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Technical Section

WarpCurves: A tool for explicit manipulation of implicit surfaces

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ABSTRACT

We introduce *WarpCurves*, a technique for interactively manipulating an implicit surface using curve-based spatial deformations. Although implicit surfaces have several advantages in 3D modeling, current workflows are limited by the compositional nature of implicit modeling. Wide classes of surface features that are easy to create with the direct manipulation tools available for explicit surface representations are difficult to reproduce using volumetric implicit operations. We describe a novel spatial deformation that can be used to approximate direct surface manipulation. With our method an artist first draws a curve on the current surface to indicate the feature region-of-interest. Deformations applied to this handle curve are transferred to the implicit surface via an automatically constructed C^2 continuous space mapping. Additional curves can be added in a hierarchical manner to create complex shapes. Our technique is implemented as a node in the BlobTree hierarchical implicit volume representation, and hence can be used along with other volumetric nodes (operators) such as blending and CSG. Our results show that surface deformations which would be difficult to reproduce using existing volumetric operations can be quickly constructed using warp curves, making them a valuable addition to the implicit modeling toolbox.

1. Introduction

Implicit surfaces offer several modeling advantages compared to parametric and point-sampled representations [5]. Since blending and CSG operators can be defined with simple formulations, smooth transitions and topological changes can be easily handled. By organizing these operators in a hierarchical structure called the BlobTree [37], complex solid models can be created. Tools like ShapeShop [27] have demonstrated that even novice users are capable of creating 3D models with implicit surfaces.

Despite these benefits, volumetric implicit modeling requires the artist to think in terms of shape composition, rather than surface manipulation. While composition is suitable for creating initial forms, direct manipulation of the 3D surface can be much more efficient when attempting to refine the shape, alter features, and add details. Schmidt and Singh [25] noted that artists preferred explicit representations for such tasks, but their mesh-based "surface tree" is incompatible with implicit operators. Hence, our goal is to enable explicit manipulation of implicit surfaces.

To integrate into the BlobTree functional hierarchy we must treat the input surface as a "black box", so direct manipulation must be formulated as a spatial deformation. Furthermore, unlike with point-based surfaces the "reverse" deformation is required [38], and should be very efficient to compute if it is to be used in interactive contexts. Several *space warp* techniques have been developed for implicit surfaces [21,38,23,28], but these cannot be easily adapted to the task of surface manipulation. Recently Sugihara et al. [33] described a space deformer based on a curve handle which can approximate small surface deformations, but no attempt is made to have the surface explicitly track the curve.

We present *WarpCurves*, a curve-based spatial deformation technique which can be used to apply local and global deformations to implicit models, including approximate direct manipulation of an implicit surface. Our interface is inspired by curve-based deformation techniques such as Wires [31] and FiberMesh [19]. Similar to FiberMesh, warp curves can be placed by sketching on the surface and can be manipulated using peeling techniques [12]. As the artist modifies the warp curves, our method constructs an appropriate inverse warp which results in the surface approximately tracking the curve. These C^2 continuous variational warps are automatically bounded to limit their spatial influence. We demonstrate our techniques with the BlobTree [37],

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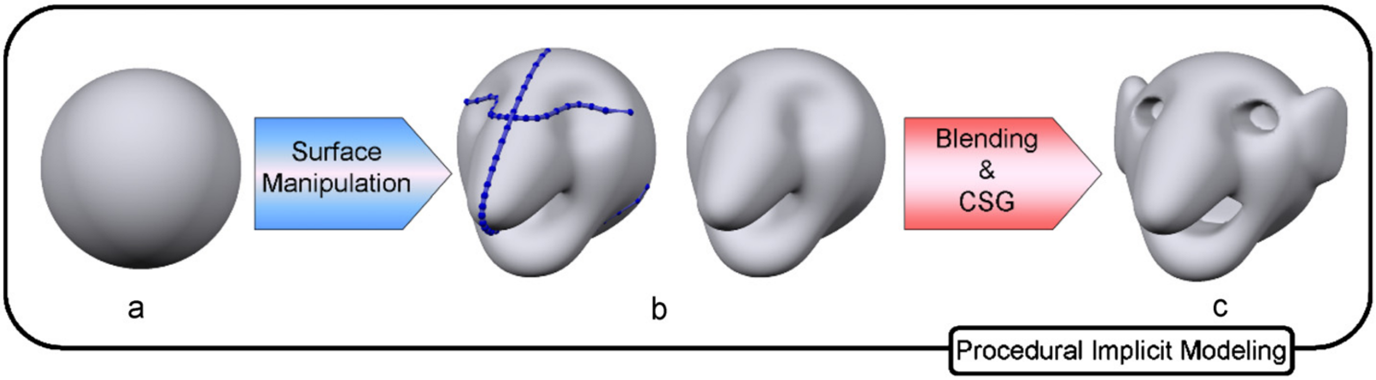

Fig. 1. An overview of the WarpCurves tool. The implicit point primitive (a) is deformed using three warp curves to create facial features (b). Soft-CSG operators are then used to add eyes and a mouth, and the ears are added with blending operators (c).

but the general approach is applicable to any implicit (or explicit) surface. The resulting spatial deformation can be integrated as a node in the BlobTree, allowing blending and CSG operators to be applied before or after deformation (Fig. 1). Our contributions can be summarized as follows:

- A novel and flexible curve-based spatial deformation technique which can be integrated into procedural implicit modeling as an operator node.
- An artist-oriented curve-based interface supporting direct manipulation of implicit surfaces.
- A new technique to automatically bound the influence of curve-based spatial deformations.

2. Related work

Deformation has a long history in computer graphics, so we restrict our review to spatial and curve-based deformation. For a more detailed overview of the deformation literature, we refer the reader to recent surveys of the area [18,10,32].

A well known artist-oriented deformation technique is free-form deformation (FFD), which is based on spatial deformation, originally introduced by [29]. Conceptually, the target object is embedded in a 3D grid or *lattice*, which is used to define a deformation field. As the artist manipulates the control points of the lattice, the embedded surface is deformed. Several extensions have been developed to make a 3D lattice more controllable [7,16,20]. Implicit fields are also used as deformation fields of FFD [8], although the target object of this technique is limited to point-based surfaces.

Recently, cage-based methods have been proposed which embed the target object within an arbitrary non-convex polyhedral cage, and then generate a spatial deformation based on deformations of the cage [14,13,15,3]. The cage is a closed surface and typically a coarse mesh of the target object is used. Thus, a cage is geometrically and topologically more flexible than a lattice as a deformation controller. In general, FFD-style techniques provide simple and intuitive control over spatial deformation, but it is difficult to control changes to the surface, as the target object is not edited directly. Also, they are designed for point-based surfaces and do not easily extend into the implicit domain.

Curve-based techniques are often more efficient when adding or modifying surface features via deformation. The Wires system [31] binds the target object with several curves called *wires* and then constructs a bounded spatial deformation according to the displacements of the Wires. This approach is highly interactive, easy to incorporate into procedural models, and intuitive for artists, and hence is used extensively in commercial modeling tools. Since the Wires can be aligned with important features of the target object, it is easy to directly manipulate specific parts of the surface. This idea has been extended to edit man-made objects while automatically preserving salient features (iWIRES [11]). In sketch-based modeling, curves are also used to define the features of the free-form surfaces [19]. All of these techniques provide efficient, artist-oriented interfaces, and have inspired our approach; however, they are limited to point-based surface representations because they are difficult and/or inefficient to invert.

Sculpting interfaces can also be used to deform surfaces. Swirling Sweepers [1] and zero-divergence vector field deformation [36] are efficient and highly intuitive tools for direct manipulation of discrete 3D surfaces. These techniques can be applied to functional surfaces, but involve a relatively expensive path integration for each point. During interactive sculpting this cost is amortized over many frames, but in the implicit context each evaluation of the scalar field would require a prohibitively expensive reverse-integration along the entire path. A recent curve-based sculpting technique for level-set models [9] has similar limitations, and also involves a temporal component in the form of per-frame partial differential equation (PDE) evolution. In this case the result is not strictly a spatial deformation and cannot be directly applied to functional implicit models.

To be applied to an arbitrary implicit surface, a deformation must be formulated as a spatial deformation and the "inverse warp" (the map from the deformed to initial surface) is required. Early work adapted the Barr deformations [2] for several implicit representations such as the function-representation (FRep) [21], skeletal implicit surfaces [38], and the BlobTree [37]. The work of Wyvill and van Overveld [38] also presented deformation fields suitable for animation, such as those which squash or stretch implicit models as they pass through the field. A variational warp was applied to implicit surfaces in [24] and this technique was incorporated into a general framework for FRep deformations called extended space mapping [23]. A deformation field is constructed by interpolating the displacements of control points. Since this technique interpolates an arbitrary set of control points, the control points can be placed on the important features of the target object. Due to a global feature of the variational technique, however, local influence cannot be guaranteed. A more controllable deformation technique for FRep was developed by [28] which defines another FRep object as a deformation field. However, such deformation fields must be defined manually by