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Geometry seam carving

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HIGHLIGHTS

- Mesh deformation with preservation of salient features.
- Transfer of the concept of seam carving from images to 3D meshes.
- Combination of elastic mesh editing with a novel discrete mesh deformation approach.
- Adaptation of the surface tessellation to the degree of the deformation distortion.

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ABSTRACT

We present a novel approach to feature-aware mesh deformation. Previous mesh editing methods are based on an elastic deformation model and thus tend to uniformly distribute the distortion in a least-squares sense over the entire deformation region. Recent results from image resizing, however, show that discrete local modifications such as deleting or adding connected seams of image pixels in regions with low saliency lead to far superior preservation of local features compared to uniform scaling — the image retargeting analog to least-squares mesh deformation. Hence, we propose a discrete mesh editing scheme that combines elastic as well as plastic deformation (in regions with little geometric detail) by transferring the concept of seam carving from image retargeting to the mesh deformation scenario. A geometry seam consists of a connected strip of triangles within the mesh's deformation region. By collapsing or splitting the interior edges of this strip, we perform a deletion or insertion operation that is equivalent to image seam carving and can be interpreted as a local plastic deformation. We use a feature measure to rate the geometric saliency of each triangle in the mesh and a well-adjusted distortion measure to determine where the current mesh distortion asks for plastic deformations, i.e., for deletion or insertion of geometry seams. Precomputing a fixed set of low-saliency seams in the deformation region allows us to perform fast seam deletion and insertion operations in a predetermined order such that the local mesh modifications are properly restored when a mesh editing operation is (partially) undone. Geometry seam carving hence enables the deformation of a given mesh in a way that causes stronger distortion in homogeneous mesh regions while salient features are preserved much better.

1. Introduction

The deformation of three-dimensional (3D) models has a wide range of applications in artistic as well as industrial design. Nowadays, the predominant representations of surfaces are triangle meshes which come at high resolution, often acquired using 3D laser scanning, and exhibiting geometric details at various scales. For a deformation technique to be considered useful for editing of such meshes, it is hence crucial that it meets certain requirements: apart from providing visual feedback for interactive application, it should provide easy to control modeling metaphors. Most importantly, it should generate intuitive and predictable deformation results that are physically plausible and aesthetically pleasing. In order to meet these quality requirements, a deformation method has to preserve local characteristics of a surface, i.e., geometric detail or features, under deformation.

This paper presents a novel mesh deformation technique that puts special emphasis on the aspect of feature preservation. Previous mesh editing approaches are mostly based on an elastic deformation model and usually distribute the distortion over the entire deformation region in a least-squares sense. Recent research on image resizing, however, demonstrated that discrete modifications produce results that are far superior to those obtained by applying uniform scaling, which can be considered as the analog in the image processing world to a least-squares deformation in the mesh editing world.

In their work on image seam carving, Avidan and Shamir [1] insert or delete a connected seam of image pixels in regions with low energy, yielding realistically looking and visually pleasing resizing

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results. In our work, we transfer the concept of discrete modifications from the image retargeting to the mesh deformation scenario. Our definition of a seam is closely related to the image setting: a *geometry seam* is a closed and connected path of low-energy triangles and runs through the modeling region of a mesh. Depending on the characteristics of the deformation, geometry seams can be removed from the mesh by collapsing their interior edges and they can be inserted by splitting these edges, which resembles the delete or insert operations in image seam carving. By precomputing a set of low-saliency seams, we can perform deletion and insertion operations at interactive rates. Furthermore, applying the operations in a predetermined order allows us to properly undo previous editing operations and hence to restore the original model. We use a well-established elastic mesh deformation method which we significantly adapt such that it jointly works with this novel plastic and discrete modification scheme which intervenes when the surface distortion exceeds certain thresholds and calls for additional remeshing. This enables editing of a 3D model, thereby distributing the distortion non-homogeneously over the model, and hence causing stronger deformations in low-saliency mesh regions, while features are preserved much better compared to purely elastic mesh editing methods.

2. Related work

There exists a wide variety of surface deformation techniques in the literature which, in order to position our work, we roughly classify into two categories. First, there are general deformation techniques that allow for general editing operations and that distribute the deformation error over the entire object. Second, there exist structure-aware techniques that perform a structure analysis in a preprocessing phase and then restrict the allowed modifications to application-dependent editing operations that preserve the structure-defining mesh features. The first class of methods comprises purely geometric general deformation techniques ranging from surface-based methods (linear as well as non-linear (e.g. Botsch et al. [2])) over physically based techniques (e.g. Nealen et al. [3]) to space- or free-form deformation methods (e.g. Bechmann [4]). Due to their fast, efficient, and robust nature, linear surface-based techniques (see Botsch and Sorkine [5] for an excellent survey) have been an intensively investigated field in Computer Graphics and object modeling. They usually formulate the surface deformation as a global quadratic variational optimization problem whose solution can be obtained by solving a sparse linear system of equations subject to a set of modeling constraints that are inferred from the user interaction. The deformation error is thereby distributed over the modeling region in a least-squares sense, and the mesh topology remains unchanged. We characterize these methods as *elastic* deformation techniques, since the deformed models are always elastically distorted versions of the original input geometry. While these approaches generate very intuitive and aesthetically pleasing results for organic objects such as animals, faces, body parts, and so on, they often fail in providing intuitive deformations of man-made objects such as mechanical parts, furniture, architectural models, etc. The latter type of objects usually exhibits flat regions and sharp characteristic features that define the shape of the entire object. When these surface characteristics are distorted, the model' s defining structure is seriously disturbed. Masuda et al. [6] proposed a surface-based mesh editing framework that introduces hard constraints into the deformation and hence allows one to rigidly preserve sharp features or hole boundaries under deformation. However, these hard constraints need to be manually selected by the user in a preprocessing step.

The shortcomings of general deformation methods in preserving certain inherent structures of an object gave rise to a research field that has gained a lot of attention in recent years. This second class of deformation techniques focuses on structure-aware shape deformation. They usually analyze the input shape and detect regular patterns (e.g. Pauly et al. [7], Bokeloh et al. [8]) or extract a set of characteristic curves that define the surface (e.g. Singh and Fiume [9], Gal et al. [10]) in a preprocessing step. The models are then edited by either adding and removing local pattern elements or by manipulating the characteristic curves. However, these techniques are usually targeted at man-made objects, as this class of models typically exhibits the required feature structures. Decomposing a model into its structural elements and replicating or scaling these structures is often applied in architectural applications (e.g. Lin et al. [11]), as buildings usually exhibit strong regularity. Restricting the type of possible editing operations to these characteristic entities preserves the defining surface structure under editing operations. We characterize the techniques comprised in this second class of methods as *plastic* deformation methods, since the deformed models are generated by adding or removing certain structures or "surface material" from the original input geometry.

Related to these approaches is the work on non-homogeneous resizing of complex models by Kraevoy et al. [12]. They detect mesh regions that are likely to suffer from distortion artifacts and embed the model into a protective grid. During resizing, the grid is scaled non-homogeneously while respecting the varying vulnerability, and hence the method distributes the scaling throughout less vulnerable regions of the model. However, the types of supported deformations are again restricted, this time to scaling or stretching along orthogonal directions. General deformations introduced by affine transformations cannot be applied, as the vulnerability map depends on the axis along which the model is scaled. In material-aware deformations by Popa et al. [13], the deformation error is also distributed non-homogeneously over the model in a way that respects predefined material properties in order to introduce varying stiffness into the deformation.

The observation we share with the second class of editing techniques is that visual artifacts are caused by distorted features, and hence are localized in surface regions exhibiting high saliency, while other regions are less vulnerable to shape distortions. Hence, the deformation should be distributed non-homogeneously over the model, thereby protecting feature parts while others are deformed more excessively. However, instead of using regular patterns or curves as modeling metaphors, or restricting the supported editing operations to certain directions or special transformations, our method uses the well-established handle metaphor that enables the user to apply arbitrary affine transformations to the model. Hence, our approach combines the efficient and very intuitive control offered by the first class of methods, the unrestricted linear surface deformation techniques, with a content-respecting distribution of the distortion as provided by the second class of restricted methods. We combine the advantages of both approaches by augmenting a widely used general and *elastic* Laplacian-based deformation technique with a novel discrete and *plastic* mesh modification scheme that adopts the mesh tessellation to the varying degree of surface distortion.

Although we propose a new method for 3D surface deformation, the technique that is most closely related to our work concentrates on 2D image retargeting. In their paper on image seam carving, Avidan and Shamir [1] present a method for resizing images that respects the image content. A seam is a connected path of low-energy pixels crossing the image from top to bottom or from left to right. By successively removing or inserting seams, the image can be resized in both dimensions. Storing the order of all removing and insertion operations enables multi-size images that can change their size dynamically while their content is preserved as well as possible.