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Feature-preserving mesh denoising via normal guided quadric error metrics

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ABSTRACT

While modern optical and laser 3D scanners can generate high accuracy mesh models, to largely avoid their introducing noise which prohibits practical applications still results in high cost. Thus, optimizing noisy meshes while preserving their geometric details is necessary for production, which still remains as challenging work. In this paper we propose a novel and efficient two-stage feature-preserving mesh denoising framework which can remove noise while preserving fine features of a surface mesh. We improve the capability of feature preservation of our vertex updating scheme by employing an extension of the quadric error metrics (QEM), which can track and minimize updating errors and hence well preserve the overall shape as well as detailed features of a mesh. We further leverage vertex normals to guide the vertex updating process, as the normal field of a mesh reflects the geometry of the underlying surface. In addition, to obtain a more accurate normal field to guide vertex updating, we develop an improved normal filter by integrating advantages of existing filters. Compared with traditional gradient descent based schemes, our method performs better on challenging regions with rich geometric features. Moreover, a local entropy metric is proposed to measure stability of a mesh and the effectiveness of vertex updating algorithms. Qualitative and quantitative experiments demonstrate that our approach can effectively remove noise from noisy meshes while preserving or recovering geometrical features of original objects.

1. Introduction

As optical and laser scanners become more and more accurate and purchasable with low price, 3D high-resolution models, especially with mesh representations, are widely used in a variety of domains such as computer-aided industrial design, reverse engineering and prototyping, interactive virtual reality systems and medical applications. However, even with high fidelity scanners, the obtained models will inevitably be affected by noises from various sources [13]. As a result, along with the hardware development of the scanners, it is often essential to consider the mesh processing technique such as denoising to optimize a noisy mesh before using it in subsequent applications [29].

Mesh denoising is an important research topic in geometric modeling and processing. In early investigations, researchers gave attention to mesh smoothing [4,8] in which surface smoothness is reinforced by removing certain high-frequency information. This operation, however, can lead to some side effects such as blurring of sharp features, significant distortion of intrinsic shapes, and shrinkage of surfaces. This results in processed models that are not applicable to some applications where high quality models are required, including CAD, architecture design and medical simulation. In this regard, more effort has been dedicated to feature-preserving mesh denoising techniques in which geometric information at all frequencies of the original object should be well preserved while eliminating noise.

Although a lot of mesh denoising approaches have been proposed, research on feature preservation denoising is far from mature and remains active due to its complexity. On one side, local geometric details of all frequencies ought to naturally be kept during the mesh denoising procedure. On the other side, the features of high-frequency corresponding to sharp edges, curves and corners, are difficult to be distinguished from noise, because noise is generally of high-frequency. Therefore, when there simultaneously exist local geometric details containing sharp features and noise in a mesh, it is difficult to denoise the mesh while maintaining details. Though some recent proposed techniques, such as bilateral normal filters [11,32] and random walk normal filters [25], have yielded promising results, denoising models

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having rich characteristic regions with sharp edges and corners, such as models used in CAD, remain a challenging task.

We propose a novel two-stage approach for mesh denoising with feature preservation. Specially, we update the vertex positions by minimizing a proposed quadric error function, where the quadrics is a natural extension from the quadric error metrics (QEM) [7], which is a popular feature-preserving technique in mesh simplification. Furthermore, considering that the normal field can reflect to a large extent the geometry of a mesh, we integrate the information of vertex normals to guide the QEM-based vertex updating process. Compared with widely used gradient descent based schemes, the proposed method achieves higher mesh stability during the iterations and can better recover underlying surface of a mesh with the help of the vertex normal field. To obtain a more accurate normal field, we develop a new formulation for normal filtering by integrating advantages of existing normal filters [24,32]. Our improved weight function is formulated as a binomial function, taking into account the facet area and the distance between the barycenters of facets. Our normal filtering scheme considers face normal changes in normal filtering iterations and irregular surface connectivity and sampling in a mesh. In addition, we extend the usage of the local entropy from 2D image case to 3D mesh. We propose a local entropy metric to measure vertexes' stability of a mesh during iterations of denoising algorithm. We employ this local entropy metric to evaluate the effectiveness of different vertex updating schemes.

We have tested our approach on a variety of noisy models, especially CAD-like models, and demonstrated that our approach is able to effectively keep local geometric details and recover sharp features blurred by noise, no matter the noise is artificial or caused by measurement errors of scanning devices. Compared with recent state-of-the-art mesh denoising techniques, our approach works better at challenging regions with sharp features and/or irregular sampling (see Fig. 1).

In summary, the main contributions of our paper are the following:

- we propose a *normal guided QEM-based vertex updating scheme* that performs effectively at challenging regions with rich geometric features and converges stably;
- we develop an improved normal filter which can counteract the effects of dispersion of normal differences and compensate the irregular connectivity and sampling in a mesh;
- we propose a local entropy metric to evaluate stability of a mesh during denoising iterations that is used to gauge the capability of feature preservation of vertex updating algorithms.

The rest of this paper is organized as follows. In Section 2, we give a brief overview of related work. Section 3 introduces the improved normal filter. Section 4 presents the normal guided QEM-based vertex position updating scheme. Section 5 introduces the proposed local entropy metric. Section 6 gives experimental results and discussion. Concluding remarks are presented in the last section.

2. Related work

In early investigations, most of the mesh denoising approaches adopt anisotropic geometric diffusion on 3D surfaces in order to preserve sharp features. Fleishman et al. [6] and Jones et al. [10] independently extended the bilateral filtering method proposed by Tomasi and Manduchi [28] to denoise 3D meshes. Fleishman et al. use an iterative one-stage scheme that performs relatively fast, but cannot accurately preserve or recover fine features of irregular meshes. Jones et al. [10] use a non-iterative two-stage scheme, but this approach is slow because it treats normal smoothing and vertex updating as global problems. In addition, both of these methods suffer from the problem of volume shrinkage.

Taubin [26] pioneered a two-step Laplacian operator to expand the mesh after smoothing to counteract shrinkage. Though this method is fast and simple, it will cause distortion of prominent features. This method can avoid volume shrinkage by re-scaling the mesh. However, it also inevitably results in distortion of sharp features. Later, Meyer et al. [15] further extended this idea to handle anisotropy to preserve features.

In succession, Ohtake et al. [19] and Taubin [27] proposed two-stage linear isotropic mesh filtering methods, where face normals are first filtered by applying a rotation determined by the weighted sum of neighboring face normals. Then, the vertex positions are updated by solving a system of linear equations using the least squares error method. Other researchers, e.g Yagou et al. [30,31], Shen and Barner [21], Lee and Wang [11], Sun et al. [24,25], Zheng et al. [32], designed similar two-stage denoising frameworks which first performed filtering on face normals, and then adjusted the mesh by repositing the vertexes' position in agreement with the rectified face normal field. The framework proposed in this paper is also a two-stage one.

On the other hand, several global, noniterative mesh optimization methods have been proposed, which are usually based on mesh's differential property. Liu et al. [12] presented a smoothing approach based on a global Laplacian operator with geometric constraints. Nehab et al. [17] used a global framework by using the common error characteristics of measured 3D positions or orientations. Nealen et al. [16] presented a framework which is guided by a uniformly weighted Laplacian and the discrete mean curvature normal. Su et al. [23] applied mean filtering to differential coordinates of a given mesh and then reconstructed the surface to fit the modified differential coordinates. In general, these approaches are numerically more robust, and could generate smoothed results. However, unlike the local, iterative approaches, they do not guarantee convergence and inevitably weaken high-frequency features because of the intrinsic characteristic of isotropic filtering.

In recent years, Bian and Tong [1] and Fan et al. [5] have proposed to first distinguish feature vertices from non-feature vertices using clustering and then proceed a two-stage denoising framework. However, it is arguable that features can be detected out effectively when noise exists. He et al. [9] adopted the ℓ_0 norm and proposed a denoising approach by minimizing the curvature of a surface except at sharp features. It achieves good results particularly when dealing with high-noise case. However, for meshes with fine local details, it would sometimes over-smooth the being handled meshes.

3. Normal filtering

In principle, normal filters for denoising iteratively adjust face normals based on the following formula:

$$\mathbf{n}_i^{t+1} = normalize\left(\sum_{j \in N(i)} \omega_{ij}\mathbf{n}_j^t\right) \tag{1}$$

where $\mathbf{n}_i^{t+1}$ is the normal of facet i at iteration step $t+1$; $N(i)$ is the set of facet i's neighbors and ω_{ij} is a weight function. Different filters use different weight functions and work with different definitions of neighborhood $N(i)$. In order to obtain a more accurate face normal field to guide vertex updating, we formulate a new normal filter by combining the advantages of existing filters.