Computer-Aided Design 42 (2010) 67–75

Contents lists available at ScienceDirect

Computer-Aided Design

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

Carving for topology simplification of polygonal meshes

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ARTICLE INFO

Article history:
Received 15 July 2008
Accepted 2 April 2009

Keywords:
Model simplification
Topology simplification
Level-of-detail generation
Shape approximation
Geometric modeling

ABSTRACT

The topological complexity of polygonal meshes has a large impact on the performance of various geometric processing algorithms, such as rendering and collision detection algorithms. Several approaches for simplifying topology have been discussed in the literature. These methods operate locally on models, which makes their effect on the topology hard to predict and analyze. Most existing methods tend to exhibit several disturbing artifacts, such as shrinking of the input and splitting of its components. We propose a novel top-down approach for topology simplification that avoids most problems that are common in existing methods. We start with a simple, genus-zero mesh that bounds the input and gradually introduce topologic features by a series of carving operations. This process yields a multiresolution stream of meshes with increasing topologic level of detail. We further present a carving algorithm that is based on constrained Delaunay tetrahedralization. The algorithm first constructs the tetrahedral mesh of the complement of the input with respect to its convex hull. It then proceeds to eliminate tetrahedra in a prioritized manner. We present quality results for two families of meshes that are difficult to simplify by all existing methods known to us: topologically complex meshes and highly clustered meshes.

1. Introduction

Topology simplification has been identified in the graphics literature as a critical task for various general and domain-specific applications. Simplifying the topology of complex models is often necessary for geometric simplification to achieve quality results. Topology simplification might also be necessary for generating level-of-detail representations. For this purpose, aggregating a large number of objects or components might be required before simplifying each of the objects thoroughly. Topology simplification is important for efficiency reasons as well. The performance of collision-detection algorithms is known to depend heavily on the genus of objects [1]. Finally, topologic features can cause several undesirable artifacts, such as image-space aliasing. It is thus desirable to simplify the topology of polygonal models before or through geometric simplification.

Given a mesh, we are interested in generating a topological multiresolution stream of approximations. The component count and genus of the approximations will be represented with increasing detail through the stream. We would also like the geometric complexity of the mesh to be monotonic in the number of vertices in order to provide progressively refined geometric approximations. Another important property we require from the algorithm is to produce approximations that are guaranteed to be free of self-intersection.

Several approaches have been proposed in the literature to reduce the topologic complexity of polygonal meshes. In most of these approaches, the simplification process affects the topology in a way that is hard to predict and analyze. Proximity-based methods, such as pair-collapse [2,3] and clustering [4,5], are based on the proximity between vertices. They allow topological changes and aggregation but do not identify and remove parts of the surface that become internal. Thus, they may end up complicating the topology rather than simplifying it. Such methods can also join components or do the opposite (see Fig. 1). The number of components in the model is then not monotonic, as it can increase and decrease unexpectedly. In contrast, one would like each component of the original surface to be represented by at most one component in each generated approximation. In general, the number of components is preferred to be monotonically decreasing or increasing through the decimation or refinement, respectively.

Shrinking of the input is another problem that is common in most existing simplification methods. In addition to a reduction in the overall size of the model, shrinking causes small components to reach sub-pixel dimensions and finally disappear. A class of meshes particularly vulnerable to shrinking consists of meshes whose center is highly clustered, i.e., consists of a large number of small components. In such models the vertices in the center pull

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doi:10.1016/j.cad.2009.04.001

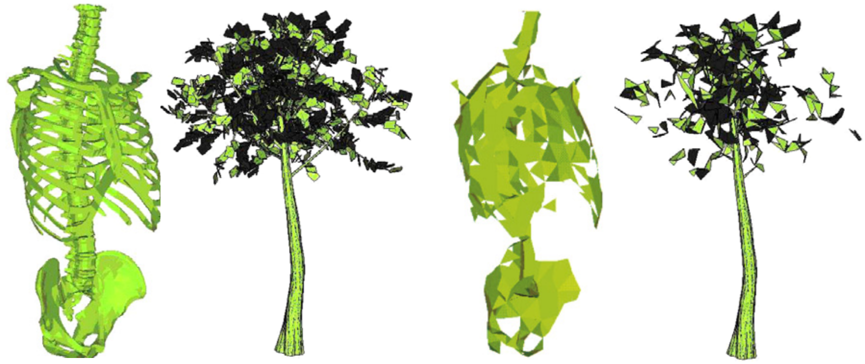

Fig. 1. The effect of the pair-collapse operator on a topologically complex model and a highly clustered non-manifold model: (a) Original models, (b) pair-collapse simplified models. Note the increased number of disconnected components and shrunk appearance.

the approximation towards the inside. In contrast, when viewing from the outside, one would like a highly clustered model to be coarsened from the inside towards the outside. This can maintain the general shape and dimensions of the model. It can also be motivated by a basic assumption that usually the central part of a complex model is less visible to an outside viewer. For instance, to simplify a model of a detailed motor that includes all the internal mechanical parts, it is reasonable to begin with a more aggressive simplification on the inside than on the outside.

This work presents a novel approach for topology simplification of unstructured polygonal surfaces. Our method addresses all the above issues and avoid problems that are common in most topology simplification schemes. We simulate the action of a carver and draw from the α-shape [6] and shrink-wrapping [7] concepts. Using a top-down refinement scheme, we construct a multiresolution representation that coarsens topologically. We start with a genus-zero bounding object, such as the convex hull, as an initial approximation and gradually introduce topologic features by splitting to components and creating tunnels. We achieve this by tetrahedralizing the complement of the input with respect to the initial approximation, and carving the resulting tetrahedra from the initial approximation until the input is reached. To control the order, we prioritize the tetrahedra according to the error they introduce into the model. We further propose two parameterizations to the algorithm for controlling its effect and avoiding two problems that can arise, referred to as snaking and spiking. We demonstrate that the proposed method allows both aggregation of multiple components and genus reduction in a natural way, while maintaining the visual properties of meshes.

The remainder of this paper is organized as follows. Section 2 reviews related topology simplification approaches, as well as surface reconstruction and remeshing concepts. Section 3 outlines our approach and discusses design decisions regarding the implementation of a carving algorithm. Section 4 describes our carving algorithm, which is based on constrained Delaunay tetrahedralization (CDT) [8,9]. Section 5 describes two useful parameterizations of the algorithm that provide control over the process and avoid problems in produced approximations. Section 6 presents some results and discussion. Section 7 summarizes our contribution, and describes limitations and future work.

2. Related work

In this section we briefly review related work from the field of topology simplification, as well as concepts from surface reconstruction and remeshing.

2.1. Topology simplification

In various cases, topology simplifying steps have to be taken for performing aggressive geometric simplification. This can be necessary in order for the input not to degenerate or lose its basic characteristics. Meshes consisting of multiple geometrically disjoint components or scenes consisting of a large number of objects demand a different approach than simplifying each component separately. In such cases, even after each component has reached minimum resolution, the number of components can still imply a massive model size. The problem we address is thus the simplification of a topologically complex model, which consists of multiple disconnected components and high genus.

Rossignac and Borrel [5] propose imposing a global grid over the input dataset and cluster vertices into cells, which are then replaced by unified vertices. Later, Luebke and Erikson [4] extended this method and defined a tight octree over an input model to generate a view-dependent hierarchy. These approaches can reduce the genus and number of components if the desired simplification regions fall within a grid cell. However, it can also widen holes and tunnels that fall across grid cells.

He et al. [10] proposed using a low-pass filter in the volumetric domain to simplify the genus of the input in a controlled fashion. This method is capable of aggregating disjoint components and reducing the genus of objects. However, there is no correlation between vertices of the input and vertices of the simplified mesh. In addition, meshes simplified by this method are subject to shrinking. Wood et al. [11] developed an algorithm for removing topological errors in isosurfaces in the form of tiny handles by sweeping the models and constructing a Reeb graph. Bischoff et al. [12] extract isosurfaces with controlled topology. They start with an initial estimate of the final surface and then morph the model into the final result using a topology-preserving growing scheme. Zhou et al. [13] recently proposed a solid modeling approach that repairs topological errors in the form of small surface handles. Gerstner and Pajarola [14] proposed a technique for controlled topology simplification by multiresolution isosurface extraction. Andujar et al. [15] have developed an automatic simplification algorithm to generate a multiresolution representation from an initial boundary representation of a polyhedral solid. However, this method is not straightforward to implement and produces non-regular regions. These methods work in the volumetric domain and perform topology simplification by converting a three-dimensional (3D) polygonal model to and from its volumetric representation. This conversion usually does not preserve the correspondence between the vertices of the input model and the vertices of the simplified one. It also often results in an increased