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An effective quad-dominant meshing method for unorganized point clouds ☆

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ABSTRACT

To perform quad meshing on raw point clouds, existing algorithms usually require a time-consuming parameterization or Voronoi space partition process. In this paper, we propose an effective method to generate quad-dominant meshes directly from unorganized point clouds. In the proposed method, we first apply Marinov's curvature tensor optimization to the input point cloud to reduce the umbilical regions in order to obtain a smooth curvature tensor. We then propose an efficient marching scheme to extract the curvature lines with controllable density from the point cloud. Finally, we apply a specialized K-Dimension (KD) tree structure, which converts the nearest neighbor searching problem into a sorting problem, to efficiently estimate the intersections of curvature lines and recover the topology of the quad-dominant meshes. We have tested the proposed method on different point clouds. Our results show that the proposed method produces good quality meshes with high computational efficiency and low memory requirement.

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1. Introduction

Quadrilateral meshing has been one of the most popular geometric shape description methods in computer graphics and surface modeling. For a given number of mesh elements, if the mesh anisotropy follows the principal directions of the curvature tensor, the quadrilateral mesh could be the best approximation of a smooth surface [1,2]. Due to this appealing tensor-product nature of quad-dominant meshes, anisotropic quad meshing techniques are of great interests in many applications, such as computer aided geometric design, reverse engineering of geometry models and computer simulation. Significant progress in quadrilateral mesh generation and processing has been reported in recent years [3–5].

1.1. Related work

Numerous works have contributed to quad-dominant meshing on triangular meshes. In [4], Alliez et al. generate quad-dominant meshes by intersecting curvature lines extracted from a global parameterization domain. In [5], Marinov and Kobbelt improve Alliez's algorithm by applying local parameterization so that it can be applied to surfaces with arbitrary genus. Ray et al. [6] propose a periodic global parameterization-based approach to build a quadrilateral mesh by tracking the isolines in the parameterization domain. In [7], Kalberer et al. convert the triangular meshes into anisotropic quadrilaterals under the principal curvature frames via the proposed global parameterization method. Bommes et al. [8] formulate the cross field construction and global parameterization as a mixed-integer optimization problem to produce high quality quadrilateral meshes. All these works demonstrate that

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the parameterization-based approach can deal with quad-dominant remeshing of triangular meshes effectively.

On the other hand, there are only a limited number of works that focus on quad-dominant meshing of point clouds. In [9], Pietroni et al. propose a quad meshing method based on global parameterization. It represents the surface by height maps over a set of planes. In [10], Kalogerakis et al. extend Marinov's anisotropic polygonal remeshing method [5] to the point cloud domain. Since the topological information is not available from raw point clouds, a global Voronoi space partitioning step is needed before calculating intersections of curvature lines. In [11], Li et al. present an algorithm for quad-dominant meshing of unorganized point clouds, which is applicable to the surface of arbitrary shapes. It first applies periodic global parameterization [6] to the point clouds and then a local Delaunay triangulation to smooth the calculated principal directions. Although these point cloud-based quad-dominant meshing methods can produce high quality quad meshes, the computational cost and memory requirements are relatively high due to the time consuming parameterization or Voronoi space partitioning processes.

Our objective in this work is to improve the efficiency of quad-dominant meshing algorithms for raw point clouds. The main contributions of our work include:

- Instead of performing the parameterization and triangulation steps, a novel marching method is proposed to control the resolution of the generated curvature lines in a distinct and definite way.
- By constructing a specialized KD-tree structure over the curvature lines, the nearest neighbor searching problem can be converted into a sorting problem. Thus, the intersections and topology of the curvature lines can be retrieved efficiently.
- Since the curvature lines may not exactly intersect with each other in 3D space, a new approach is proposed to estimate the intersections of curvature lines by computing the common perpendicular lines of different kinds of line segments.

We have tested the proposed method using various unorganized point clouds. The results show that satisfactory quad-dominant meshes at multi-resolution can be obtained with high efficiency and lower memory requirement. Fig. 1 shows a quad-dominant meshing result of a point cloud of the Squirrel model.

1.2. Overview of the proposed method

We use Fig. 2 as an example to illustrate the workflow and the major steps of the proposed method. With an unorganized point cloud as input, our method can be summarized as follows:

(1) The oriented normals of the point cloud are first estimated (Fig. 2a). A locally smooth manifold patch is fitted for each point via the Moving Least Squares (MLS) method [12,13] (Fig. 2b). By building a second-order tensor over the local surface approximation, the curvature tensors weighted with a confidence term can be calculated. Then, the curvature tensors can be optimized via a propagation operator (Fig. 2c).

(2) The curvature lines are integrated directly on the point cloud with adaptive step size and line intervals using the proposed marching method (Fig. 2d).

(3) The intersections of curvature lines can be calculated directly in 3D space (Fig. 2e). The quad-dominant meshes over the point cloud can then be built via the half-edge structures (Fig. 2f).

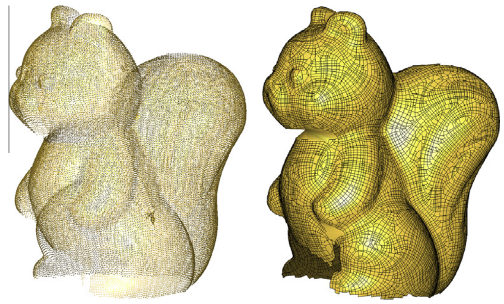

Fig. 1. Quad-dominant meshes (right) produced by applying the proposed method on a point cloud of the squirrel model (left).

The rest of this paper is organized as follows. Section 2 introduces methods for estimating and optimizing curvature tensors from point cloud data. Section 3 shows how the curvature lines can be extracted from the estimated curvature tensors. Section 4 then presents the proposed quad-dominant meshing method. Section 5 discusses some experimental results. Finally, Section 6 concludes this work and suggests possible future works.

2. Estimation and optimization of curvature tensors

Given an unorganized point cloud P as:

$$P = \{p_i : i \in \{1, \ldots, N\}, p_i \in \boldsymbol{R}^3\} \tag{1}$$

the moving least squares (MLS) method is first adopted to fit a smooth patch over the neighbors of each point p_i. In this paper, a paraboloid surface constructed in a local coordinate with the z-axis as the symmetry axis is used to fit each local area for its natural anisotropic attribute [14].

2.1. Polynomial surface fitting

For each point p_i, we compute a reference plane D_i and a normal n_i by performing a weighted covariance analysis over the r-neighborhood of p_i. We denote the average station distance of P (i.e., the average distance between every point in P and its k neighbors) as κ. The value of k is typically set between 5 to 8, and r is empirically set to $10 * \kappa$. An alternative simplified method is to select n points from the point set randomly and then calculate κ as follows:

$$\kappa = \left(\sum_{i=0}^{n} \left(\sum_{m=0}^{k} ||p_i - p_{i_m}|| \right) / k \right) / n \tag{2}$$

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