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A feature extracting and meshing approach for sheet-like structures in rocks

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Abstract

Meshing rock samples with sheet-like structures based their CT scanned volumetric images, is a crucial component for both visualization and numerical simulation. In rocks, fractures and veins commonly exist in the form of sheet-like objects (e.g. thin layers and distinct flat shapes), which are much smaller than the rock mass dimensions. The representations of such objects require high-resolution 3D images with a huge dataset, which are difficult and even impossible to visualize or analyze by numerical methods. Therefore, we develop a microscopic image based meshing approach to extract major sheet-like structures and then preserve their major geometric features at the macroscale. This is achieved by the following four major steps: (1) extracting major objects through extending, separation and recovering operations based on the CT scanned data/microscopic images; (2) simplifying and constructing a simplified centroidal Voronoi diagram on the extracted structures; (3) generating triangular meshes to represent the structure; (4) generating volume tetrahedron meshes constrained with the above surface mesh as the internal surfaces. Moreover, a shape similarity approach is proposed to measure and evaluate how similar the generated mesh models to the original rock samples. It is applied as criteria for further mesh generation to better describe the rock features with fewer elements. Finally, a practical CT scanned rock is taken as an application example to demonstrate the usefulness and capability of the proposed approach.

Keywords: 3D image; Feature extraction; Unstructured mesh generation; Fractures; Rock veins; Sheet-like structure

1. Introduction

An increasingly used source of information describing rock samples is obtained in the form of 3D images scanned from realistic entities by using the advanced imaging technology such as the computed tomography (CT) and the magnetic resonance imaging (MRI). Sheet-like structures (e.g. fractures and veins) widely distributed in rocks are important sources of material heterogeneity and thus should be particularly addressed

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for better evaluating the geomechanical and flow behaviors. Due to easy generation of regular mesh, most numerical simulations for volumetric rock images are based on finite difference method [1] and/or lattice Boltzmann method [2]. While finite element method has more advantages over the finite different method for the complicated structure analysis especially for those with faults/fractures and sheet-like structures [3,4]. However, the related unstructured mesh generation remains a quite challenging topic.

Image-based sheet-like structure meshing relies on high quality digital image. Rocks are usually made up of many constituents, ambiguities may happen if there is no prior knowledge about the constructive minerals. Besides, partial volume effect is another reason for generating poor quality digital images. Digital imaging such geomaterials is difficult in itself but gets achievable [5–7]. Segmentation algorithms [8], together with the CT imaging techniques, are critical for labeling different rock objects and describing fracture structures. Such algorithms may be sensitive to the local image noise and could not produce reasonable results for the sheet-like structures due to the thin features if without high enough resolution [9]. Therefore, high-resolution volumetric images are utilized to capture such geometric features, but such high resolution images lead to a huge dataset, which may be out of current computer capability to analyze and even visualize [10,11]. Thus there is an emerging need for generating analysis-suitable meshes for the segmented rock images involving sheet-like structures, which is also the research focus of this paper.

The mesh generation for 3D images has been studied in many communities [12,13] (e.g. visualization, medical imaging and FEM-based simulation) and is an active subject of a number of on-going studies [5,14–18]. For meshing 3D images, the simplest way is to directly convert voxels into brick elements [14]. However, the drawbacks of this method are evident, besides of the huge dataset generated, the jagged boundaries lead to poor results and even errors in simulations [19]. Marching cubes method [20] and its extensions [15,21,22] are developed to capture interface surfaces and further smooth them for multi-material volumetric dataset. These algorithms suffer from topological defects, ambiguous structures, and an exponential growth in the element numbers with respect to its grid resolution. Alternate image meshing approaches [16,17] based on a Delaunay refinement method are recently studied to identify material interfaces and preserve the geometric features. As the sheet-like objects cause opposite boundaries to be close to each other, there is no guarantee for the topological correctness of the mesh generated by Delaunay triangulation. Therefore, such approaches are not acceptable for the problems addressed here. Zhang et al. [5,23] innovatively proposed an octree-based approach to generate meshes from images. They also designed a surface smoothing strategy [24] to improve the boundary element quality. The advantage of their approach is the ability of creating quality hexahedral elements from images. However, automatic hexahedral mesh generation for complex structures is still difficult and unachievable. In general, the mesh generation for sheet-like structures in rocks is still challenging and current image meshing methodologies in computational medicine and biology are not necessarily suitable for meshing fractures and veins.

Based on the surface meshes generated by marching cubes methods [15,20], mesh coarsening approaches can further reduce the element number. The existing coarsening algorithms could be roughly classified into three groups: decimation, scattering and remeshing. The decimation approach [25,26] reduces the number of elements through a series of elementary simplifications such as collapsing edge and merging face. These operations are efficient but they could produce a number of thin or flat elements leading to poor mesh quality. The Vertex scattering technique [27,28] is to firstly scatter vertices on the surface and then smooth these vertices until a given precision is achieved. Comparing with the decimation method, it could generate high quality mesh but is quite time-consuming due to the large number of background element required. The remeshing approach [29–32] could coarsen meshes with a desired element gradation through a parameterized space, which requires the background surface mesh could be well partitioned. Although these coarsening approaches could decrease element numbers of the surface mesh, they are not suitable for the problems addressed here.

A better representation for a sheet-like structure is surface mesh to represent such a thin object. Therefore, it is necessary to develop a rock image based meshing approach to extract sheet-like structures (major fractures and veins) in rocks and describe them with approximated surface meshes, which ensure capture their major geometric features by using a limited number of high quality elements.