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Automatic segmentation of unorganized noisy point clouds based on the Gaussian map

Yu Liu*, Youlun Xiong[1]

State Key Laboratory of Digital Manufacturing Equipment & Technology, School of Mechanical Science & Engineering, Huazhong University of Science & Technology, Wuhan, Hubei, 430074, PR China

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Abstract

A nonparametric clustering algorithm, called cell mean shift (CMS), is developed to extract clusters of a set of points on the Gaussian sphere $\mathbf{S}^2$. It is computationally more efficient than the traditional mean shift (MS). Based on the singular value decomposition, the dimensional analysis is introduced to classify these clusters into point-, curve-, and area-form clusters. Each cluster is the Gaussian image of a set of points which will be examined by a connected search in $\mathbf{R}^3$. An orientation analysis of the Gaussian map to area-form clusters is applied to identify hyperbolic and elliptical regions. A signed point-to-plane distance function is used to identify points of convex and concave regions. Segmentation results of several real as well as synthetic point clouds, together with complexity analyses, are presented.
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Keywords: Segmentation; Clustering; Gaussian map; Mean shift; Dimensional analysis

1. Introduction

1.1. Related work

Segmentation is a necessary intermediate process in tasks such as object recognition, autonomous navigation, reverse engineering, or industrial inspection. Many segmentation methods have been reported, which fall into three categories: edge-based [1–4], region-based [5–7], and hybrid [8–10].

Edge-based methods detect edge points based on the behaviour of some features, such as normal or curvatures, in a cross-section perpendicular to the edge dividing different surfaces [2,3]. Points are usually classified according to the differences of the features between two adjacent points. However, to detect points on a sharp edge at the junction of two planes with a small difference in their normals, a threshold of normal differences may mistakenly take points on a highly-curved surface as edge points. Normal and curvatures used in segmentation are estimated from input data. Due to the sensitivity of curvatures to noise and the smooth effect in estimation results, edge-based methods are sensitive to noise in points, and suffer from edge fragmentation and the need for efficient post processing, e.g. gap filling.

Using global information such as the homogeneity or similarity of surface properties, region-based methods are more robust to noise than edge-based ones. Smooth surfaces can be classified into eight surface types according to a curvature sign map, which are taken as input for the further segmentation processes in [5,6]. However, the region growing method in [5,6] is time costly as it is iterative and needs to fit surface continually. Based on the scan line grouping idea, a faster image segmentation method is proposed in [7]. There are some demerits of region-based methods, including that the possibility of over- or under-segmentation, the difficulty to localize region borders accurately, and the sensitivity to the choice of the initial seed regions.

In order to overcome the limitations involved in the above two kinds of approaches, hybrid methods have been developed by combining the edge- and region-based information. An algorithm based on clustering is proposed in [8], in which a similarity measure for region merging is obtained from a statistical test. In [9], K-means clustering method is used to produce redundant regions first, the number of

* Corresponding author. Tel.: +86 27 8754 1765 607; fax: +86 27 8754 4175.
E-mail addresses: mse.liuyu@gmail.com (Y. Liu), ylxiong@mail.hust.edu.cn (Y. Xiong).
[1] Tel.: +86 27 8754 0052; fax: +86 27 8754 4175.

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which will be reduced by the following region growing and merging processes. Then boundary edges are rectified in a contour-tracking process. In [10], the standard deviation of the point normal vectors within each cell is used in subdivisions of initial cells, which indicates the level of changes in the shape of the object within each cell. Then the input is segmented by grouping the cells with the same or similar size.

Most objects in man-made environments have surface shapes that may be represented by portion of primitive surfaces including planes, cylinders, cones, spheres, and so on. It is interesting to note that object models perceived in a human mind are composed of primitives [11]. Therefore, it is desirable to identify the simple surface types and extract the associated geometrical parameters in segmentation processes. An approach to detect quadric features from range images based on the fuzzy C-shell clustering and geometrical invariants is developed by Cai et al. [12]. Unfortunately, their method requires a good initial estimation and the optimal cluster number to lead to fast and global convergence. Chen and Liu [13] proposed a general quadric surface extraction method using genetic algorithms (GA). In [14], an improved robust estimator was combined with GA to extract planar and quadric surfaces from range images. A drawback of GA-based methods is the difficulty in setting many parameters, which are problem-bound and must be empirically and carefully determined to avoid premature convergence. Recently, an approach using the normal sensitivity analysis was proposed to characterize the geometrical regularities of an arbitrary surface [15].

One problem existing in all of the segmentation tasks is that the structures or the mathematical model of the input data can not be determined a priori. In the processes to solve this problem, a series of new problems mentioned previously, such as the sensitivity to noise and the bridging of multiple structures, need to be considered. As demonstrated by Hoover et al. [16] and restated later by Jiang et al. [17], the segmentation problem is still not solved even for simple scenes containing only polyhedral objects.

1.2. Problem formation

Normal vectors are used in [1–3,10] to detect crease borders where two object surfaces have not the common tangent planes or surface normal vectors. If differences of normal vectors between a point and its neighbours are greater than a predefined threshold, the point is considered as a point on a crease border and is called a crease point. However, due to the smooth effect in estimation, changes of normal vectors become less obvious when across a crease border. And in previous works, normal vectors seem helpless to detect transition borders where two object surfaces have the same tangent planes or surface normals but they have not the same curvatures or curvature directions. Different from previous works, clustering characteristic of normal vectors is used to divide surfaces separated by both crease borders and transition borders in the approach presented.

Gaussian images and extended Gaussian images are useful for representing the shapes of surfaces [18,19]. They are used in applications such as visibility maps construction [20,21], 3D pose determination [22,23], 3D symmetry detection [24], segmentation [25], and so on. In [21], the optimal workpiece orientation problems are formulated as geometrical problems on the Gaussian sphere and solved by finding a spherical band of predefined width or a great circle which intersects the maximum number of spherical polygons. In [25], planar and extrusion surfaces are characterized by dimensions of their Gaussian images. However, the Gaussian image of a surface of an object has not been distinguished from the others before the segmentation task. Otherwise, it would be reasonably simple to divide the object into regions corresponding to different surfaces. It is known that the area of a surface is related with the area of its Gaussian image by Gaussian curvatures. When a surface is represented by uniformly sampled point set, the distribution of points' densities of the Gaussian image of the point set is a reflection of the curvature variation of the surface. Based on this observation, points on the Gaussian sphere are grouped into different clusters in our segmentation approach. Moreover, some other operations, such as connected search, dimensional analysis, orientation analysis, and so on, are combined to distinguish different surfaces with overlapped Gaussian images.

Parametric clustering algorithms, such as K-means clustering, are used in some segmentation methods mentioned previously [9,12]. These clustering algorithms often rely upon the correctly specifying the values for tuning parameters and have embedded assumptions. For example, K-means clustering algorithm needs to know the number of clusters beforehand and assumes that the clusters have spherical shapes. A nonparametric clustering algorithm, such as mean shift (MS), has none of the above limitations. The MS procedure is proposed by Fukunaga and Hostetler [26], and revisited by Cheng [27]. In spite of great popularity in the computer vision community recently [28,29], few works have been done for its application in segmentation of 3D coordinated points. In [30], each triangle of a mesh is represented by a six dimensional vector composed of its centroid and normal. Then MS is employed for clustering such vectors and mesh triangles are grouped based on the differences of normals between two adjacent triangles. However, their method cannot identify primitives (e.g. planar, cylindrical and conical surfaces).

Based on the MS procedure, cell mean shift (CMS) is developed to cluster points on the Gaussian sphere, whose convergence has been verified. Subbarao and Meer [31] have given a general treatment of MS under analytical manifolds, including Grassman manifolds such as spheres. However, a practical implementation of their method requires the computation of gradient vectors and exponential operators, while the CMS is more intuitive and easier to implement. Moreover, the convergence of their method has not been proved. MS procedure can be accelerated by reducing the total number of iterations or the computational time of a MS iteration. The computation cost of a MS iteration depends on the computation of MS vectors, which should be considered especially in high dimensional spaces [32]. To reduce the total number of iterations performed, a cell quantization can be integrated with the MS procedure [33]. Instead of in a general space, cells in the

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