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Image processing for the non-destructive characterization of porous media. Application to limestones and trabecular bones

Ahmad Almhdie[a,c], Olivier Rozenbaum[a], Eric Lespessailles[b], Rachid Jennane[c,*]

[a] ISTO, UMR 7327, University of Orleans, 1A, rue de la Férollerie, 45071 Orléans, France
[b] Univ. Orléans, I3MTO Laboratory, EA 4708, Hospital of Orleans, 1 rue Porte Madeleine, F-45032 Orléans, France
[c] Univ. Orléans, PRISME Laboratory, EA 4229, 12 rue de Blois, BP 6744, F-45067 Orléans, France

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Abstract

Different image processing techniques have recently been investigated for the characterization of complex porous media, such as bones, stones and soils. Among these techniques, 3D thinning algorithms are generally used to extract a one-voxel-thick 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 not only at a global level but also 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 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 proposed method to provide significant topological and morphological information.

Keywords: Segmentation; Skeleton; Classification; Topological and morphological information; Porous media

1. Introduction

Various domains are concerned with the characterization of porous media. Natural materials (e.g. wood, stones, Fontainebleau sands, biological materials such as bones) and manmade materials (e.g. industrial foams, ceramics, electronic nanodevices) are examples of porous media from different application fields. These porous objects are usually considered not only in industry but also in research as multiphase materials composed of several elements arranged in space as a complex, sometimes messy, network. The problems of porous media have raised considerable interest among the scientific community as they cover a wide range of applications and scales: the exploration of underground entities at the microscopic scale in geology, and the examination of soil structures [18], the degradation of monuments [27], or the analysis of bones and the synthesis of industrial materials [8]. In most of these problems, the challenge is to study the physical behavior of these objects by characterizing their complex geometry, in order to improve and enhance their performance (glass or carbon fiber), to avoid (or limit) weathering or deterioration (stones, metal oxidation), and to understand or predict their behaviors (soils, rock reservoir, concrete, bones). This requires

* Corresponding author. Tel.: +33 238 494 538; fax: +33 238 417 245.
E-mail address: Rachid.Jennane@univ-orleans.fr (R. Jennane).

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determining the main characteristics (morphology, texture, topology, etc.) of these porous media. Furthermore, the prediction of properties (e.g. transport or mechanical properties) by models and simulations needs a realistic description of the phases constituting these porous materials.

An accurate and powerful non-destructive method to characterize the complex microstructure of porous materials is high resolution X-ray Computed Tomography (XCT). This technique has gained considerably in importance in recent years for the 3D-characterization of materials [6,44,26,9,24]. This is notably due to continuous improvements in X-ray tubes and XCT devices that have led to laboratory systems which can now achieve resolutions down to 1 μm and even below depending on the materials and their sizes [25,15,31,48].

Starting from these images, the characterization of porous material has gradually switched from classical, and often destructive, exploration methods (BET, mercury porosimetry) to a non-invasive and increasingly precise science, namely 3D digital image processing. It is often necessary to measure from the image a quantity related to the physical property to be characterized. For example, transport phenomena and permeability in rocks can be studied through the distribution of the grains and the geometry of the pore phase [18]. In materials science, the anisotropy of a structure characterized by a Fabric tensor reflects the main poroelastic directions [17]. In the biomedical field, quantification and understanding of the distribution of the structure primitives of a trabecular bone are relevant for both diagnosis and treatment of bone disease. Instead of direct mechanical testing which is destructive and life threatening, the classification of these primitives helps in simulating these mechanical tests in order to estimate certain mechanical properties, such as stiffness. These mechanical properties are usually determined not only by their porosity, but also by the arrangement of trabeculae in the 3D space [4,3,5].

The image processing methods proposed in the literature for the characterization of porous media can be classified in two main categories: global and local. Global methods, which are based on geometric models or use image averaging methods, allow the extraction of various approximated structural indices, such as the number of solid forms, spacing and orientation of the form primitives [10–12]. These architectural parameters evaluated at a global level suffer from a priori hypotheses defined in the models and lack of precision, but are often sufficient to characterize the density, morphology or the anisotropy of porous network.

In this paper, however, we focus mainly on local approaches since they allow the measurement of quantitative indices of the structure by detecting the form primitives of the network, i.e. extraction of the internal structures such as beams and plates (e.g in the case of trabecular bones), which are fundamentally different, providing a set of new measures available directly from the images [16,12,14]. Our aim is to demonstrate that using well chosen image processing procedures and an accurate skeleton, it is possible to access different morphological and topological features of huge data only from a simple and faithful representation of the original object.

In general, local-based techniques work locally on the 3D volume, and make few or no geometrical approximations by extracting useful information in each voxel or structure primitive. For example, the Hoshen–Kopelman percolation method [21] allows the isolation and characterization of the connected sets of the object, namely solid or porous clusters in the case of a porous media. It actually performs a local decomposition based on a neighborhood criterion. The numerical calculation of topological constants, such as Betti numbers or Poincare Euler characteristics (i.e. connectivity), is also based on this type of local counting process within a neighborhood [35]. All these algorithms are strictly deterministic and quantify properties of the media exactly. For example, characterization of the thicknesses of the structure primitives is based on the principle of the thickness map proposed by Hildebrand and Ruegsegger [20]. The methods of 3D skeletonization, thinning, medial axis [7] and the Voronoi distance map [22] are all methods enabling the decomposition of the media into primitives based on a simplified representation, while retaining the useful structural information. The segmentation of porous objects using these local techniques allows the measurement of many classical morphological and topological parameters, supplemented by new descriptors of structure, form and anisotropy.

In this work, the different phases of the porous media need first to be distinguished (segmentation step) prior to calculating characteristics (e.g. porosity, specific surface, Euler number) or simulating properties (e.g. conductivity, mechanical properties) on 3D images of different porous samples. Unfortunately, artifacts and/or noise often prevent segmentation of the 3D raw images [28]. As shown in the following, the segmentation of 3D images is specific to the application, imaging modality and nature of the object to be studied. Hence, the segmentation process is often preceded by an image analysis procedure (based on mathematical morphology tools and classical denoising filters in our case). After segmentation, a binarized media (represented by only two phases) is obtained. If the phase of interest is the pore phase (e.g. stones), it is assigned the value 255, and the solid phase the value 0 (the dual image is chosen if the phase of