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Improved, feature-centric EMD for 3D surface modeling and processing

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ABSTRACT

Since late 1990s, Empirical Mode Decomposition (EMD) starts to emerge as a powerful tool for processing non-linear and non-stationary signals. Nonetheless, the research on exploring EMD-relevant techniques in the domain of geometric modeling and processing is extremely rare. Directly applying EMD to coordinate functions of 3D shape geometry will not take advantage of the attractive EMD properties. To ameliorate, in this paper we articulate a novel 3D surface modeling and processing framework founded upon improved, feature-centric EMD, with a goal of realizing the full potential of EMD. Our strategy starts with a measure of mean curvature as a surface signal for EMD. Our newly-formulated measure of mean curvature is computed via the inner product of Laplacian vector and vertex normal. Such measure is both rotation-invariant and translation-invariant, facilitates the computation of different scale features for original surfaces, and avoids boundary shrinkage when processing open surfaces. Moreover, we modify the original EMD formulation by devising a feature-preserving multiscale decomposition algorithm for surface analysis and synthesis. The key idea is to explicitly formulate details as oscillation between local minima and maxima. Within our novel framework, we could accommodate many modeling and processing operations, such as filter design, detail transfer, and feature-preserving smoothing and denoising. Comprehensive experiments and quantitative evaluations/comparisons on popular models have demonstrated that our new surface processing methodology and algorithm based on the improved, feature-centric EMD are of great value in digital geometry processing, analysis, and synthesis.

1. Introduction

In 1998, Empirical Mode Decomposition (EMD) was developed for processing 1D non-linear and non-stationary signals by Huang et al. [9]. The central idea is to decompose a signal into a finite number of intrinsic mode functions (IMFs) with multi-scale oscillatory modes and a residue with monotonic trend, where the first IMF starts with the finest, temporal/spatial scale, and the subsequent IMFs gradually exhibit coarser, temporal/spatial scales (Fig. 1). The IMFs represent the natural oscillatory modes embedded in signals and can play a role of the basis functions. Such basis functions can be computed by operating on the local extremum sequence, while extracting the local energy associated with the intrinsic temporal/spatial scales of the signal itself. Consequently, such decomposi-

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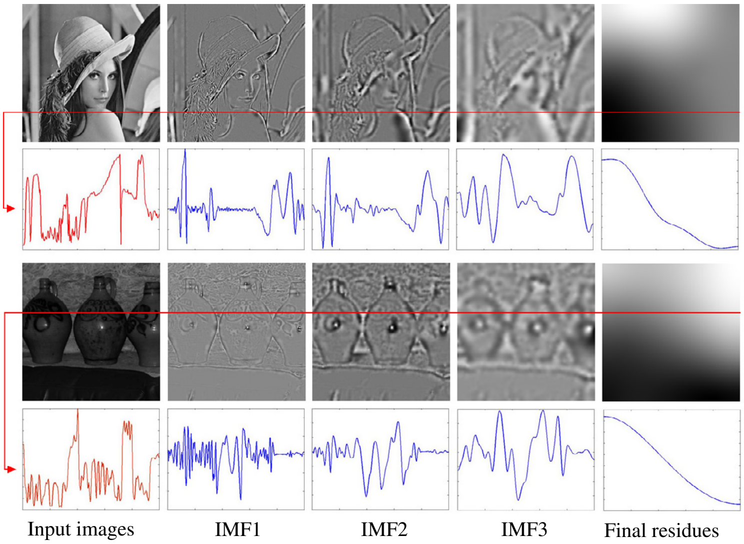

Fig. 1. EMD for lena and vase images using the method of Wang et al. [34], where the images are treated as functions defined over a planar domain. All IMF images are scaled into [0,255] for better visualization.

tion is fully data-driven and different from the other multiscale analysis technologies (e.g., Fourier analysis, short-time Fourier analysis, and wavelet analysis), which (in contrast) characterize the scale of a signal using predefined basis functions.

Ever since its inception, EMD has been considered as a revolutionary method in signal analysis and processing due to its above-documented special properties, and has given rise to a wide variety of applications in 1D and 2D data analysis and processing [10], such as biomedical engineering [24], speech processing [8], image fusion [38], image compression [12], image analysis [19], etc. However, there is little literature on how to apply EMD to 3D surface processing [22,34]. Qin et al. [22] first converted coordinate functions of 3D surfaces to 2D planar signals with the help of spherical parameterization, and then computed EMD representations using the conventional 2D EMD method, where global mesh parameterization is a pre-requisite (which might limit its application scopes). To overcome this limitation, Wang et al. [34] generalized 1D EMD to surfaces directly without resorting to any surface parameterization technique. Their method generates the upper and lower envelopes of a function defined on a 3D surface by computing a biharmonic field with Dirichlet boundary conditions. This generalized EMD on surfaces could be directly applied to coordinate functions of 3D geometry for surface filtering.

The primary reasons about the scarce use of EMD in 3D surface processing are twofold. First, 3D surfaces are represented by 3 coordinate functions independent of each other, yet meaningful geometry features must be characterized by simultaneously utilizing multiple coordinates in the computation of differential properties. However, the naive integration of 3 independent decompositions could not properly lead to surface features of different scales, therefore losing the inherent advantage of EMD completely. In the mean time, undesirable effects inherited from 1D EMD near boundary will be enlarged if simply combining separate decompositions of 3 coordinate functions, i.e., boundary shrinkage will emerge when applying EMD to open surfaces, and this becomes unacceptable in 3D surface processing. Second, the feature awareness of 3D surfaces (e.g., sharp edges and corners) is critical in many tasks of 3D surface processing, such as surface denoising and editing. However, the original EMD is only designed to obtain IMFs at different scales from the given data and does not have the feature-aware property. Hence, it could not preserve features during processing.

In this paper, we make significant efforts to tackle the aforementioned problems, with an ambitious goal of adapting EMD to 3D surface processing. We articulate a novel 3D surface modeling and processing framework founded upon a new, improved, feature-centric EMD. We first employ a measure of mean curvature as the input signal of EMD, which can be computed by the inner product of Laplacian vector at each vertex and its corresponding normal. It can help get different scale features of the original surface and prevent the boundary shrinkage when computing EMD for open surfaces. Furthermore, we design a new EMD formulation on 3D surfaces by devising a feature-preserving multiscale decomposition algorithm for surface analysis and synthesis, which defines detail as oscillation between local minima and maxima. This is motivated by the edge-preserving multiscale image decomposition based on extremal envelopes [29]. As a result, within our novel framework, we could accommodate many modeling and processing operations, such as filter design, detail transfer, feature-preserving smoothing and denoising. Fig. 2 illustrates the pipeline of our framework.

Our major contributions in this paper are summarized as follows:

1. We develop a novel 3D surface analysis and processing framework where EMD takes on the center stage. We make use of a measure of mean curvature as an input