iMorph : A 3D morphological tool to fully analyze all kind of cellular materials

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Abstract:

This paper presents the software iMorph developed in our laboratoryin order to perform geometrical measurements on porous media from 3D images (µCT, MRI…). The different morphological and segmentation methods originally developed for metallic foam *[1]* have been extended to cellular materials. We present here a study performed on a large panel of different cellular materials such as ceramic sponges, sintered polyethylene balls, and trabecular Bones.

After introducing specificity and needs of 3D analysis software, we briefly remind the automatic segmentation methods used to perform size and structural measurements (cell and throat size, tortuosity, connectivity, specific surface, skeleton analysis…). Then we present the specific parameters used for a better topology understanding of the different cellular materials.

Introduction

Metallic foams are a class of materials that are attractive for numerous applications, as they present high porosity, low relative density, high thermal conductivity of the solid phase and large accessible surface area per unit volume *[2]*. Moreover, they also promote mixing and have excellent specific mechanical properties. Metallic foams are thus used in the field of compact heat exchangers, reformers, two-phase cooling systems and spreaders *[3, 4]*. Foams have also been used in high-power compact batteries and catalytic-reactor applications such as fuel cell systems *[5]*.
X-Ray tomography is a method for determining 3-D geometry of complex objects. Tomograms contain, in principle, vast amounts of information on the locations and architectures of large numbers of objects. In the relatively short time since its first applications in the late 1980s, X-ray tomography has provided numerous new insights into material structure. In the last five years, X-ray tomography and MRI imaging have begun to evolve from a technique practiced in only a handful of specialized centers to one that is increasingly available to researchers and engineers.
Quantitative analysis of X-ray tomograms typically involves segmenting components (e.g cells struts…), measuring their dimensions, and determining spatial organizations among the components. However, even as the technology for producing tomographic reconstructions has become more sophisticated and accessible, and the data proliferate, the quantitative analysis and interpretation of the data remains a serious bottleneck.
Existing softwares (APHELION®, AMIRA®, AVIZO®) are designed for a wide range of applications (Biology, Geology Material Science…). As they have a generalist approach the

provided tools are not fully adapted to the cellular material characterization. MAVI® focuses on the characterization of the complex geometry of microstructures. Volume, surface, integrals of curvature and Euler number are determined for the whole structure or isolated objects. Anisotropies and preferred directions are found and measured, too. But these softwares require a minimum knowledge in image processing. In effect the different calculation steps have to be performed separately before obtaining the final results. Their objectives is to propose a panel of image processing methods which are more or less adapted and efficient considering the images and porous media structure.

We propose in this paper to introduce the open source software developed in our laboratory to fully analyze cellular materials for image processing non-specialists.

Measurements

To study the impact of morphology on physical properties of cellular materials the classical parameters in literature are the porosity, the specific surface, the granulometry, and cell measurements (size and volume). For instance, in *[6]* bonnet et al relies the pore diameter with the coefficients of Forchheimer equation which describes fluid flow behavior in metal foam.

But, some non-conventional parameters can be useful to understand the impact of geometry on the physical properties of porous media. For example in *[7]* we demonstrated that effective thermal conductivity is inversely proportional to tortuosity in metal foam. This tortuosity is relied to the cell shapes and their organization in the media.
From our previous studies *[8, 9]* we can extract a list of parameters we think are relevant for cellular materials :

- Tortuosity of solid and fluid phase
- Anisotropy Quantification
- Cells Organization
- Pore and Strut Connectivity
- Throat size

The first step of geometrical analysis is the phase segmentation of raw data. During the phase segmentation w have to identify voxels belonging to fluid phase and solid phase. The resulting 3D image is thus a binary image from which all morphological operations an be performed. Porosity, granulometry, is then easily deduced. The "Marching Cubes" algorithm uses the 3D density images to obtain the mesh of solid surface *[10]*. The mesh data triangles are ordered so that each triangle is included into a unique cubic mesh composing the 3D sample. Once the mesh has been generated for the sample, it is then easy to calculate a specific surface area within a small volume taken in the sample. The end user can control the marching cubes process in order to obtain a mesh usable for commercial CFD software such as Fluent® or STAR-CCM+®.

The automatic item extraction is inspired of *[11]* and a more detailed version of the algorithm is presented in *[7]*. The method is the watershed on distance map. The automated extraction of markers for the watershed is based on maximal included ball. We made the assumption that cells have convex shape and that only one complete ball is comprised into one cell. Segmentation of pores in individualized cells gives access to detailed morphometry and orientations measurement. The volume of each cell is simply obtained by counting the voxels of our segmented image. Then throat surface and orientation is deduced from our segmentation by counting voxels belonging to two adjacent cells. Figure 1 shows an example of advanced morphometry for 4 Recemat® metal foams. Statistics are carried out on more than 2000 cells for each material.

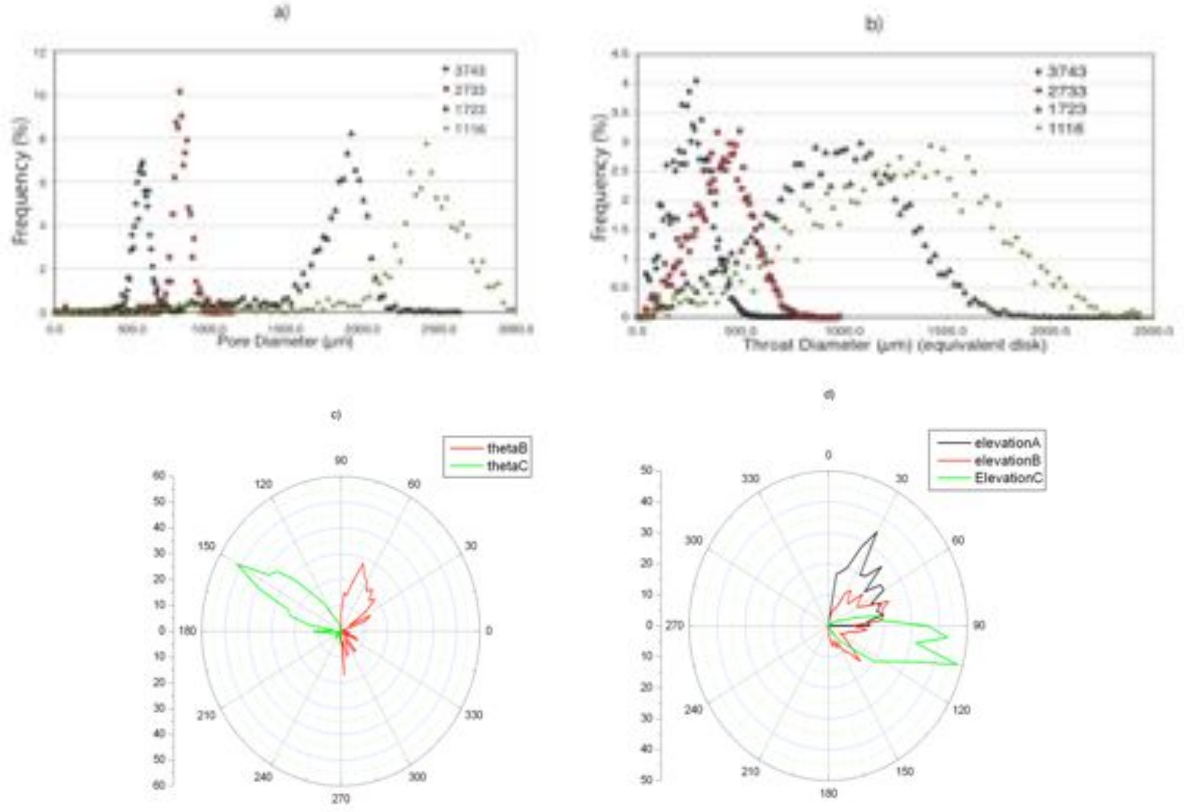

Figure 1 Advanced Morphometry a) pore diameter; b) throat diameter; c) cells elevation on 2733 NCRecemat d) cells azimuth.

The solid phase characterization is based on its skeleton. The solid phase skeleton is obtained from the previous cell segmentation. To identify nodes and ligaments, cells are inflated using an augmented fast Marching method *[12]*. Cells labels are propagated until all voxels are assigned. To retrieve the solid structure, voxels of these images are selected according to the Plateau's law. From this skeleton we measure the mean strut length and the connectivity of the solid phase. Plateau indicated that three liquid films equally inclined toward one another form edges, and that vertices are formed by four edges equally inclined. Thus, voxels in our resulting inflated images, which have 3 different cell labels, in their 27 neighboring voxels, are edges. In a similar manner, nodes are voxels with 4 different labels. Throats are then easily identified by voxels with only 2 different labels. Only nodes are kept to reconstruct the entire solid graph. Labels of adjacent cells are assigned to each node. Solid ligaments are thus obtained by connecting nodes that have in common at least 3 of their 4 labels.

Finally geodesic calculi are carried out in iMorph. The geodesics are computed with a second order Fast Marching Method *[12]*. Tortuosity values are deduced from geodesics calculations. Anisotropy quantification can be done in one hand through directional tortuosity calculation and in another hand through cell shapes and organization identification. Figure 2 presents a summary of measurements and steps of calculations with iMorph.

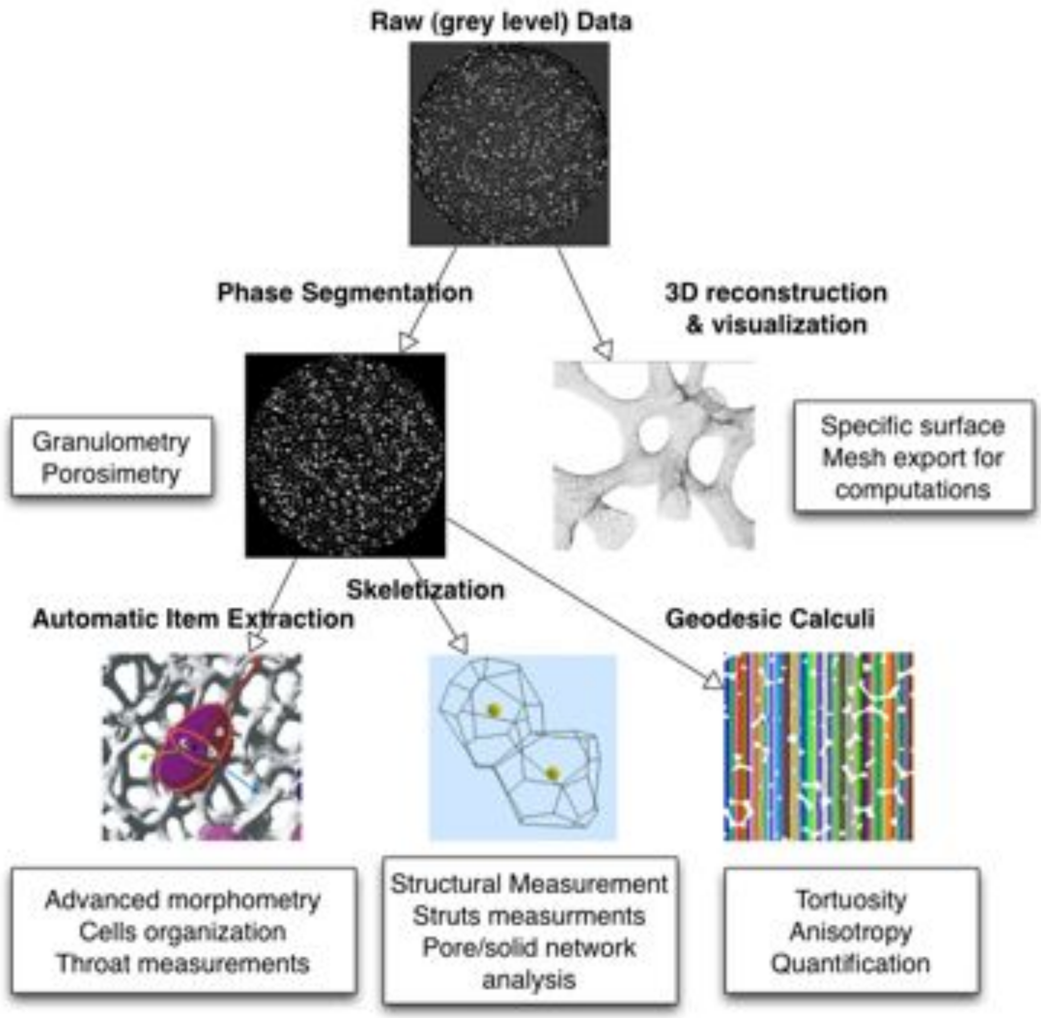

Figure 2 : Summary of measurements and steps of calculation in iMorph

Software Features

iMorph is a multi-platform software (Windows/Mac OS/Solaris) written in C++, it uses QT to propose an intuitive human interface and OpenGl frameworks for a 3D surface rendering visualization. The application is completely 64 bit, so iMorph can easily handle big data volume.

To manage different samples and their associated results and to carry out systematic statistics iMorph has a xml-based database manager. The database model is presented in figure 3.

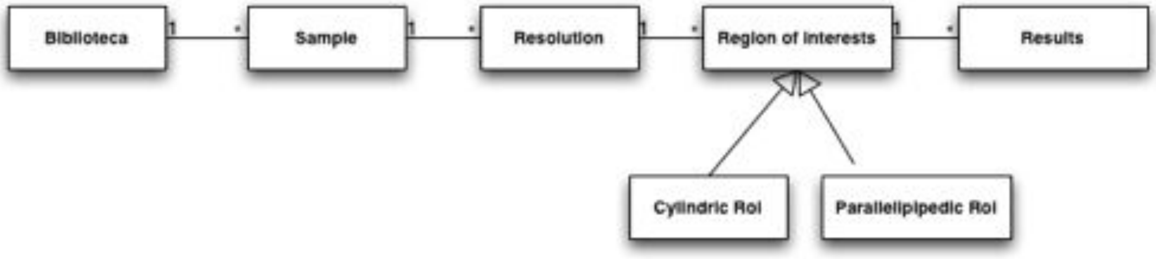

figure 3 : Uml database diagram

In this model the bibliotheca is composed of multiple samples. Numerous resolutions can be associated to a sample. Finally different Regions of Interests (ROI) can be associated to each resolution. There are two types of region of interest the parallelepipedic and the cylindric ones. All the results (measurements) are associated to a unique Roi in order to avoid confusions. Measured data, as cells characteristics, are exported through excel® format file to provide statistical analysis.
A 3D interactive window permits the visualization of segmented cells and material. Each click on the result sub-window which presents the automatic item extraction generate the 3D mesh of corresponding cells within the material. The cell is thus displayed and its characteristics are reported on a separated sub-window table. The end user can interact with the application. This interaction permits the investigation of the porous. Figure 4 presents the 3D visualization window. From left to right ; cells characteristics table; surface renderer; 3D slice viewer of results (Granulometry; Individualized Cell).

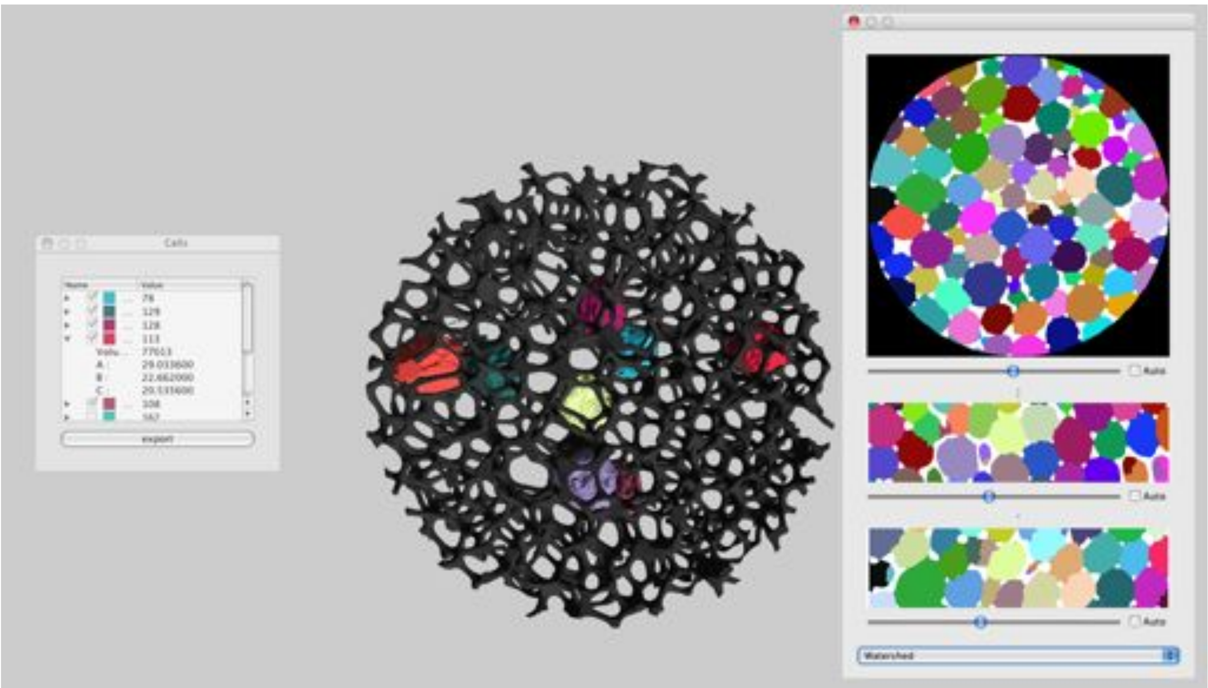

figure 4 : 3D visualization window - cells

A key point of the software is addressed to end user who are not specialists on 3D image processing and analysis. After selecting the ROI all calculations are performed automatically without the need to adjust any parameter.

Conclusion

iMorph is a multi-platform software useful for a better understanding of cellular material. It has been developed originally on a wide range of metallic foam. The automatic algorithms have been improved for all kind of cellular materials including ceramic sponges, sintered polyethylene balls, trabecular Bones and packed spheres.
iMorph is an open-source project and all new methods or specific parameters can be integrated in the software, as the main objectives of the software is to help the scientific community to better understand and explore cellular materials and porous media in general.

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