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Image processing for porous media characterization

A. Almhdie[1], R. Jennane[1], O. Rozenbaum[2], E. Lespessailles[3] and C. Leger[1]

[1]PRISME laboratory of the University of Orleans, France
{ahmad.almhdie, rachid.jennane, christophe.leger}@univ-orleans.fr

[2] ISTO institue of CNRS, Orleans, France
rozenb@cnrs-orleans.fr

[3] Inserm U658 group, Hospital of Orleans, France
Eric.Lespessailles@chr-orleans.fr

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Abstract. *In digital image processing, skeletonization is a valuable technique for the characterization of complex 3D porous media, such as bone, stone and soils. 3D thinning algorithms are usually used to extract one-voxel wide skeleton from 3D porous objects while preserving the topological information. Models based on simplified skeletons have been shown to be efficient in retrieving morphological information from large scale disordered objects at a local level. In this paper, we present a series of 3D skeleton-based image processing techniques for evaluating the micro-architecture of large scale disordered porous media. The proposed hybrid skeleton method combines curve and surface thinning methods with the help of an enhanced shape classification algorithm. Results on two different porous objects demonstrate the ability of the hybrid skeleton method to provide significant topological and morphological information.*

1 Introduction

Most variants of 3D binary skeletons are based on curve thinning or surface thinning. Since curve thinning does not preserve the geometry of non-cylindrical shapes, and surface thinning cannot erode enough beam shapes, neither curve nor surface thinning is suitable for the analysis of porous media. To overcome this problem, shape information should be integrated into the skeleton models. Hybrid skeleton has recently been proposed [1] to create structural models that take into account the shape of the object which enables a precise description of the local geometry. In this paper, different processing tools are presented and applied to the analysis of real porous objects. Different parameters are mathematically defined to demonstrate the efficiency of the hybrid skeleton technique for the characterization of 3D porous media.

2 Hybrid skeleton method

The hybrid skeleton algorithm is inspired from the work of Pothuaud [6], but takes more accurately into account the shape of the object, in order to improve the geometrical approximation. It consists in classifying all object's voxels before thinning. To highlight the performance of the proposed method, bone and stone data sets at 16-μm and 3-μm of resolution, respectively, are used, as seen in figure 1(a). Before thinning, three pre-processing operations are used. First *Filtering* with a median filter to reduce noise. Then, *binarisation* using a threshold determined as the local minimum between the modes of the histogram of each 3D image. Finally, *volume correction* for which the Hoshen-Kopelman (HK) clustering algorithm [3] is used to remove non-connected solid voxel sets. The object has hence only two phases: a *26-*$connected$ solid phase and a *6-*$connected$ pore phase. The topology of a porous medium can be characterized using the Betti numbers. Considering a 3D space, there are 3 distinct Betti numbers that completely define the topology of an object. β_0 is the number of connected elements of the solid phase Ω. β_1 is the number of loops and closed paths of Ω. β_2 is the number of internal surfaces of Ω. The connectivity of an object is usually evaluated using the Euler-Poincare Characteristic, N3, which is linked to the Betti numbers by $N3 = \beta_0 - \beta_1 + \beta_2$.

To overcome the limitations of curve and surface skeletons for modeling objects of mixed rod/plate shapes, we developed a new skeleton called $Hybrid$ which is based on an original combination of three techniques: element classification as rods or plates, surface thinning and curve thinning. First, a method of shape classification is used to decompose the object into two sets of plates and rods [2]. This classification is performed at the voxel level as shown in

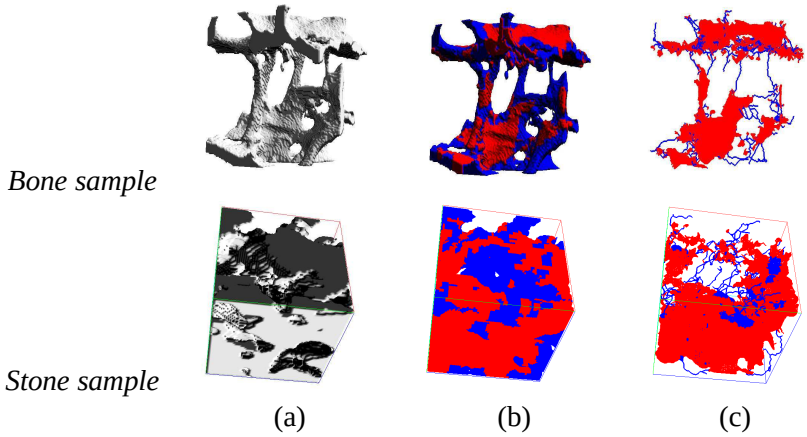

Figure 1: 3D porous object (a), classified volumes (b) and hybrid skeletons (c).

figures 1(b). After the classification step, surface [4] and curve [5], thinning techniques are applied respectively to the plate and rod subsets. The joint use of these thinning techniques generates a skeleton composed of both 2D surfaces at plate shapes and 1D paths at rod shapes, as shown in figures 1(c).

3 Results and Discussion

Let Ω and Ω_c be the set of solid and pore voxels, respectively. Interesting features characterizing the morphology and the topology of each sample can be extracted directly from the skeleton. These features include: skeleton Connectivity Density ($Conn.D$), Skeleton density (SV/TV), normalized Number of Line-end voxels ($Le.N$), normalized Number of Node voxels ($No.N$) and skeleton Rods to Plates ratio (Rd/Pl).

$$Conn.D = \frac{N3}{TV} = \frac{(\beta_0 - \beta_1 + \beta_2)}{Card\{\Omega_c \cup \Omega\} \times \rho} \tag{1}$$

$$SV/TV = \frac{Card\{S_H\}}{Card\{\Omega_c \cup \Omega\}}, \tag{2}$$

$$Le.N = \frac{Card\{m \in S_H \mid \beta_0(N(m)) = 1 and \beta_1(N(m)) = 1\}}{Card\{\Omega_c \cup \Omega\}}, \tag{3}$$

$$No.N = \frac{Card\{m \in S_H \mid \beta_0(N(m)) = 1 and \beta_1(N(m)) > 1\}}{Card\{\Omega_c \cup \Omega\}}, \tag{4}$$

$$Rd/Pl = \frac{Card\{S_{H_R}\}}{Card\{S_{H_P}\}}, \tag{5}$$

where TV is the total volume in mm^3, ρ is the voxel resolution in mm^3, $Card(y)$ is the number of elements in the set y, S_H is the set of voxels of the hybrid skeleton, $N(m)$ represents the neighborhood of voxel m, and S_{H_P} and S_H are the rod and plate parts of S_H, respectively. The results of table 1 represent the values of the previously described parameters extracted from the hybrid skeleton. The SV/TV parameter reflects the presence of plates in the porous samples which increases its density. The number of line-ends is an indicator of the number of broken branches. The hybrid skeleton distinguishes plates and rods, so as to provide two efficient and complementary values.

Feature	Conn.D (mm^{-1})	SV/TV	No.N/TV (mm^{-1})	Le.N/TV (mm^{-1})	Rd/Pl
bone sample	-4.3	0.0134	0.0018	0.00011	0.0750
stone sample	-7346.8	0.0669	0.0147	0.0005	0.2130

Table 1: Values of different parameters characterizing the porous objects of figure 1.

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