Signal Processing: Image Communication 52 (2017) 138–150

Contents lists available at ScienceDirect

Signal Processing: Image Communication

journal homepage: www.elsevier.com/locate/image

An efficient unsupervised diffusion clustering algorithm with application to shape decomposition based on visibility context

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ARTICLE INFO

Keywords:
Graph clustering
Shape decomposition
Visibility
Diffusion

ABSTRACT

In this paper the two and three dimensional of a single shape partitioning problem is revisited by means of an iterative, non supervised, very fast and effective algorithm. The notion of visibility context is used as the shape signature, which actually provides a physical meaning to the representation. The visibility serves as a means to manipulate on the shape parts applying clustering techniques to the corresponding graph. Therefore, the decomposition problem is re-casted as a clustering problem. An unsupervised Diffusion Clustering Algorithm is proposed, which efficiently achieves to capture the functional shape parts. Although the proposed algorithm is developed and fits very well to the specific problem of the shape partitioning, its utility is undoubtedly much more general. Experimental results conducted on two and three dimensional shape databases are very promising.

1. Introduction

Automatic two dimensional (2D) and three dimensional (3D) shape segmentation into functional parts is undoubtedly useful for several applications (shape retrieval, skeleton extraction etc) that employ the divide and conquer strategy – which is usually more efficient in terms of computational complexity - and obviously benefits from segmentations that match the human perception. Although some remarkable efforts have been made and many partitioning algorithms have been proposed [1], the issue is still challenging in the scientific society, mostly due to the perceptual interference. In addition, sometimes, the quality of segmentation is application dependent. All these remarks manifest the well known gap that exists between low and high level description of a shape.

In the method proposed in this paper, the shape is modeled by exploiting its visibility context which is proved to be an effective and perceptual compatible way of representation [2]. Using the visibility context indirectly implies that the convex parts of each shape are captured, which are known to imitate the human's way of partitioning. For each shape, the visibility context is tabulated into a binary adjacency matrix, resulting from the corresponding undirected graph. As in every such graph, defining an appropriate neighborhood is considered essential in order to model local geometry. Besides its contribution to better shape representation, the neighborhood restriction lays the respective matrix sparse which in turn drastically reduces the needed computational cost.

A basic notion which is used in the proposed method, is the diffusion procedure, which is efficiently alternated iteratively with a shrinking process. Diffusing the visibility context succeeds in efficiently capturing the non-rigid parts of a shape, while the shrinking procedure is actually a normalization process which aims to restrict excessive diffusion. Iterating these two distinct steps a certain number of times results in a robust shape partitioning matrix. It is worth mentioning that the visibility matrix which represents the shape is in full accordance with the proposed Diffusion Clustering Algorithm (DCA), which produces a new adjacency binary matrix at each iteration. It should be also noticed that this is a non-parametric search, very well suited to the shape decomposition problem with unknown number of output clusters. The algorithm can be applied to both 2D shape boundaries and 3D meshes, with very good results as it is shown in the experimental results section. Once the visibility matrix is constructed, the proposed iterative clustering procedure is very fast and effective. A comprehensive view of the proposed diffusion clustering algorithm decomposition method is depicted in Fig. 1.

The paper is organized as follows. In Section 2 an overview of the existing shape segmentation methods is given. The visibility graph construction is described in Section 3 and in Section 4 the novel clustering algorithm is presented. The obtained experimental results are contained in Section 5 and finally the paper concludes in Section 6.

2. Literature overview

Generally, there exist two main categories of shape segmentation. The first category consists of methods that aim to partition a shape into

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http://dx.doi.org/10.1016/j.image.2016.12.012
Received 18 June 2016; Received in revised form 29 December 2016; Accepted 30 December 2016
Available online 01 January 2017
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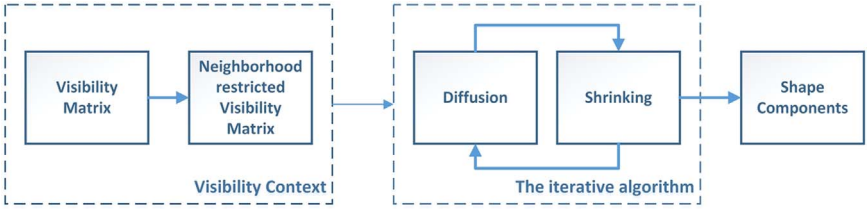

Fig. 1. An outline of the proposed shape decomposition method. In the first stage the visibility context is assigned. The neighborhood information is incorporated by canceling connections outside the defined neighborhood. In the second stage the diffusion process extends visibility while increasing adjacency in intra-class nodes. In the shrinking step a threshold is applied reducing weak connections and organizing the final classes, which emerge in the final stage.

purely geometric components, while in the second one, methods that divide a shape into meaningful components are included. As our proposed method falls into the second category, we will mainly proceed with briefing the algorithms of this group.

As already mentioned, decomposing a shape into its functional parts is not an easy task due to the involvement of the human's perception. However there exist some rules, borrowed from the field of cognitive theory that assist finding correct decomposition methods. The most important are the minima rule [3] according to which the negative curvature minima of the bounding contour are considered as potential points of shape separation, the short cut rule [4] where the assumption that humans divide a shape using the shortest possible cuts is invoked and the convexity rule [5] that requires a part to be convex. In the following paragraph methods that use the above mentioned rules, but not limited to, are briefly described.

The authors of [5] propose a method that uses both convex – that are easily obtained- and non-convex parts for decomposition. The latter parts are acquired by using a contour evolution procedure. In addition, in [6] the shape decomposition is achieved either by cutting the shape in a way that the remaining item has the simplest structure or the part itself takes on a simple shape. A method that uses the notion of cuts in a shape, is introduced in [7]. The authors solve a combinatorial optimization problem in order to select an optimum set of edges of a constrained Delaunay triangulation of a given polygonal description of a shape. To continue, other methods basically try to detect the convex parts of a shape. In [8], a polygon is used for the shape representation and a user tuning parameter determines the convexity tolerance. In [9], based on the notion of “mutex pairs”, a stricter convex shape decomposition is proposed. The method proposed in [10] achieves to relax the convexity constraint proposed in [9] in an attempt to avoid over segmentation. The convexity tolerance is also specified by a user parameter. The authors of [11] propose a 2D shape decomposition method which is based on the short cut rule. Apart from the above mentioned methods that rely on the three perceptual rules, in [12] an additional rule is introduced named part-similarity- to encourage consistent partition of similar parts, which is in accordance with the human conception.

Other category of algorithms include an appropriate graph construction stage as a head-start which represents the shape. Since the method introduced in this paper belongs to this group, we consider it essential to review some other techniques of this group. Preliminary results have been presented in [13] for 2D shape decomposition, which were very promising. In [14] a 2D shape is represented by a binary graph, which captures the mutual visibility of boundary pairs, followed by a graph theoretic clustering method in order to partition it into clusters that intuitively correspond to shape parts. A similar graph to the [14] is also used by the authors of [15] but the neighborhood information is additionally incorporated by canceling connections outside the defined neighborhood. This method uses a NMF-based algorithm, posing though additional constraints. Another technique that uses a constrained NMF algorithm is proposed in [16], which is applied in 3D meshes. At last, a dominant sets unsupervised approach which is based on the notion of the clique graphs and achieves noteworthy results is presented in [17].

Some methods that aim to address the problem of perceptual consistency in the decomposition results are stated. In [18], the skeleton has to be constructed as a first step and Discrete Contour Evolution (DCE)-based measures are required as visual features that reflect human perception. The method can handle shapes with holes, too. A question is whether this method can be extended to 3D shapes decomposition. The authors of [19] use supervised learning for their method, which means that human learning is included thus a human labeling is required. In [20] a probabilistic framework is included, where several parses of a shape are produced, that facilitate the matching process that follows. Shape skeleton is required in this method and a learning procedure takes place. Finally, in [21] the authors present a method that can successfully deals with shapes including holes. However we are not going to discuss such methods, as the proposed algorithm does not fall in this category.

For the 3D shapes, there exist two different types of segmentation, namely, the part and the surface. In the first type of methods the objective is to decompose a mesh into volumetric parts of perceptual meaning, while in the latter the aim is to partition a surface into patches, following certain criteria. We are mainly interested in the first group of algorithms, and so is the discussion that follows. The concepts supporting this type of decomposition can be mainly classified into (i) minima rule (ii) connection to the shape's volume to the mesh surface (iii) hierarchical clustering (iv) skeleton-based segmentation and (v) salient point and core estimation [22].

Methods that are based on the rationale of the convexity rule usually follow the minima rule approach. In [23] the components are first found in a fuzzy clustering method: the notion that each face belongs to exactly one partition, is relaxed. The final decomposition is accomplished by using a minimum cut algorithm. To continue, in [24] spectral clustering is applied to 3D meshes, which uses the pairwise face distances that are proposed in [23] for mesh segmentation. An eigenanalysis of the normalized affinity matrix, which tabulates the likelihood of each pair of faces belonging to the same group is performed, where the k largest eigenvectors are used. Then a k-means algorithm is applied to, that results in faces' grouping, given an initial guess of cluster number.

Methods described in [25,26] connect the shape's volume to the mesh surface. In the first one 3D shapes are decomposed using the Poisson equation as signature, which assigns a value to each internal voxel in the shape's volume. A recursive algorithm follows, and finally, a post processing refinement procedure concludes this method. Although the second method is based on the convexity rule, it uses morphological operations to embed this rationale. Experiments in 2D shapes are conducted, but it can be directly applied to 3D shapes by using voxelization.

Other methods include hierarchical algorithms which create a hierarchy of decomposition results, appropriately organized into a tree. Attene et al. [27] use the hierarchical clustering in order to partition the mesh triangles so that they can be approximated by certain geometric shapes.

To continue, there also exist methods that presuppose the skeleton construction for the 3D object and use it for the decomposition issue. Such method is studied in [28] where the notion of 3D shape

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