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Technical Section

Exploration of porous structures with illustrative visualizations

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ABSTRACT

The analysis of porous structures from CT images is emerging as a new computer graphics application that is useful in diverse scientific fields such as BioCAD and geology. These structures are very complex and difficult to analyze visually when they are presented with traditional rendering techniques. In this paper, we describe a visualization application based on illustrative techniques for rendering porous structures. We provide various interactive pore selection mechanisms and visualization styles that allow users to better perceive the connectivity between pores and how they are distributed by radii throughout the structure. The application also shows simulations of fluid intrusion or extrusion through the structure, and it allows users to navigate inside. We describe our application and discuss the experimental results with phantom models, BioCAD scaffolds, implants and rock samples.

1. Introduction

A porous material is a material composed of two differentiated spaces: the solid and pore (empty) spaces. Normally, the solid space consists of a single component while the pore space can consist of several components that are connected to the outside or isolated [12]. Each component of the pore space can be represented by a set of pores. A pore can be defined as a local aperture of the pore space connected with other pores and with the exterior through local narrowings called throats.

Porous structures are present in a wide range of scientific fields. Geologists analyze porous rocks to evaluate the potential volume of water or oil that they may contain. In the construction field, the porosity of building materials is an important issue, because it is related to their weight and drainage capacity. In medicine, porosity is one of the fundamental properties of bones, and is used to evaluate characteristics such as the degree of osteoporosis. Moreover, in the design of biomaterial implants for fracture repair, porosity is a crucial feature to allow blood circulation and, hence, tissue growth and healing.

A number of porosimetry technologies have been designed for physically measuring the porosity of materials. They are essentially based on the intrusion of a non-wetting fluid into the porous structure at incremental pressure levels. The size of the pores is approximated according to the differential intruded fluid volumes. More recently, analytical methods based on the study of 3D scanned images of the structures have been developed to measure the porosity virtually. The 3D images are used to construct a binary voxel model that represents the solid region and the pore region. Using region-growing or skeletonization-based methods, it is possible to determine the distribution of pore size.

The numerical results provided by physical porosimetry and virtual methods are very abstract, so they need to be complemented with images. However, most porous materials have a very complex structure, so their visualization is difficult to understand. Visually tracking paths through the structures is puzzling, if not impossible.

In this paper, we propose a novel illustrative application for visualizing porous materials. It uses 3D scanned images of the material and a graph structure of the interconnected pores inside it. The graph is constructed using two different pore space reconstruction methods described by the authors in previous papers [24,25]. Users interactively select one or more pores of the model and our system renders the pores connected to them. Our method provides focus+context clues on the material. It uses color and opacity ramps to color pores and adjust their transparency depending on their size and distance from the selected ones. Moreover, it uses view-dependent cut-away to provide a better insight into internal paths. The major advantage of our application is that all these effects are obtained in real time. Our system uses a labeled voxel model that stores for each voxel a unique identifier of the pore to which it belongs. The model is rendered using a GPU-driven volume ray-casting that applies an on-purpose computed transfer function. The visualization is complemented with a fluid intrusion simulation and a navigation inside the structure. We show several examples of our application on phantom data and on two different types of real materials: rocks and bioimplants.

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2. Related work

The related work falls into three categories: BioCAD analysis of porous structures, graph visualization, and illustrative volume rendering. We briefly discuss them in three separate subsections.

2.1. Porous structure analysis

Porous materials include biological tissues such as bone [23] and biomaterial scaffolds [7], geological materials such as sedimentary rocks [8,19] and industrial materials such as concrete [11]. The essential parameters that are used to evaluate a porous material sample are:

- global porosity: i.e. the proportion of empty volume in relation to the total volume of the sample;
- effective porosity: i.e. the proportion of empty volume reachable from outside the sample in relation to the total volume of the sample;
- pore-size distribution.

Mercury intrusion porosimetry is a physical experiment that computes the effective porosity and estimates the pore-size distribution of the pore space part connected to the outside. It injects mercury at incremental pressures into the samples, inwards from the outside in all directions, and it computes the differential intruded volumes. Each connected region filled in one iteration is considered as being one cylindrical pore with the radius of the intrusion throat. The Washburn equation relates each pressure with the corresponding radius [10]. The results are shown as a curve with the pore radii in the x-axis and the differential volume in the y-axis. Fig. 1 shows an example of such a curve for a sedimentary rock sample. Generally, scientists pay attention to the peak of the curve which indicates the pore size corresponding to the maximum amount of the pore space volume. However, the main drawbacks of this physical method are that it does not provide clues on the internal distribution of the pores and that it does not measure the pore space not connected to the outside.

In the last 10 years the quantification of structural properties of porous structures from CT scanned images has emerged as a valid experimental approach complementary to traditional physical measurements. Given the CT images, a 3D voxel model is constructed. The global porosity of the materials is then computed by simple empty cell counting [23]. In order to compute the effective porosity, the pore space is divided into connected components. Moreover, to evaluate the radial distribution of pores, several approaches simulate mercury intrusion porosimetry [10,19,24]. Some methods are based on fitting non-overlapping spheres into the pore region [7,25], while others perform successive morphological openings [27,8]. Some also reconstruct the pore space topology as a pore connectivity graph [10,7,19,24,25].

All these studies obtain numerical results and use volume-rendered images to illustrate these results. However, the structures are too complex to be visually understandable. Fig. 2 shows an example of a rock porous material model. It is clear that this basic visualization provides few clues on the material structure and that illustrative types of visualization are needed. Delerue et al. [10] and Vogel et al. [27] present separate snapshots that represent successive intrusion pressures using two different colors, one for the pore region already intruded and the other for the region not yet included. The approach presented by Schulz et al. [20] illustrates fluid simulation in a similar way and contextualizes it by showing the solid region as semi-transparent. In the work of Schema and Favretto [19], the pore space is shown with semi-transparency and central lines are outlined inside. However, none of these approaches focus on visualization. They do not present specific tools for interactively exploring the topology of the porous samples, and their use of illustrative techniques is limited.

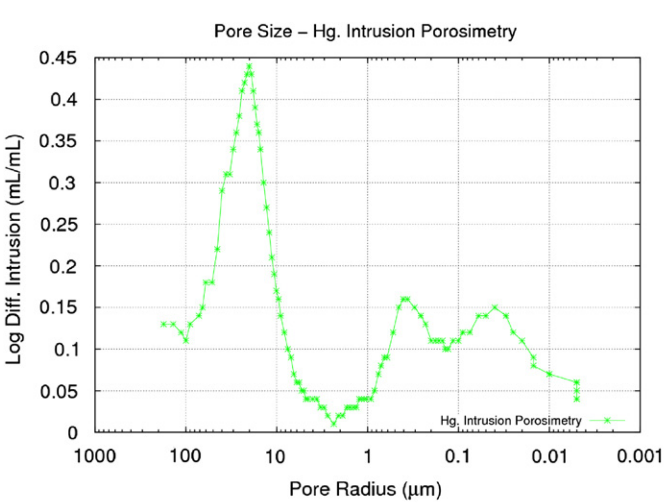

Fig. 1. Output curve of mercury intrusion porosimetry for the bioimplant foam dataset.

2.2. Graph visualization

Graphs play an important role in computer science. They are convenient abstractions of many relationships, and have applications in fields ranging from web development (sitemaps, P2P networks, etc.) to hardware design (circuit layout) and business management (organization charts). Visualization helps to understand the structure of what graphs represent. Moreover, graphs can be used as tools of feature selections for multi-classified structured volume datasets [1].

Graph drawings are pictorial representations of an embedding of the graph onto a compact connected two-manifold surface where graph nodes are associated with vertices and arcs with edges. The design of graph drawings can be optimized according to aesthetic or functional criteria. For instance, force-based algorithms try to avoid edge crossing and to keep edge length approximately equal [4]. The visualization of large and complex graphs can be addressed through a multi-level perspective, by creating a graph hierarchy that collapses subgraphs into single nodes [2]. Three-dimensional representations of graphs that use 3D hyperbolic geometry have also been addressed [17]. In addition to data browsing, graph drawing applications let users select nodes and paths interactively. This is an important feature

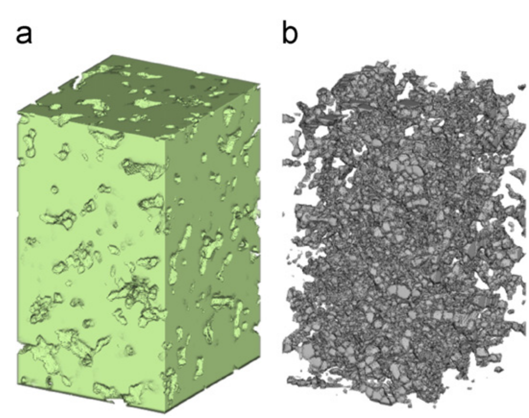

Fig. 2. A porous rock material sample: (a) the solid region and (b) pore region.