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Dual Contouring for domains with topology ambiguity

Yongjie Zhang *, Jin Qian

Department of Mechanical Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, USA

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ABSTRACT

This paper describes an automatic and robust approach to generate quality triangular and tetrahedral meshes for complicated domains with topology ambiguity. In previous works, we developed an octree-based Dual Contouring (DC) method to construct surface and volumetric meshes for complicated domains. However, topology ambiguity exists and causes non-conformal meshes. In this study, we discuss all possible topology configurations and develop an extension of DC which guarantees the correct topology. We first generate one base mesh with the previous DC method. Then we analyze all the octree leaf cells and categorize them into 31 topology groups. In order to discriminate these cells, we compute the values of their face and body saddle points based on a tri-linear representation inside the cells. Knowing the correct categorization, we are able to modify the base mesh and introduce more minimizer points within the same cell. With these minimizer points we update the mesh connectivities to preserve the correct topology. This method is further extended to 3D tetrahedral mesh generation via an advancing front technique. Finally we use a Laplacian smoothing technique to improve the mesh quality; for tetrahedral mesh a combination of edge-contraction, smoothing and optimization is also applied. Our main contribution is the topology categorization and mesh modification. We have applied our algorithm to three complicated domains and obtained good results.

1. Introduction

Accurate representation of an iso-surface is one important problem in scientific visualization and mesh generation. Given 3D scanned images, we aim to generate quality triangular surfaces with correct topology. The Marching Cubes (MC) algorithm [19] visits each cell in the volume and performs local triangulation based on the sign configuration of the eight grid points. Accelerated algorithms [1,30] were further developed to reduce the running time by avoiding visiting unnecessary cells. The iso-surface inside the cubic cells may have complicated shapes or topology ambiguities. To handle them, the function values of the face and body saddles in the cell are used to decide the correct topology and to generate consistent triangulation [20,18]. Main drawbacks of MC include uniform and large-size mesh, badly shaped triangles as well as the loss of sharp features. To generate an adaptive iso-surface, people developed ways to triangulate cells with different levels. However, when adjacent cells have different resolution levels, cracks are introduced and a fan of triangles have to be inserted around the gravity center of the coarse triangles [29]. Octree based Dual Contouring (DC) method [11] combines SurfaceNets [8] and the extended Marching Cubes [13] algorithms, and it is able to generate adaptive iso-surfaces with good aspect ratios and sharp feature preservation. Despite being adaptive and feature-preserving, DC has the drawback that one cell can contain only one minimizer, leaving possible non-manifold meshes. To address this deficiency, the vertex clustering algorithm [31,28] together with topology constraints [24,3,12] was developed. However, for datasets with very complicated topology (see the trabecular bone structure in Fig. 1), the existing DC methods fail to recognize all the topology ambiguities and may lead to non-conformal meshes.

To distinguish the topology ambiguities, we need to study the function properties inside the cubic cell. Since the function value is only given at the eight grid points of each cell, we model the interior region with a tri-linear interpolation. Depending on the function values of these eight grid points, there are 14 unique configurations for one cell. For some of these configurations, topology ambiguities arise. These ambiguities are either on the face of the cell or interior to the cell. To discriminate them, we compute the function values at body and face saddle points [20]. With respect to the values at the saddle points, we decide whether the iso-surface forms a tunnel linking the two grid points or it is separated into several parts. With all these ambiguities resolved, we develop a new algorithm that modifies the mesh generated using the standard DC cell by cell. In this algorithm, multiple minimizers may be introduced to one cell, eliminating the drawback that the DC method has only one minimizer within one cell. To improve the mesh quality, we relocate the vertex positions via a Laplacian smoothing technique [34]. Furthermore, we develop an advancing front

* Corresponding author. Tel.: +1 (412) 268 5332; fax: +1 (412) 268 3348.
E-mail address: jessicaz@andrew.cmu.edu (Y. Zhang).

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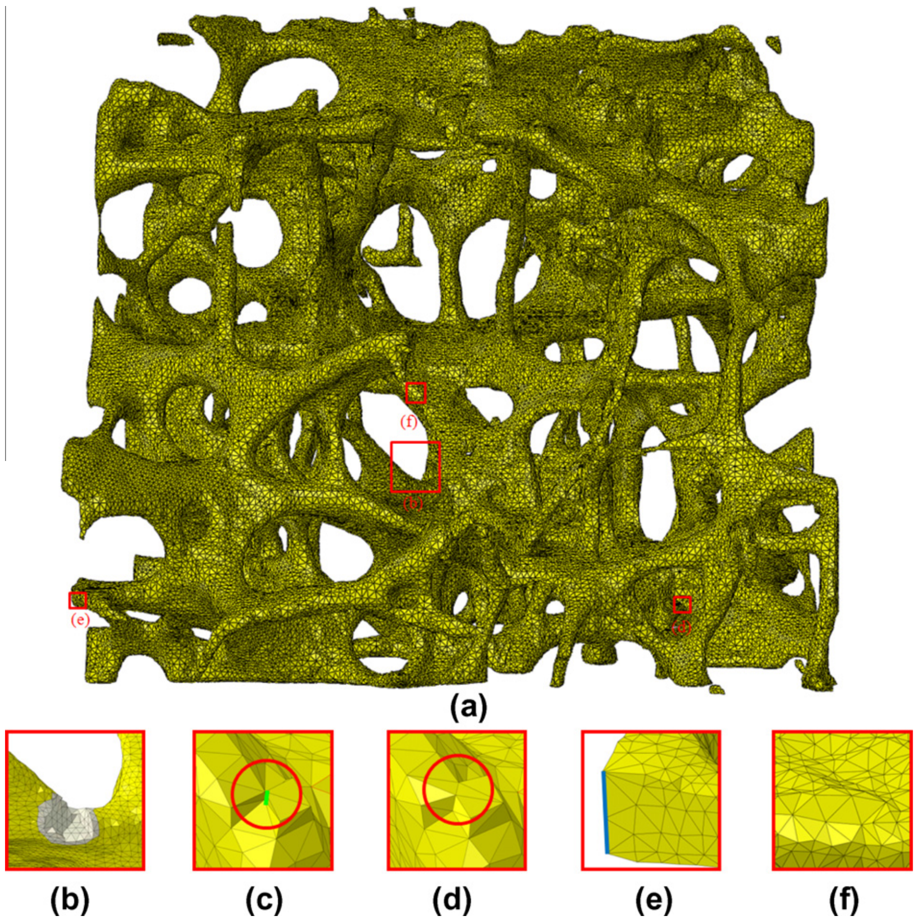

Fig. 1. (a) Triangular and tetrahedral meshes of a trabecular bone structure with complicated topology. (b) One local region with some tetrahedral elements removed. (c) and (d) show zoom-in details of a local region with topology ambiguity (see the red circle). The green line in (c) denotes one non-manifold edge, which is resolved in (d). (e) shows one sharp edge (blue). (f) shows one adaptive region in the mesh. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

method to generate tetrahedral meshes based on the discussed ambiguities. The quality of the tetrahedral mesh is improved via a combination of edge-contraction, smoothing and optimization. Our algorithm keeps the mesh conformal across cell faces and attains quality meshes with correct topology.

The remainder of this paper is organized as follows: Section 2 reviews related previous work. Section 3 talks about the standard DC method. Sections 4 and 5 discuss resolving and triangulating 2D and 3D ambiguities. Section 6 illustrates the extension of this method to tetrahedral mesh generation using an advancing front technique. Section 7 presents results and discussion, and finally Section 8 draws conclusions.

2. Previous work

Marching Cubes. As one of the most popular iso-contouring techniques, the MC algorithm [19] classifies cubic cells into 256 configurations, depending on whether the eight vertices are positive or negative. After considering symmetry and complementary, the 256 cases can be reduced to 14 unique ones. If the two endpoints of any edge have different signs, then the edge is intersected by the iso-surface. The intersection point can be estimated via a linear interpolation. For each of the 14 cases, the approximation of the iso-surface can be created by the triangulation of multiple intersection points. These configurations are incorporated into a lookup table, and each entry in the table contains a triangulation pattern. Then the MC visits one cell at a time until all the cells are treated.

The MC is straight-forward and easy to implement; however, it has several drawbacks. The main problem of MC is that it requires uniform cell structure, which may lead to huge mesh size. Meanwhile, the vertices in MC are restricted on the cell edges, and this introduces many elements with small angles. Furthermore, sharp features in the data are not well preserved. Another drawback is that there is a possibility for discrepancy in the connection of the shared face of two adjacent cells, which are caused by un-categorized ambiguities.

Extended Marching Cubes. The MC has been the focus of much further research to improve its quality of iso-surface representation [18]. To preserve sharp features, additional information in the volume, such as surface normals, are utilized [13]. To make the iso-surface adaptive, people developed ways to triangulate cells with different levels. However, when the resolution levels of adjacent cells are different, there will be cracks and a fan of triangles needs to be inserted around the gravity center of the coarse triangle [29]. In addition, some other techniques involved with the body centered cubic lattice were developed to generate tetrahedral meshes [14]. These techniques generate good quality meshes, but they are not able to solve topology ambiguity problems. To handle the topology ambiguities, face ambiguity [22,5] and interior ambiguity [20,4] have been discussed. In order to distinguish these ambiguities, a strategy based on saddle points,