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Technical Section

Constrained illustrative volume deformation

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ABSTRACT

Interactive volume deformation has received a lot of attention recently thanks to the advances of graphics processing units. The ability to transform volumetric objects constitutes an essential tool for generating illustrative visualizations. Previous approaches to this problem have adapted techniques used for surface meshes and applied it to an embedding mesh. This method, however, often results in low quality due to the resolution of the mesh. Other alternatives consider the volume as a homogeneous collection of points, and therefore, cannot simulate physical laws that govern the deformation of different materials. In this paper, we aim at obtaining high-quality illustrations of deformable volumes that mimic physically inspired constraints. For example, although skin and muscle can be illustrated as deforming elastically, bone tissue should move rigidly. Here, we show that we can obtain constrained illustrative deformations with algebraic operations on displacement maps. Through a number of examples, we show that this is a faster alternative to costly physical simulations, with wide applications in computer-aided medical illustration, interactive volume manipulation and data exploration.

1. Introduction

Illustrative deformation is a family of interactive techniques that deform a graphical model to obtain an illustrative visualization. For example, for medical illustration, one may interactively manipulate a volumetric model of a scanned human body to obtain illustration of typical surgical effects such as bending, peeling, and cutting open. While this family of techniques does not exclude physically based deformation, the goal is to achieve a realistic appearance of the deformed model, rather than physical accuracy of the deformation interaction, such as force feedback.

Truly physically accurate deformation is difficult to obtain for volume datasets because most physically based simulation relies on surface meshes. Since a volume is a sampled representation of a continuous field, simulating cuts are also difficult via mesh. Moreover, accurate physically based deformation would require a precise specification of material properties of every voxel, and embedding of a volume in a 3D mesh where physics is applied. Since a deformed volume has to be reconstructed from the deformed mesh using interpolation, the quality obtained is usually low, and depends largely on the tessellation resolution of the mesh. In addition, the speed for simulating a slightly complex volume model would render the computation non-interactive.

In recent years, illustrative volume deformation using empirical (i.e., non-physically based) displacement operations has shown to be a practical technique for creating illustrative visualization featuring various deformation effects (e.g., [1,2]). One limitation of the existing methods is that all voxels to be deformed response to the force in the same way. For instance, when the knee model in Fig. 1(a) is deformed using axis-aligned deformation [3], the bone will be deformed in the same way as soft tissues around it as shown in Fig. 1(b). Although one may use feature-aligned manipulation [1] to mask the bone as a rigid object, as shown in Fig. 1(c), the rigid bone does not influence the deformation of the soft tissues around it. It is thus desirable to make soft tissues around the bone deform non-uniformly under the influence of the rigid bone. This provided this work with the motivation.

In this work, we introduce the notion of *constrained displacement fields*, which allows us to confine the deformation within certain limits. This is useful for preventing self-intersections and avoiding collisions with features of interest. Furthermore, it allows us to define deformation on heterogeneous materials, where parts of an object move rigidly and others elastically. Fig. 1(d) illustrates the application of this method to the knee model in Fig. 1(a). In Fig. 1(d), we can observe that the bone does not response the deformation force as a rigid part, while the soft tissues around the bone deform not only according to the force, but also under the constraints of the bone. Our novel contribution is that we achieve this through an empirical deformation function that is linear combination of displacement fields. Without using

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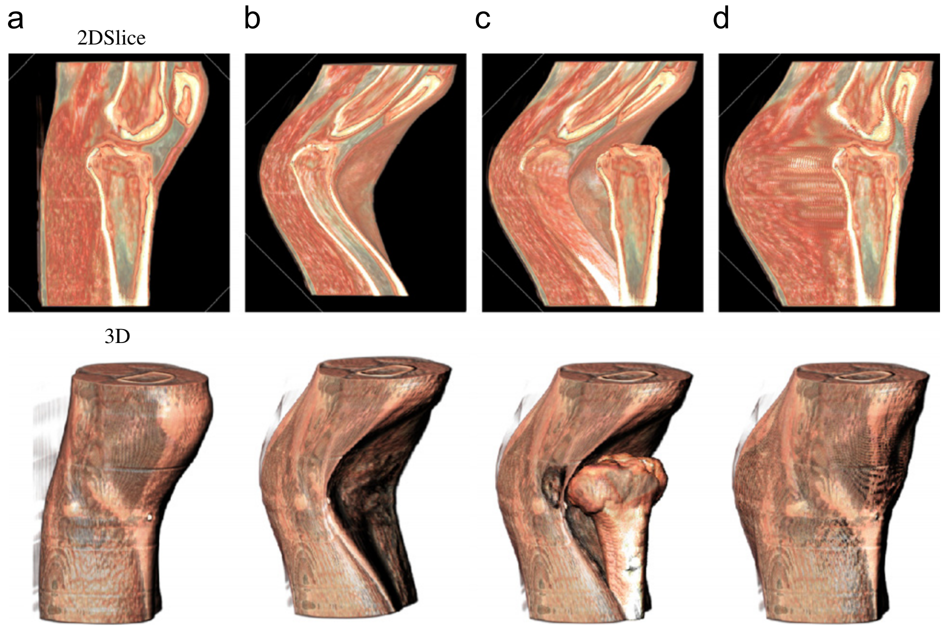

Fig. 1. Deformation of a knee CT scan. We compare different methods for deformation. Axis-aligned deformation transforms all voxels without regards on their material. We see that tissue and bone are applied the same transformation. Feature-aligned deformation [1] allows the bone to stay rigid while everything deforms around it. However, it results in self-intersections. Finally, constrained deformation ensures that no unwanted intersections are produced: (a) Original; (b) axis-aligned; (c) feature-aligned and (d) constrained.

physically based methods, we can maintain the interactive rate as unconstrained deformation [1], hence maintaining the usability of the tool for illustrative volume deformation. Previous attempts at introducing constraints can create compelling volume illustrations that do not only mimic the appearance of a reference illustration, but also the shape style [4]. Our approach is a different mechanism to control the effects of deformation to mimic the physical constraints of anatomical features.

Our approach is amenable to contemporary GPUs, as deformation is defined as a look-up on a displacement field, which can be efficiently stored as a 3D texture.

The rest of the paper is organized as follows: Section 2 describes the state-of-the-art in volume deformation, including the notion of discontinuous displacement mapping. To allow constrained deformation, we must be able to combine algebraically these displacements. To this purpose, Section 3 describes a series of unary and binary operations on displacement maps, including addition and modulation. Section 4 describes our method that uses algebraic operations on displacements to realize constrained deformation. We describe a series of applications in illustrative visualization, such as collision-free volume manipulation and fast simulation of rigidity constraints.

2. Background

Illustrative visualization: Illustrative visualization is mainly seen as a tool for the effective communication of knowledge. The goal of illustrative visualization is to develop software that enables domain experts and scientists to make illustrations of their work [5]. The main illustrative visualization technology falls into two classification. The first one relies on the manipulation of viewing attributes of the rendering engine and optical attributes of the objects, such as non-photorealistic rendering [6,7], ghosted views [8], magic lenses [9], ClearView [10] and close-ups [11]. The second one relies on volume deformation to effectively resolve the occlusion problem [1,12]. In [13], Correa et al. proposed a data exploration framework, which combines active manipulation of the spatial data with opacity and color transformations. In [14], Li et al. present a system for creating and viewing interactive exploded views of complex 3D models.

Volume deformation: The general notion of a *sampled object representation* (SOR) is a set of samples $V=\{(\mathbf{p}_i,v_i)|i=1,2,\ldots,n\}$, where v_i is a value of a specific data type (e.g., Boolean, scalar, vector or tensor), which represents some property at each sample location $\mathbf{p}_i$ in k-D Euclidean space E^k. Typically these samples are associated with a spatial domain Ω, which is normally continuous or consists of several disjoint sub-domains. An object specified by an SOR is thus a function $F(\mathbf{p})$ that defines the value at every $\mathbf{p}\in\Omega$ [15].

Deformation refers to the intended change of geometric shape of an object under the control of some external influence such as a force. We can classify deformation along two dimensions. Depending on the underlying model, we can refer to deformation methods as either physics-based or empirical. Most of the physics-based approaches have been devoted to mesh deformation. For an up-to-date compendium of such techniques, see Nealen et al.'s survey [16]. Models such as mass-springs and finite elements are used to ensure desired physical properties such as conservation of mass, elasticity and viscosity. Extending this to volumetric objects has been proposed in the form of tetrahedral meshes, or other embedding geometry. Because of the size of volumetric objects compared to meshes, the results obtained by this method are usually of low quality. Empirical approaches, in contrast, have little or no physics in their computation. Methods include free-form [17], global and local deformation [18], sketch-based [19] and skeleton driven deformation [20].

Another dimension for classifying deformation is determined by the stage at which it is applied. Most mesh-based deformations are done at the *modeling* stage, where each application of deformation leads to a new mesh, which can be rendered using traditional methods. Deformation at the *rendering* stage has recently surfaced thanks to the programmability of GPUs [21]. Early volumetric deformation approaches were applied at the modeling stage, [22–26]. However, this is impractical for interactive applications. One of the most notable problems is the need