Computer Aided Geometric Design 59 (2018) 1–16

Contents lists available at ScienceDirect

Computer Aided Geometric Design

www.elsevier.com/locate/cagd

Feature-preserving, mesh-free empirical mode decomposition for point clouds and its applications ☆

Xiaochao Wang [a,c], Jianping Hu [b,c,*], Lixin Guo [c], Dongbo Zhang [c], Hong Qin [d], Aimin Hao [c]

[a] School of Science, Tianjin Polytechnic University, Tianjin 300387, China
[b] College of Sciences, Northeast Electric Power University, Jilin 132012, China
[c] State Key Laboratory of Virtual Reality Technology and Systems, Beihang University, Beijing 100191, China
[d] Department of Computer Science, Stony Brook University, Stony Brook, NY 11794-4400, USA

ARTICLE INFO

Article history:
Received 27 September 2016
Received in revised form 25 May 2017
Accepted 22 November 2017
Available online xxxx

Keywords:
Empirical mode decomposition
Point clouds
Feature-preserving analysis and processing
Multi-scale decomposition
Structure measurement

ABSTRACT

Point clouds have been extensively employed to represent 3D shapes with the increasing availability of various data acquisition devices/technologies. As a result, more novel techniques are urgently needed for point clouds' analysis and processing. To date, empirical mode decomposition (EMD) has become a powerful and effective analytical tool for non-stationary, non-linear signals, and has been widely applied to time series processing. Despite the fact that EMD has exhibited its potential in 3D geometry processing, extending the existing techniques of EMD to operate directly on point clouds remains to be extremely challenging. This is primarily because of imperfect point clouds, as well as their absence of topological information. In this paper, we develop a multi-scale mesh-free EMD algorithm for point clouds and their analysis and processing. The multi-scale mesh-free EMD is achieved by iteratively extracting the detail level from the input signal and leaving the overall shape in residue. Furthermore, in order to preserve sharp features during point-based EMD analysis/processing, we devise an anisotropic structure measurement assisted envelope computation scheme. The structure measurement is computed by the eigenvalue decomposition of voting tensor, which could faithfully characterize the structure of any input model. Under the guidance of the structure measurement, the envelope is computed in a structure-aware manner and the sharp features are well preserved. Unlike previous feature-preserving EMD methods for meshed models, our algorithm does not explicitly resort to sharp feature detection, which is more suitable for complex geometric models. With the well decomposed multi-scale representation, we could explore various applications of point clouds, such as detail enhancement and smoothing, feature points extraction, and feature-preserving denoising. We showcase comprehensive experimental results to demonstrate the utility of our novel multi-scale mesh-free EMD algorithm.

☆ This paper has been recommended for acceptance by Marc Alexa.

* Corresponding author at: College of Sciences, Northeast Electric Power University, Jilin 132012, China.
E-mail addresses: wangxiaochao18@163.com (X. Wang), neduhjp307@163.com (J. Hu), guolx@buaa.edu.cn (L. Guo), zhangdongbo9212@163.com (D. Zhang), qin@cs.stonybrook.edu (H. Qin), ham@buaa.edu.cn (A. Hao).

https://doi.org/10.1016/j.cagd.2017.11.002
0167-8396/

1. Introduction

In digital geometry processing, point clouds are one of the most commonly-available types of data and they have been extensively employed to represent 3D shapes with the increasing availability of modern hardware devices and data acquisition technologies. The explosive growth of the data brings us more opportunities and challenges, as a result, more novel techniques are urgently needed for point clouds' analysis and processing. To date, empirical mode decomposition (EMD) has become a powerful and effective analytical tool for non-stationary, non-linear signals, which could decompose a signal into a number of intrinsic mode functions (IMFs) and could represent the signal at different scales ranging from higher-frequency to lower-frequency in a multi-scale manner. EMD is first proposed by Huang et al. (1998) and has shown its advantages in handling non-linear and non-stationary signals. Benefiting from the attractive properties, there are plenty of EMD-based methods that have been proposed in 1D signal processing (Huang et al., 1998, 2003; Kopsinis and McLaughlin, 2009; Mandic et al., 2013; Di et al., 2014) and 2D image analysis (G. Xu et al., 2009; Subr et al., 2009; Çelebi and Ertürk, 2012; Niang et al., 2012; Krinidis and Krinidis, 2013; Xie, 2014; Zang et al., 2014, 2015; Ali et al., 2015).

Recently, EMD has attracted much attention in computer graphics and a few EMD-based methods for triangular mesh are proposed in Qin et al. (2009), H. Wang et al. (2012), Hu et al. (2014, 2016), Wang et al. (2015, 2017), Zhang et al. (2017). Despite the fact that EMD has exhibited its potential in 3D mesh processing, extending the existing techniques of EMD to operate directly on point clouds remains to be extremely challenging. This is primarily because of the point clouds are unorganized without topological information.

Furthermore, for irregular, curved, and complex geometric models, sharp features are usually contained in point clouds, more efforts should be taken to preserve them during EMD-enabled geometry processing. The original EMD is conducted via the sifting process by iteratively computing the mean envelope of the signal, in such a way the sharp feature could not be preserved. In the literature, a few attempts have modified the original EMD to achieve a feature-preserving EMD-based algorithm on triangular meshes, such as H. Wang et al. (2012) which was seeking an interpolation by minimizing a quadratic function that measures the similarity between the current vertex with its neighbors. However, the proposed feature-aware interpolation method is not sufficiently robust. In Hu et al. (2014), Hu et al. explicitly detected the feature vertices as soft constraints during envelope computation. In another way, a divide-and-conquer scheme of EMD is proposed in Wang et al. (2015) by explicitly separating the feature signals from non-feature signals. However, they have a drawback that the effectiveness of feature-preserving heavily depends on the result of sharp feature detection. If the models are contaminated with heavy noise, and features are not faithfully extracted, unpleasant artifacts emerge and sharp features turn out to be absolutely blurred.

In this paper, in order to overcome these limitations, we propose a multi-scale mesh-free EMD algorithm directly functioning over point clouds without building explicit connectivity among discrete points. We further explore its widespread applications in geometry analysis and processing. The multi-scale mesh-free EMD is achieved by iteratively extracting the detail level from the input signal and leaving the overall shape in residue. Furthermore, in order to preserve sharp features during point-based EMD analysis/processing, we devise a new envelope computation scheme aided by an anisotropic structure measurement. Inspired by the work of Zang et al. (2015), Park et al. (2012), the structure measurement is first constructed from the unstructured point clouds by the eigenvalue decomposition of voting tensor, which could faithfully characterize the micro-structure of any input model. Under the guidance of the structure measurement, the envelope is computed in a structure-aware manner and the sharp features could be well preserved. Then, the mean envelope is computed by creating adaptive shocks near salient structures and the input signal of the scattered point clouds is the finally represented in a multi-scale manner with features preserved in residue. The pipeline of proposed EMD algorithm on point clouds is illustrated in Fig. 1.

In comparison with previous works, the main contributions of this paper can be summarized as follows:

- Generalizing the classical EMD algorithm from Euclidean space to the setting of surfaces represented as unorganized point clouds, we are proposing the multi-scale mesh-free EMD. To the best of our knowledge, this is the first attempt to devise the EMD algorithm directly over discrete point clouds without the need of explicit mesh construction.
- Under the guidance of the structure measurement, we develop an efficient and novel feature-preserving EMD algorithm. Unlike previous feature-preserving EMD methods for meshed models, our algorithm does not explicitly resort to sharp feature detection, as a result, our new algorithm is more robust to noise and suitable for much more complicated point-based models.
- With the well decomposed multi-scale representation, we could explore various applications of point clouds, such as detail enhancement and smoothing, feature points extraction, and feature-preserving denoising, which collectively can demonstrate the utility of our novel multi-scale mesh-free EMD algorithm.

2. Related work

EMD is an important multi-scale decomposition method and initially proposed by Huang et al. (1998). In this section, we briefly introduce the related work of EMD on Euclidean space, 3D surfaces, and the feature-preserving EMD.