tradition process in texture synthesis in order to reduce computation – PCA is the main reason for loss of fine features in the EM based algorithms. We adopt a K-coherence search technique to avoid the heavy computation caused by discarding PCA. (How to rephrase it so that it shows more importance and more brief?)

In this paper, we have presented a new framework for reconstructing 3D porous media using 2D training images, inspired by the solid texture synthesis algorithm. Based on our study we find that the distance map transformation greatly enriches the information of training images and could be used as a general pre-processing step for most training image based algorithms. On the other hand, the commonly used PCA process is proved to affect quality in the scenario of porous media reconstruction and should not be applied.

Our results demonstrate that we have successfully accomplished the difficult task of preserving both geometric and petro-physical properties for a wide variety of porous structures. The versatile capability and high quality exceed that of conventional reconstruction methods. With the easy implementation of parallelization, the efficiency of our method also outperforms or at least is comparable to previous algorithms.

This algorithm provides a general alternative for characterizing 3D porous media by using 2D thin sections. Moreover, as a scale-free algorithm it can be easily adjusted to cope with conditioning data and applied to geo-statistics reconstruction at larger scale.

For future work, we would like to further improve the capability by using multiple training images in each direction to deal with more heterogeneous structures which cannot be accurately characterized by single slice. Besides, 3D control map could be applied to reconstruct globally varying structure such as layered porous media.