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Technical Section

A contour-based segmentation algorithm for triangle meshes in 3D space

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ABSTRACT

This paper introduces the first contour-based mesh segmentation algorithm that we may find in the literature, which is inspired in the edge-based segmentation techniques used in image analysis, as opposite to region-based segmentation techniques. Its leading idea is to firstly find the contour of each region, and then to identify and collect all of its inner triangles. The encountered mesh regions correspond to ups and downs, which do not need to be strictly convex nor strictly concave, respectively. These regions, called relaxedly convex regions (or saliences) and relaxedly concave regions (or recesses), produce segmentations that are less-sensitive to noise and, at the same time, are more intuitive from the human point of view; hence it is called human perception-oriented (HPO) segmentation. Besides, and unlike the current state-of-the-art in mesh segmentation, the existence of these relaxed regions makes the algorithm suited to both nonfreeform and freeform objects.

1. Introduction

Mesh segmentation is a fundamental procedure in areas as diverse as geometric modeling, computer-aided design, computer graphics, and so forth [37]. This procedure consists in partitioning a mesh into a number of sub-meshes in conformity with some convexity criterion. Intuitively, this is equivalent to detect and delimit the ups (saliences) and downs (recesses) of the mesh, as illustrated in Fig. 1. But, as argued by Attene et al. [3], mesh segmentation can be driven by either geometric criteria or semantic criteria or both.

In geometry-based segmentation techniques, the mesh is divided into a number of sub-meshes or regions that satisfy some geometric property (e.g., curvature and distance to a fitting plane). On the other hand, in semantics-based segmentation techniques, the division of a mesh into sub-meshes takes place when each sub-mesh delimits a perceptually meaningful region (e.g., an arm of the human body). In this respect, Biederman [6] states that the people perceive objects as collections of parts, while Hoffman [20] refers that the human vision defines boundaries of parts along the negative minima of principal curvatures. Note that, in a way, Hoffman's assertion implies that the meaningful parts are essentially convex.

Hoffman's assertion has inspired the development of our algorithm, so we follow the leading idea of how human vision perceives the boundaries of parts. Let us say that our algorithm has been also inspired in the well-known family of edge-based segmentation algorithms found in image analysis and algorithms. With these edge-based algorithms, we first find the boundaries of each region, filling it afterwards; hence, the contour-based segmentation (region contour or boundary first, then its interior). On the contrary, the region-based algorithms work in the other way round: first the region is formed incrementally, being its frontier defined by some stopping condition.

As far as we know, we are here proposing the first contour-based segmentation in the domain of mesh segmentation in 3D. For this purpose, the point membership test (PMT) is here used as a convexity classifier, i.e., we use PMT to classify edges as convex, concave or flat. PMT is a particular case of the SMC (set membership classification) test, which is very popular in CSG (constructive solid geometry) modeling, and has been around for the last three to four decades [43]. Nevertheless, recesses and saliences on the mesh are not classified in a so strict manner in terms of convexity. We introduce the notion of *relaxed convexity* to classify those shape features of the mesh. A salience is a relaxedly convex region, while a recess is a relaxedly concave region. A relaxedly convex region is not strictly convex, i.e., it admits small concavities. On the other hand, a relaxedly concave region is not strictly concave, i.e., it admits small convexities. This shape relaxation allows us to minimize the effects of noise related to over-segmentation, and makes it suited to the segmentation of freeform objects such as, for example, the ant shown in Fig. 1.

The remainder of the paper is organized as follows. Section 2 briefly reviews the related work existing in the literature. Section 3

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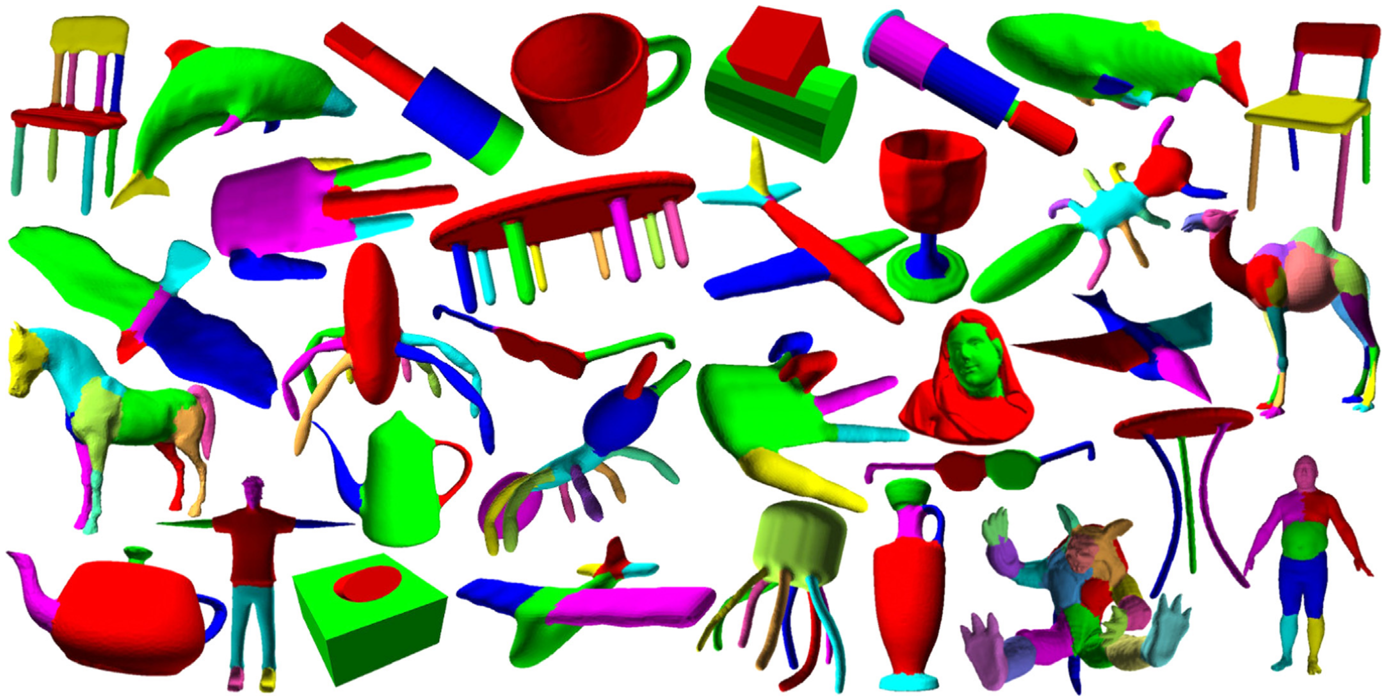

Fig. 1. Segmented meshes (or models) using the human perception-oriented (HPO) segmentation. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

details the background that is on the basis of our algorithm, including PMT and the concept of relaxed convexity. Section 4 outlines our contour-based segmentation algorithm, called HPO segmentation. Section 5 details the region filling step of HPO segmentation algorithm. Section 6 introduces the mesh smoothing step (a Laplacian filter, in particular) for noisy meshes, which uses the cumulative area histogram analysis to identify whether a mesh is noisy or not. Section 7 describes the region merging step of HPO segmentation algorithm. Section 8 presents the most relevant experimental results produced by the HPO segmentation algorithm, in particular the benchmarking results produced by Princeton's benchmark software. Finally, Section 9 concludes the paper.

2. Related work

Intuitively, mesh segmentation consists in dividing a mesh into meaningful sub-meshes (or regions). With reference to the structural dimension of mesh regions, segmentation algorithms can be categorized as follows: *volume-based*, *surface-based*, and *skeleton-based*. These three segmentation categories are all based on geometry, including concepts of the convexity theory, topology, and homology. Independently of the nature of the segmentation technique, most algorithms make use of some geometric or topological criteria that guide the segmentation of a given mesh [37]. Examples of geometric criteria are the curvature [24], geodesic distances [46], dihedral angles [48], shape diameter function [38], planarity [21], symmetry [34], convexity [27,31], concavity [25,15], volume [19], etc. Topological criteria include Reeb graphs [42] and spectral analysis [47].

Volume-based segmentation (also called *part-type* segmentation) algorithms can be considered as the former category of segmentation algorithms. In this case, the segments are volumes. This family of algorithms follows the principle of decomposing a 3D volumetric object into a set of convex sub-objects (or convex volumes). The basic problem of convex decomposition of polyhedra was firstly addressed by Chazelle [11,5,9], but such decompositions usually are costly in terms of time performance and memory space. More amenable decompositions, called approximate convex decompositions (ACD), have been proposed in the literature [29,26,15]. This sort of decomposition is based on a measure of concavity; for example, the ACD proposed in [30] is guided by the volume ratio between the actual object and its convex hull, Ghosh et al. [15] propose a new strategy that improves the results of the ACD, while the one due to Kraevoy et al. [26] is generated by measuring the average distance from all object's triangles to the object's convex hull.

In *surface-based* segmentation (also known as *surface-type*) algorithms, the segments are regions of a 2D triangle mesh. Each region consists of a number of connected triangles that have similar geometric properties (e.g., convexity and curvature). In the literature, we find the following major sub-categories surface-based algorithms: region growing [10,21], watersheds [33,48], hierarchical clustering [14], iterative clustering [36,23], spectral clustering [32,35], and fuzzy clustering [23].

In *skeleton-based* segmentation (also known as *skeletonization*) algorithms, the segments are line segments. The input is either a 3D volumetric mesh or a 2D surface mesh, but the output is a 1D skeleton that represents the structural shape of the mesh. A skeleton provides us with the one-dimensional topological shape of a given higher-dimensional object. Generating such a skeleton is a process known as skeleton extraction or skeletonization [8,23]. Examples of automatic skeletonization techniques are found in the literature, including the Medial Axis Transform (MAT) [7], Shock graph [41] (i.e., another MAT representation), and Reeb graph extracted from various Morse functions [39].

Note that our algorithm falls into the category of surface-based algorithms, but it does not fit any of its sub-categories. Making a parallel with the two more important families of segmentation algorithms we may find in image analysis and processing [17], a region-based segmentation algorithm starts somewhere in the interior of each region and stops on its frontier, while a contour-based segmentation algorithm starts on the frontier of each region and stops in its interior. This means that, we do not need to calculate