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Watertight and 2-manifold surface meshes using Dual Contouring with tetrahedral decomposition of grid cubes

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Abstract

The Dual Contouring algorithm (DC) is a grid-based process used to generate surface meshes from volumetric data. The advantage of DC is that it can reproduce sharp features by inserting vertices anywhere inside the grid cube, as opposed to the Marching Cubes (MC) algorithm that can insert vertices only on the grid edges. However, DC is unable to guarantee 2-manifold and watertight meshes due to the fact that it produces only one vertex for each grid cube. We present a modified Dual Contouring algorithm that is capable of overcoming this limitation. Our method decomposes an ambiguous grid cube into a maximum of twelve tetrahedral cells; we introduce novel polygon generation rules that produce 2-manifold and watertight surface meshes. We have applied our proposed method on realistic data, and a comparison of the results of our proposed method with results from traditional DC shows the effectiveness of our method.

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Keywords: Surface meshing, 2-manifold; watertight; dual contouring; mesh generation; tetrahedral decomposition

1. Introduction

Surface meshing is an invaluable tool and one of the most commonly used methods in scientific research for visualizing volumetric data. A surface mesh of a real-world object can be generated in one of two ways: (1) by using a scanning device such as the NextEngine 3D Laser Scanner or Microsoft's Kinect, or (2) by isosurface extraction from volumetric data such as MRI or CT using contouring algorithms such as *Marching Cubes* (MC) [1], *Dual Contouring* (DC) [2] or *Dynamic Particle Systems* [3]. In both cases, the resulting polyhedral mesh may contain geometric errors such as non-manifold edges and/or vertices, holes and intersecting polygons, especially if the surface

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being meshed is complex. The survey of Ju in [4] discusses the wide range of techniques that have been developed for repairing polygonal models.

Non-manifold geometry is problematic for a variety of situations, such as rendering of refractive surfaces, computation of surface normals and curvatures, bounding tetrahedral meshes suitable for finite element analysis and fluid simulations, as well as CAD-based manufacturing and 3D printing. The repairing of geometric errors in meshes is an active research area and there is no one-fits-all algorithm that can fix all the different types of geometric errors. Of course, this is not to say that topologically and geometrically correct surface mesh generation is a poorly researched field. Reference [5] presents an extensive review of the many variants of the MC algorithm that have been developed over the years. *Tight Cocone* [6] is another meshing algorithm that guarantees watertight meshes. *Marching Tetrahedra* [7] is another method similar to MC that can produce topologically correct meshes.

This work focuses primarily on surface meshing with Dual Contouring. DC offers the advantage of producing meshes with sharp features. In MC, the newly created vertices are constrained to the edges of the grid while in DC, the vertices can be anywhere inside the grid cube. However, the traditional DC algorithm produces non-manifold edges and vertices in certain situations. In this work, we present a modified Dual Contouring algorithm that is capable of generating watertight and 2-manifold meshes and thereby avoid non-manifold geometric errors in the first place.

The remainder of this paper is divided into the following sections: Section 2 discusses in general how the traditional DC algorithm works and what the current state of the art is. Section 3 describes our proposed solution in detail. Section 4 describes some of the results of the proposed method and Section 5 discusses the advantage of having geometrically correct surface meshes for tetrahedral mesh generation. Section 6 concludes with a discussion of some of the limitations of the proposed method.

2. Dual Contouring

2.1. An overview of Dual Contouring

Dual Contouring (DC) is a method used for extracting the surface boundary of an implicit volume. The method is dual in the sense that vertices generated by DC are topologically dual to faces in the Marching Cubes (MC) algorithm. In DC, a uniform grid is superimposed on the implicit volume. The grid cubes are represented as nodes in an octree data structure. For each grid cube intersecting the volume, the eight corners of the cube are assigned inside/outside labels, and a quadratic error function (QEF) is defined as:

$$E[x] = \sum (N_i \cdot (x - p_i))^2 \tag{1}$$

where x is the computed dual vertex or *minimizer*, and p_i and N_i represent the intersections and unit normal, respectively, of the volume boundary with the edges of the cube.

Fig. 1 illustrates the basic concept of QEFs in 2D. The bounding surface of the volume shown in light blue color intersects the lower left corner of a square. The lower left corner of the square is marked with a "+" sign indicating that it lies inside the volume while the remaining corners of the square are marked with a "-" sign indicating that they lie outside the volume. Furthermore, the surface intersects the left and bottom edges of the square at points p_0 and p_1, respectively.

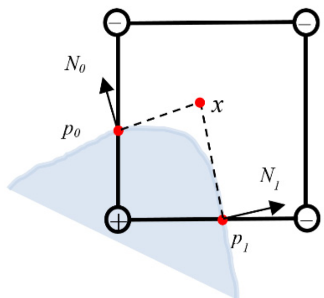

Fig. 1. Formulation of Quadratic Error Functions. The blue region represents the surface/volume.