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# Quality point cloud normal estimation by guided least squares representation

Xiuping Liu [a], Jie Zhang [a], Junjie Cao [a,b,*], Bo Li [b], Ligang Liu [c]

[a] School of Mathematical Sciences, Dalian University of Technology, Dalian, China
[b] School of Mathematics and Information Science, Nanchang Hangkong University, Nanchang, China
[c] School of Mathematical Sciences, University of Science and Technology of China, Hefei, China

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ABSTRACT

In this paper, we present a quality point cloud normal estimation method via subspace segmentation based on guided least squares representation. A structure guided low-rank subspace segmentation model has been employed in normal estimation (LRRSGNE). In order to select a consistent sub-neighborhood for a point, the subspace segmentation model is adopted to analyze the underlying structure of its neighborhood. LRRSGNE generates more faithful normals than previous methods but at the price of a long runtime which may take hours. Following its framework, two improvements are proposed. We first devise a novel least squares representation based subspace segmentation model with structure guiding (LSRSG) and design a numerical algorithm which has a natural parallelism for solving it. It segments subspaces as quality as the low-rank model used in LRRSGNE but with less runtime. We prove that, no matter whether the subspaces are independent or disjoint, it generates a block-diagonal solution which leads to a quality subspace segmentation. To reduce the computational cost of the normal estimation framework further, we develop a subspace structure propagation algorithm. Only parts of the candidate feature points' neighborhoods are segmented by LSRSG and those of the rest candidate points are inferred via the propagation algorithm which is faster than LSRSG. The experiments exhibit that our method and LRRSGNE generate comparable normals and are more faithful than other state-of-the-art methods. Furthermore, hours of runtime of LRRSGNE is reduced to just minutes.
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## 1. Introduction

A tremendous amount of works on point clouds processing and analyzing, such as high quality point based rendering [3,4], surface reconstruction [5,6] and anisotropic smoothing [7], benefit from a quality normal associated with each point.

Although several kinds of 3D scanners output normals with point positions simultaneously, more of the ever-broadening range of general digitizing devices are not equipped with normals. Taking the most commonly used laser scanners as an example, points digitized by them are not intrinsically equipped with normals, which have to be estimated from acquired image or geometry data [8].

However, the acquired points are inevitably defect-ridden and normal estimation is sensitive to these detects including noise, non-uniformities, and so on. Hence the computation of quality normals is a challenge especially in the presence of sharp features, e.g., see Fig. 1.

Regression-based normal estimation methods [9–12] are most widely employed. They use all neighbors of a point to estimate its normal and tend to smooth sharp features. Some robust statistics approaches [13,14,1] estimate consistent sub-neighborhoods to compute normals for feature preserving. However the most recently proposed statistics-based method [1] generates unfaithful results for points with variational density near the sharp features, as shown in the top row of Fig. 1. To overcome the sampling anisotropy, Boulch and Marlet [2] design an uniform sampling strategy. However, in the vicinity of sharp features, some erroneous normals may still persist, as shown in Fig. 1. Moreover, the performance of this method drops when the dihedral angel is large. Utilizing the subspace structures of the underlying piecewise surfaces, LRRSGNE [15] selects a consistent sub-neighborhood to estimate quality normals in the presence of noise and anisotropic samplings. It generates more faithful normals than previous methods but at the price of a long runtime which may take hours. Hence it is impractical to employ it in practice.

In this paper we present a fast and robust approach to estimate normals for point clouds with sharp features. It follows the framework of LRRSGNE with two improvements, which contribute to make it generate quality normals as faithful as LRRSGNE, but

* Corresponding author.
*E-mail address:* jjcao@dlut.edu.cn (J. Cao).

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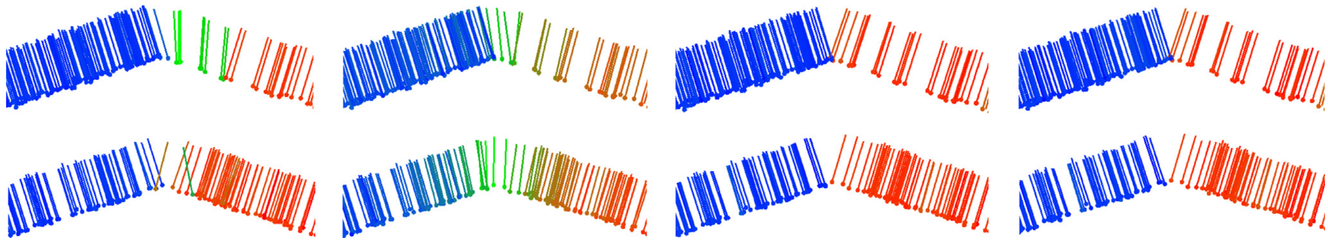

**Fig. 1.** Estimated normals of two planes with a shallow angle. The results of Li et al. [1], Boulch and Marlet [2], LRRSGNE, and our method are shown from the first column to the last. The points are sampled non-uniformly in the top row and uniformly in the bottom row. The points and normals are colored according to the normals' direction. Normals consistent with normals of left and right plane are colored in blue and red respectively, and the rest are colored in green. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

with far less runtime. First, the core of LRRSGNE is the neighborhood segmentation via subspace segmentation. It employs the structure guided low-rank representation model (LRRSG), which is a time-consuming non-smooth optimization problem. We formulate the neighborhood segmentation as a least squares representation with structure guiding (LSRSG). A rapid algorithm to solve it is devised and the algorithm has a natural parallelism. Large-scale dataset can be handled efficiently using the parallel implementation. We also prove that LSRSG generates a block-diagonal solution no matter whether the subspaces are independent or disjoint, which leads to a quality subspace segmentation.[1] Second, to reduce the runtime further, a subspace structure propagation algorithm is proposed. After analyzing the subspace structures for a small percentage points near sharp features via LSRSG, the rest candidate feature points' sub-neighborhoods are inferred from the previous computed structures. This speeds up the normal estimation significantly and reduces the process from hours to minutes. The contributions of our work are summarized as follows:

- A novel linear subspace segmentation model, LSRSG, is proposed. Even if the subspaces are not independent, it can exactly recover the subspace structure as well as LRRSG with less runtime.
- We prove the effectiveness of LSRSG in theory, and design a rapid numerical algorithm for solving it. The algorithm has a natural parallelism which makes it more suitable for handling the large-scale dataset efficiently.
- Combining LSRSG and the subspace structure propagation algorithm, we devise a fast and robust feature preserving normal estimation method. Comparable normals are estimated in minutes instead of LRRSGNE's hours of runtime and they are more faithful than other state-of-the-art methods.

## 2. Related work

### 2.1. Normal estimation

Normals play an important role in surface reconstruction and point rendering. There has been a considerable amount of works on normal estimation. Hoppe et al. [9] (PCA) estimate a point's normal by fitting a local plane to all neighbors of it. The method is the pioneer of regression based normal estimation and many variants of it are proposed [16]. Some higher order algebraic surfaces are used to replace planes. The properties of the spherical fitting are exploited by Guennebaud and Gross [10]. Cazals and Pouget [17] introduce the quadrics fitting to the normal estimation. Pauly et al. [18] propose a weighted version of PCA. They assign the Gaussian weights to the neighbors when estimating the local plane. By analyzing local information, such as curvature and noise, Niloy et al. [12] find the size of neighborhoods adaptively. For each point, Yoon et al. [14] obtain several different normals by generating random subsets of point cloud. Then an ensemble technique is used to combine the several different normals into a single. It is more robust to noise and outliers. However, all these methods fail to correctly estimate normals near sharp features.

Inspired by the feature preserving image filters, methods based on the improvement of preliminary normals are studied. Jones et al. [19] derive more faithful normals by 3D bilateral filter. Given a point, Calderon et al. [20] select the nearest neighbors belonging to the same plane with it by half-quadratic regularization which takes into account both positions and preliminary normals of the points. By fitting the points and their preliminary normals, [21,22] define normals as the gradients of locally reconstructed implicit surfaces. Although these methods improve the preliminary normals, estimating the preliminary normals roughly respecting sharp features are necessary.

Another class of methods is based on Voronoi diagram or Delaunay triangulation. For each point, Amenta and Bern [23] define the normal as the line through it and the furthest Voronoi vertex in its Voronoi cell. But it works only for the noise-free point clouds. By finding big Delaunay balls, Dey and Goswami [24] extend this technology to noisy point clouds. Alliez et al. [25] introduce a more stable normal estimation method which combines the advantages of PCA and Voronoi diagram. However, none of these methods are designed for the point clouds with sharp features.

More recently, various works on feature preserving normal estimation are proposed. Huang et al. [26] present an interesting combination of point cloud resampling and normal estimation. It is capable of producing accurate normals for the models with noise and outliers. However, the output of this method is a new consolidated point cloud, thus the normals corresponding to the original points are not computed. By maximizing the objective function based on kernel density estimation, Li et al. [1] reduce the influence of neighbors lying on different surfaces. It generates quality normals only for the point clouds which are sampled uniformly, since the kernel density estimation is sensitive to the sampling anisotropy. An uniform sampling strategy is proposed by Boulch and Marlet [2] to overcome the problem. However, this method still fails to correctly estimate the normals for the points extremely near sharp features. Moreover, it tends to smooth out the edges when the dihedral angles are large. Wang et al. [27] identify an anisotropic neighborhood via iterative reweighted plane fitting. Three kinds of weight functions related to point distance, fitted residual, and normal difference are considered.

[1] $N$ subspaces are called independent if and only if $dim(\oplus_{i=1}^{N}\mathcal{S}_i)=\sum_{i=1}^{N}dim(\mathcal{S}_i)$, where $\oplus$ is the direct sum. Two subspaces are said to be disjoint if they intersect only at the origin. $\mathcal{S}_i|_{i=1}^{N}$ are said to be disjoint if every two subspaces are disjoint. Notice that if $N$ subspaces are independent, they are disjoint as well. Hence disjointness is a more general assumption for the subspace set.

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