Shape Transformation Using Variational Implicit Functions

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Abstract

Traditionally, shape transformation using implicit functions is performed in two distinct steps: 1) creating two implicit functions, and 2) interpolating between these two functions. We present a new shape transformation method that combines these two tasks into a single step. We create a transformation between two N-dimensional objects by casting this as a scattered data interpolation problem in $N+1$ dimensions. For the case of 2D shapes, we place all of our data constraints within two planes, one for each shape. These planes are placed parallel to one another in 3D. Zero-valued constraints specify the locations of shape boundaries and positive-valued constraints are placed along the normal direction in towards the center of the shape. We then invoke a variational interpolation technique (the 3D generalization of thin-plate interpolation), and this yields a single implicit function in 3D. Intermediate shapes are simply the zero-valued contours of 2D slices through this 3D function. Shape transformation between 3D shapes can be performed similarly by solving a 4D interpolation problem. To our knowledge, ours is the first shape transformation method to unify the tasks of implicit function creation and interpolation. The transformations produced by this method appear smooth and natural, even between objects of differing topologies. If desired, one or more additional shapes may be introduced that influence the intermediate shapes in a sequence. Our method can also reconstruct surfaces from multiple slices that are not restricted to being parallel to one another.

CR Categories: I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling—surfaces and object representations

Keywords: Shape transformation, shape morphing, contour interpolation, implicit surfaces, thin-plate techniques.

1 Introduction

The shape transformation problem can be stated as follows: Given two shapes A and B, construct a sequence of intermediate shapes so that adjacent pairs in the sequence are geometrically close to one another. Playing the resulting sequence of shapes as an animation would show object A deforming into object B. Sequences of 2D shapes can be thought of as slices through a 3D surface, as shown in Figure 1. Shape transformation can be performed between objects of any dimension, although 2D and 3D shapes are by far the most common cases. Shape transformation has applications in medicine, computer aided design, and special effects creation. We give an overview of these three applications below.

One important application of shape transformation in medicine is contour interpolation. Non-invasive imaging techniques often collect data about a patient's internal anatomy in "slices" of a particular size such as 512×512 samples. Usually many fewer slices are taken along the third dimension so that a resulting volume might, for example, be sampled at $512 \times 512 \times 30$ resolution. To reconstruct a 3D model of a particular organ, the samples are segmented to create shapes (contours) within the slices. Intermediate shapes are then created between slices in the sparsely sampled dimension. The reconstructed 3D object is formed by stacking together the original and the interpolated contours. This is an example of 2D shape transformation.

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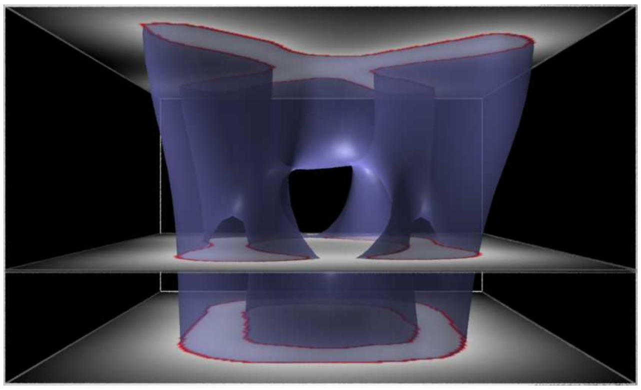

Figure 1: Visualization of transformation between X and O shapes. Top and bottom planes contain constraints for the two shapes. Translucent surface is the isosurface of a 3D variational implicit function, and slices through it give intermediate shapes.

Shape transformation can also be a useful tool in computer aided geometric design. Consider the problem of creating a join between two metal parts with different cross-sections. It is important for the connecting surface to be smooth because those places with sharp ridges or creases are the locations that are most likely to form cracks. The intermediate surface joining the two parts can be created using shape transformation, much in the same way as with contour interpolation for medical imaging. Because of the smoothness properties of variational interpolation methods, we consider them a natural tool to explore for shape transformation in CAD.

Finally, animated shape transformations have been used to create dramatic special effects for feature films and commercials. One of the best-known examples of shape transformation is in the film *Terminator 2*. In this film, a cyborg policeman undergoes a number of transformations from an amorphous and highly reflective surface to various destination shapes. 2D image morphing would not have accurately modeled the reflection of the environment off the surface of the deforming cyborg, hence tailor-made 3D shape transformation programs were used for these effects [9].

In this paper we use variational interpolation in a new way to produce high-quality shape transformations that may be used for any of the previously mentioned applications. Our method allows a user to control the transformation in several ways, and it is general enough to produce transformations between shapes of any topology.

2 Previous Work

Most shape transformation techniques can be placed into one of two categories: parametric correspondence methods and implicit function interpolation. Parametric methods are typically faster to compute and require less memory because they operate on a lower-dimensional representation of an object than do implicit function methods. Unfortunately, transforming between objects of different topologies is considerably more difficult with parametric methods. Parametric approaches also can suffer from problems with self-intersecting surfaces, but this is never a problem with implicit function methods. Techniques that use implicit function interpolation gracefully handle changes in topology between objects and do not create self-intersecting surfaces.

A parametric correspondence approach to shape transformation attempts to find a "reasonable" correspondence between pairs of locations on the boundaries of the two shapes. Intermediate shapes are then created by computing interpolated positions between the corresponding pairs of points. Many shape transformation techniques have been created that follow the parametric correspondence approach. One early application of this approach is the method of contour interpolation described by Fuchs, Kedem and Uselton [10]. Their method attempts to find an "optimal" (minimum-area) triangular tiling that connects two contours using dynamic programming. Many subsequent techniques followed this approach of defining a quality measure for a particular correspondence between contours and then invoking an optimization procedure [22, 25]. There have been fewer examples of using parametric correspondence for 3D shape transformation. One quite successful 3D parametric method is the work of Kent et al. [17]. The key to their approach is to subdivide the polygons of the two models in a manner that creates a correspondence between the vertices of the two models. More recently, Gregory and co-workers created a similar method that also allows a user to specify region correspondences between meshes to better control a transformation [12].

An entirely different approach to shape transformation is to create an implicit function for each shape and then to smoothly interpolate between these two functions. A shape is defined by an implicit function, $f(\mathbf{x})$, as the set of all points $\mathbf{x}$ such that $f(\mathbf{x}) = 0$. For contour interpolation in 2D, the implicit function can be thought of as a height field over a two-dimensional domain, and the boundary of a shape is the one-dimensional curve defined by all the points that have the same elevation value of zero. An implicit function in 3D is a function that yields a scalar value at every point in 3D. The shape described by such a function is given by those places in 3D whose function value is zero (the isosurface).

One commonly used implicit function is the *inside/outside function* or *characteristic function*. This function takes on only two values over the entire domain. The two values that are typically used are zero to represent locations that are outside and one to signify positions that are inside the given shape. Given a powerful enough interpolation technique, the characteristic function can be used for creating shape transformations. Hughes presented a successful example of this approach by transforming characteristic functions into the frequency domain and performing interpolation on the frequency representations of the shapes [15]. Kaul and Rossignac found that smooth intermediate shapes can be generated by using weighted Minkowski sums to interpolate between characteristic functions [16]. They later created a generalization of this technique that can use several intermediate shapes to control the interpolation between objects [24]. Using a wavelet decomposition of a characteristic function allowed He and colleagues to create intermediates between quite complex 3D objects [13].

A more informative implicit function can provide excellent intermediate shapes even if a simple interpolation technique is used. In particular, the *signed distance function* (sometimes called the *distance transform*) is an implicit function that gives very plausible intermediate shapes even when used with simple linear interpolation of the function values of the two shapes. The value of the signed distance function at a point $\mathbf{x}$ inside a given shape is just the Euclidean distance between $\mathbf{x}$ and the nearest point on the boundary of the shape. For a point $\mathbf{x}$ that is outside the shape, the signed distance function takes on the negative of the distance from $\mathbf{x}$ to the closest point on the boundary.

Several researchers have used the signed distance function to interpolate between 2D contours [19, 14]. The distance function for each given shape is represented as a regular 2D grid of values, and an intermediate implicit function is created by linear interpolation between corresponding grid values of the two implicit functions. Each intermediate shape is given by the zero iso-contour of this interpolated implicit function. In contrast to the global interpolation methods described above (frequency domain, wavelets, Minkowski sum), this interpolation is entirely local in nature. Nevertheless, the shape transformations that are created by this method are quite good. In essence, the information that the signed distance function encodes (distance to nearest boundary) is enough to make up for the purely local method of interpolation. Payne and Toga were the first to transform three dimensional shapes using this approach [23]. Cohen-Or and colleagues gave additional control to this same approach by combining it with a warping technique in order to produce shape transformations of 3D objects [7].

Our approach to shape transformation combines the two steps of building implicit functions and interpolating between them. To our knowledge, it is the only method to do so. The remainder of this paper describes how variational interpolation can be used to simultaneously solve these two tasks.

3 Variational Interpolation

Our approach relies on *scattered data interpolation* to solve the shape transformation problem. The problem of scattered interpolation is to create a smooth function that passes through a given set of data points. The two-dimensional version of this problem can be stated as follows: Given a collection of k constraint points $\{\mathbf{c}_1, \mathbf{c}_2, \ldots, \mathbf{c}_k\}$ that are scattered in the plane, together with scalar height values at each of these points $\{h_1, h_2, \ldots, h_k\}$, construct a smooth surface that matches each of these heights at the given locations. We can think of this solution surface as a scalar-valued function $f(\mathbf{x})$ so that $f(\mathbf{c}_i) = h_i$, for $1 \le i \le k$.

One common approach to solving scattered data problems is to use variational techniques (from the calculus of variations). This approach begins with an energy that measures the quality of an interpolating function and then finds the single function that matches the given data points and that minimizes this energy measure. For two-dimensional problems, thin-plate interpolation is the variational solution when using the following energy function E:

$$E = \int_{\Omega} f_{xx}^2(\mathbf{x}) + 2f_{xy}^2(\mathbf{x}) + f_{yy}^2(\mathbf{x}) \qquad (1)$$

The notation f_{xx} means the second partial derivative in the x direction, and the other two terms are similar partial derivatives, one of them mixed. The above energy function is basically a measure of the aggregate squared curvature of $f(\mathbf{x})$ over the region of interest Ω. Any creases or pinches in a surface will result in a larger value of E. A smooth surface that has no such regions of high curvature will have a lower value of E. The thin-plate solution to an interpolation problem is the function $f(\mathbf{x})$ that satisfies all of the constraints and that has the smallest possible value of E.

The scattered data interpolation problem can be formulated in any number of dimensions. When the given points $\mathbf{c}_i$ are positions in N-dimensions rather than in 2D, this is called the N-dimensional scattered data interpolation problem. There are appropriate generalizations to the energy function and to thin-plate interpolation for other dimensions. In this paper we will perform interpolation in two, three, four and five dimensions. Because the term *thin-plate* is only meaningful for 2D problems, we will use *variational interpolation* to mean the generalization of thin-plate techniques to any number of dimensions.

The scattered data interpolation task as formulated above is a variational problem where the desired solution is a function, $f(\mathbf{x})$, that will minimize equation 1 subject to the interpolation constraints $f(\mathbf{c}_i) = h_i$. Equation 1 can be solved using weighted sums of the

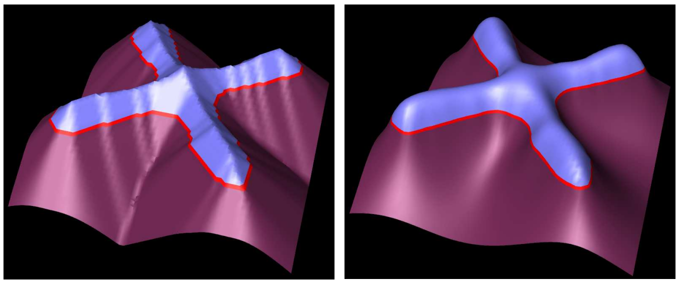

Figure 2: Implicit functions for an X shape. Left shows the signed distance function, and right shows the smoother variational implicit function.

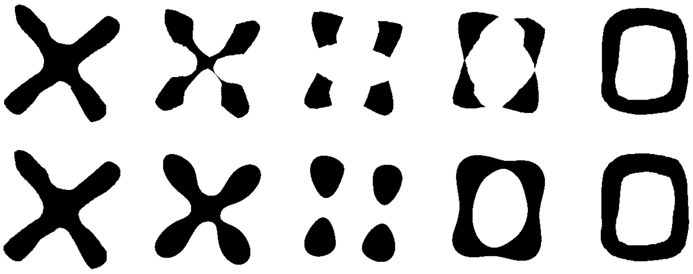

Figure 3: Upper row is a shape transformation created using the signed distance transform. Lower row is the sequence generated using a single variational implicit function.

radial basis function $\phi(\mathbf{x}) = |\mathbf{x}|^2 \log(|\mathbf{x}|)$. The family of variational problems that includes equation 1 was studied by Duchon [8].

Using the appropriate radial basis function, we can then express the interpolation function as

$$f(\mathbf{x}) = \sum_{j=1}^{n} d_j \phi(\mathbf{x} - \mathbf{c}_j) + P(\mathbf{x}) \tag{2}$$

In the above equation, $\mathbf{c}_j$ are the locations of the constraints, the d_j are the weights, and $P(\mathbf{x})$ is a degree one polynomial that accounts for the linear and constant portions of f. Because the thin-plate radial basis function naturally minimizes equation 1, determining the weights, d_j, and the coefficients of $P(\mathbf{x})$ so that the interpolation constraints are satisfied will yield the desired solution that minimizes equation 1 subject to the constraints. Furthermore, the solution will be an exact analytic solution, and is not subject to approximation and discretization errors that may occur when using finite element or finite difference methods.

To solve for the set of d_j that will satisfy the interpolation constraints $h_i = f(\mathbf{c}_i)$, we can substitute the right side of equation 2 for $f(\mathbf{c}_i)$, which gives:

$$h_i \quad = \quad \sum_{j=1}^{k} d_j \phi(\mathbf{c_i} - \mathbf{c_j}) + P(\mathbf{c_i}) \tag{3}$$

Since this equation is linear with respect to the unknowns, d_j and the coefficients of $P(\mathbf{x})$, it can be formulated as a linear system. For interpolation in 3D, let $\mathbf{c}_i = (c_i^x, c_i^y, c_i^z)$ and let $\phi_{ij} = \phi(\mathbf{c}_i - \mathbf{c}_j)$. Then this linear system can be written as follows:

$$\begin{bmatrix} \phi_{11} & \phi_{12} & \dots & \phi_{1k} & 1 & c_1^x & c_1^y & c_1^z \\ \phi_{21} & \phi_{22} & \dots & \phi_{2k} & 1 & c_2^x & c_2^y & c_2^z \\ \vdots & \vdots & & \vdots & \vdots & \vdots & \vdots & \vdots \\ \phi_{k1} & \phi_{k2} & \dots & \phi_{kk} & 1 & c_k^x & c_k^y & c_k^z \\ 1 & 1 & \dots & 1 & 0 & 0 & 0 & 0 \\ c_1^x & c_2^x & \dots & c_k^x & 0 & 0 & 0 & 0 \\ c_1^y & c_2^y & \dots & c_k^y & 0 & 0 & 0 & 0 \\ c_1^z & c_2^z & \dots & c_k^z & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_k \\ p_0 \\ p_1 \\ p_2 \\ p_3 \end{bmatrix} = \begin{bmatrix} h_1 \\ h_2 \\ \vdots \\ h_k \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

The above system is symmetric and positive semi-definite, so there will always be a unique solution for the d_j and p_j [11]. For systems with up to a few thousand constraints, the system can be solved directly with a technique such as symmetric LU decomposition. We used symmetric LU decomposition to solve this system for all of the examples shown in this paper.

Using the tools of variational interpolation we can now turn our attention to creating implicit functions for shape transformation.

4 Smooth Implicit Function Creation

In this section we will lay down the groundwork for shape transformation by discussing the creation of smooth implicit functions for a single shape. In particular, we will use variational interpolation of scattered constraints to construct implicit functions. Later we will generalize this to create functions that perform shape transformation.

Let us first examine the signed distance transformation because it is commonly used for shape transformation. The left half of Figure 2 shows a height field representation of the signed distance function of an X shape. The figure shows sharp ridges (the *medial axis*) that run down the middle of the height field. Ridges appear in the middle of shapes where the points are equally distant from two or more boundary points of the original shape. The values of a signed distance function decrease as one moves away from the ridge towards the boundaries. Figure 3, top row, shows a shape interpolation sequence between an X and an O shape that was created by linear interpolation between two signed distance functions. Note the pinched portions of some of the intermediate shapes. These sharp features are not isolated problems, but instead persist over many intermediate shapes. The cause of these pinches are the sharp ridges of signed distance functions. In many applications such artifacts are undesirable. In medical reconstruction, for example, these pinches are a poor estimate of shape because most biological structures have smooth surfaces. Because of this, we seek implicit functions that are continuous and that have a continuous first derivative.

4.1 Variational Implicit Functions in 2D

We can create smooth implicit functions for a given shape using variational interpolation. This can be done both for 2D and 3D shapes, although we will begin by discussing the 2D case. In this approach, we create a closed 2D curve by describing a number of locations through which the curve will pass and also specifying a number of points that should be interior to the curve. We call the given points on the curve the *boundary constraints*. The boundary constraints are locations at which we require our implicit function to take on the value of zero. Paired with each boundary constraint is a *normal constraint*, which is a location at which the implicit function is required to take on the value one. (Actually, any positive value could be used.) The locations of the normal constraints should be towards the interior of the desired curve, and also the line passing through the normal constraint and its paired boundary constraint should be parallel to the desired normal to the curve. The collection of boundary and normal constraints are passed along to a variational interpolation routine as the scattered constraints to be interpolated. The function that is returned is an implicit function that describes our curve. The curve will exactly pass through our boundary constraints.

Figure 4 (left) illustrates eight such pairs of constraints in the plane, with the boundary constraints shown as circles and the normal constraints as plus signs. When we invoke variational interpo-

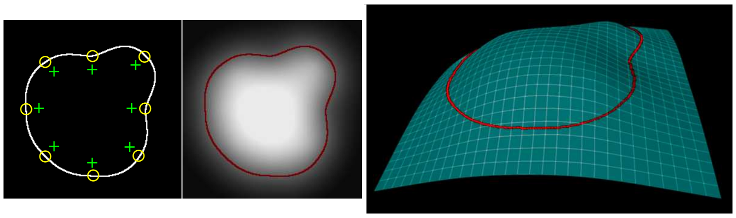

Figure 4: At left are pairs of boundary and normal constraints (circles and pluses). The middle image uses intensity to show the resulting variational implicit function, and the right image shows the function as a height field.

lation with such constraints, the result is a function that takes on the value of zero exactly at our zero-value constraints and that is positive in the direction of our normal constraints (towards the interior of the shape). The closed curve passing through the zero-value constraints in Figure 4 (middle) is the iso-contour of the implicit function created by this method. Figure 4 (right) shows the resulting implicit function rendered as a height field. Given enough suitably-placed boundary constraints we can define any closed shape. We call an implicit function that is created in this manner a *variational implicit function*. This new technique for creating implicit functions also show promise for surface modeling, a topic that is explored in [27].

We now turn our attention to defining boundary and normal constraints for a given 2D shape. Assume that a given shape is represented as a gray-scale image. White pixels represent the interior of a shape, black pixels will be outside the shape, and pixels with intermediate gray values lie on the boundary of the shape. Let m be the middle gray value of our image's gray scale range. Our goal is to create constraints between any two adjacent pixels where one pixel's value is less than m and the other's value is greater. Identifying these locations is the 2D analog of finding the vertex locations in a 3D marching cubes algorithm [21].

We traverse the entire gray-scale image and examine the east and south neighbor of each pixel $I(x,y)$. If $I(x,y) < m$ and either neighbor has a value greater than m, we create a boundary constraint at a point along the line segment joining the pixel centers. A boundary constraint is also created if $I(x,y) > m$ and either neighbor takes on a value less than m. The value of the constraint is zero, and we set the position of the constraint at the location between the two pixels where the image would take on the value of m if we assume linear interpolation of pixel values. Next, we estimate the gradient of the gray scale image using linear interpolation of pixel values and central differencing. We then create a normal constraint a short distance away from the zero crossing in the direction of the gradient. We have found that a distance of a pixel's width between the boundary and normal constraints works well in practice. Figure 2 (right) shows the implicit function for an X shape that was created using variational interpolation from such constraints. It is smooth and free of sharp ridges.

4.2 Variational Implicit Functions in 3D

We can create implicit functions for 3D surfaces using variational interpolation in much the same way as for 2D shapes. Specifically, we can derive 3D constraints from the vertex positions and surface normals of a polygonal representation of an object. Let (x,y,z) and (n_x,n_y,n_z) be the position and the surface normal at a vertex, respectively. Then a boundary constraint is placed at (x,y,z) and a normal constraint is placed at $(x-kn_x, y-kn_y, z-kn_z)$, where k is some small value. We use a value of $k = 0.01$ for models that fit within a unit cube for the results shown in this paper. All of the 3D models that we transform in this paper were constructed by building an implicit function in this manner. Note that we can use this method to build an implicit function whenever we have a collection of points and normals— polygon connectivity is not necessary.

Now that we can construct smooth implicit functions for both two- and three-dimensional shapes, we turn our attention to shape transformation. It would be possible to create variational implicit functions for each of two given shapes and then linearly interpolate between these functions to create a shape transformation sequence. Instead, however, we will examine an even better way of performing shape transformation by generalizing the implicit function building methods of this section.

5 Unifying Function Creation and Interpolation

The key to our shape transformation approach is to represent the entire sequence of shapes with a single implicit function. To do so, we need to work in one higher dimension than the given shapes. For 2D shapes, we will construct an implicit function in 3D that represents our two given shapes in two distinct parallel planes. This is actually simple to achieve now that we know how to use scattered data interpolation to create an implicit function.

5.1 Two-Dimensional Shape Transformation

Given two shapes in the plane, assume that we have created a set of boundary and normal constraints for each shape, as described in Section 4. Instead of using each set of constraints separately to create two different 2D implicit functions, we will embed all of the constraints in 3D. We do this by adding a third coordinate value to the location of each boundary and normal constraint. For those constraints for the first shape, we set the new coordinate t for all constraints to $t = 0$. For the second shape, all of the new coordinate values are set to $t = t_{max}$ (some non-zero value). Although we have added a third dimension to the locations of the constraints, the values that are to be interpolated remain unchanged for all constraints.

Once we have placed the constraints of both shapes into 3D, we invoke 3D variational interpolation to create a single scalar-valued function over $\mathbf{R}^3$. If we take a slice of this function in the plane $t = 0$, we find an implicit function that takes on the value zero exactly at the boundary constraints for our first shape. In this plane, our function describes the first shape. Similarly, in the plane $t = t_{max}$ this function gives the second shape. Parallel slices at locations between these two planes ($0 < t < t_{max}$) represent the shapes of our shape transformation sequence. Figure 1 illustrates that the collection of intermediate shapes are all just slices through a surface in 3D that is created by variational interpolation.

Figure 3 (bottom) shows the sequence of shapes created using this variational approach to shape transformation. Topology changes (e.g. the addition or removal of holes) come "for free", without any human guidance or algorithmic complications. Notice that all of the intermediate shapes have smooth boundaries, without pinches. Sharp features can arise only momentarily when there is a change in topology such as when two parts join. Figure 5 shows two more shape transformations that use this approach and that also incorporate warping. Warping is an another degree of control that may be added to any shape transformation technique, and is in fact

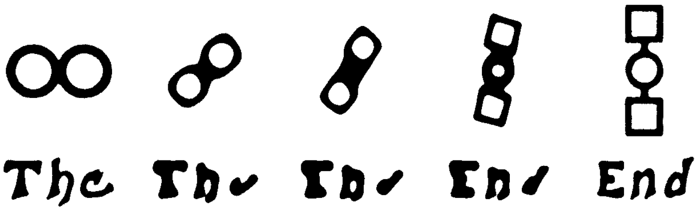

Figure 5: Two shape transformation sequences (using the variational implicit technique) that incorporate warping.

an orthogonal issue to those of implicit function creation and interpolation. Although it is not a focus of our research, for completeness we briefly describe warping in the appendix.

Why has this implicit function building method not been tried using other ways of creating implicit functions? Why not, for example, build a signed distance function in one higher dimension? Because a *complete* description of an object's boundary is required in order to build a signed distance function. When we embed our two shapes into a higher dimension, we only know a *piece* of the boundary of our desired higher-dimensional shape, namely the cross-sections that match the two given objects. In contrast, a complete boundary representation is *not* required when using variational interpolation to create an implicit function. Variational interpolation creates plausible function values in regions where we have no information, and especially in the "unknown" region between the two planes that contain all of our constraints. This plausibility of values comes from the smooth nature of the functions that are created by the variational approach.

5.2 Three-Dimensional Shape Transformation

Just as we create a 3D function to create a transformation between 2D shapes, we can move to 4D in order to create a sequence between 3D shapes. We perform shape interpolation between two 3D objects using boundary and normal constraints for each shape. We place the constraints from two 3D objects into four dimensional space, just as we placed constraints from 2D contours into 3D. Similar to contour interpolation, the constraints are separated from one another in the fourth dimension by some specified distance. We place all the constraints from the first object at $t = 0$, and the constraints from the second object are placed at $t = t_{max}$, where t_{max} is the given separation distance. We then create a 4D implicit function using variational interpolation. An intermediate shape between the two given shapes is found by extracting the isosurface of a 3D "slice" (actually a volume) of the resulting 4D function.

Figure 6 shows two 3D shape transformation sequence that were constructed using this method. To extract these surfaces we use code published by Bloomenthal that begins at a seed location on the surface of a model and only evaluates the implicit function at points near previously visited locations [4]. This is far more efficient than sampling an entire volume of the implicit function and then extracting an isosurface from the volume. The matrix solution for the transformation sequence of Figure 6 (left) required 13.5 minutes, and each isosurface in the sequence took approximately 2.3 minutes to generate on an SGI Indigo2 with a 195 MHz R10000 processor. Figure 6 (right) shows a transformation between 3D shapes that used warping to align features.

6 Surface Reconstruction from Contours

So far we have only considered shape transformation between pairs of objects. In medical reconstruction, however, it is often necessary to create a surface from a large number of parallel 2D slices. Can't we just perform shape interpolation between pairs of slices and stack the results together to create one surface in 3D? Although this method will create a continuous surface, it is almost certain to produce a shape that has surface normal discontinuities at the planes of the original slices. In the plane of slice i, the surface created between slice pairs $i-1$ and i will usually not agree in surface normal with the surface created between slices i and $i+1$. Nearly all contour interpolation methods consider only pairs of contours at any one time, and thus suffer from such discontinuities. (A notable exception is [1]).

To avoid discontinuities in surface normal, we must use information about more than just two slices at a given time. We can accomplish this using a generalization of the variational approach to shape transformation. Assume that we begin with k sets of constraints, one set for each 2D data slice. Instead of considering the contours in pairs, we place the constraints for all of the k slices into

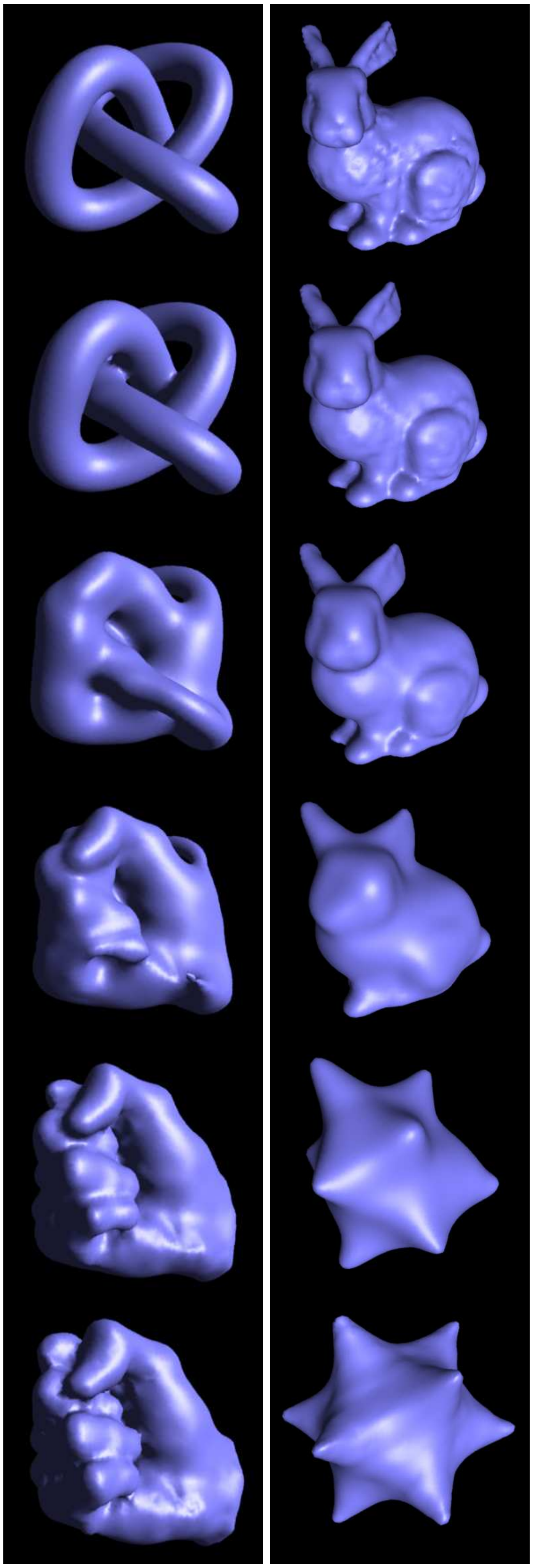

Figure 6: 3D shape transformation sequences.

3D simultaneously. Specifically, the constraints of slice i are placed in the plane $z = si$, where s is the spacing between planes. Once the constraints from *all* slices have been placed in 3D, we invoke

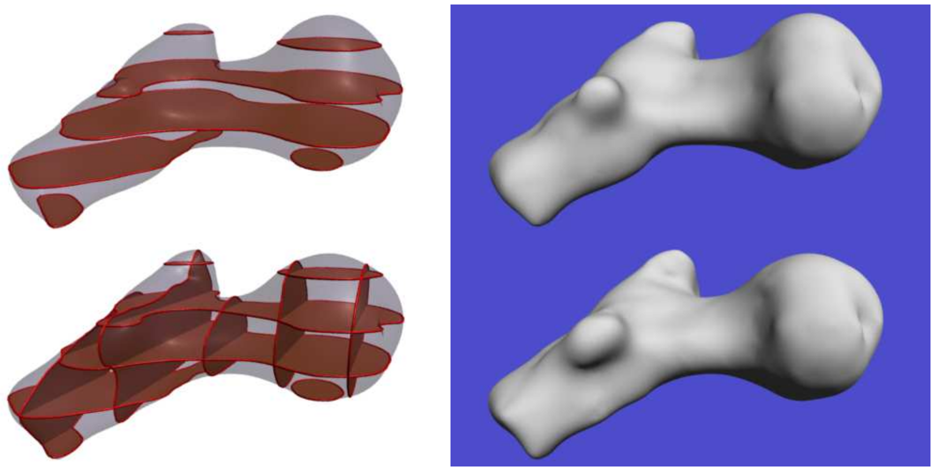

Figure 7: Reconstruction of hip joint from contours. Top row shows the five parallel slices used and the final surface. Bottom row shows intersecting contours and the more detailed surface that is created.

variational interpolation *once* to create a single implicit function in 3D. The zero-valued isosurface exactly passes through each contour of the data. Due to the smooth nature of variational interpolation, the gradient of the implicit function is everywhere continuous. This means that surface normal discontinuities are rare, appearing in pathological situations when the gradient vanishes such as when two features just barely touch. Figure 7 (top row) illustrates the result of this contour interpolation approach. The hip joint reconstruction in the upper right was created from the five slices shown at the upper left.

A side benefit of using the variational implicit function method is that it produces smoothly rounded caps on the ends of surfaces. Notice that in Figure 7 (top left) that the reconstructed surface extends beyond the constraints in the positive and negative z direction (the direction of slice stacking). This "rounding off" of the ends is a natural side effect of variational interpolation, and need not be explicitly specified.

6.1 Non-Parallel Contours

In the previous section, we only considered placing constraints within planes that are all parallel to one another. There is nothing special about any particular set of planes, however, once we are specifying constraints in 3D. We can mix together constraints that are taken from planes at any angle whatsoever, so long as we know the relative positions of the planes (and thus the constraints). Most contour interpolation procedures cannot integrate data taken from slices in several directions, but the variational approach allows complete freedom in this regard. Figure 7 (lower row) shows several contours that are placed perpendicular to one another, and the result of using variational interpolation on the group of constraints from these contours.

6.2 Between-Contour Spacing

Up to this point we have not discussed the separating distance s between the slices that contain the contour data. This separating distance has a concrete meaning in medical shape reconstruction from 2D contours. Here we know the actual 3D separation between the contours from the data capture process. This "natural" distance is the separating distance s that should be used when reconstructing the surface using variational interpolation. Upon reflection, it is odd that some contour interpolation methods do not make use of the data capture distance between slices. In some cases a medical technician will deliberately vary the spacing between data slices in order to capture more data in a particular region of interest. Using variational interpolation, we may incorporate this information about varying separation distances into the surface reconstruction process.

For both special effects production and for computer aided design, the distance between the separating planes can be thought of as a control knob for the artist or designer. If the distance is small, only pairs of features from the two shapes that are very close to one another will be preserved through all the intermediate shapes. If the separation distance is large, the intermediate shape is guided by more global properties of the two shapes. In some sense, the separating distance specifies whether the shape transformation is local or global in nature. The separation distance is just one control knob for the user, and in the next section we will explore another user control.

7 Influence Shapes

In this section we present a method of controlling shape transformation by introducing an *influence shape*. The idea to use additional objects as controls for shape transformation was introduced by Rossignac and Kaul [24]. Such intermediate shape control can be performed in a natural way using variational interpolation. The key is to step into a still higher dimension when performing shape transformation.

Recall that to create a transformation sequence between two given shapes we added one new dimension, called t earlier. We can think of the two shapes as being two points that are separated along the t dimension, and these two points are connected by a line segment that joins the two points along this dimension. If we begin with three shapes, however, we can in effect place them at the three points of a triangle. In order to do so we need not just one additional dimension but two, call them s and t.

As an example, we may begin with three different 3D shapes A, B and C. To each constraint that describes one of the shapes, we can add two new coordinates, s and t. Constraints from shape A at (x,y,z) are placed at $(x,y,z,0,0)$, constraints from shape B are placed at $(x,y,z,1,0)$ and shape C constraints are placed at $(x,y,z,1/2,1/2)$. Variational interpolation based on these 5-dimensional constraints results in a 5D implicit function. Three-dimensional slices of this function along the s-dimension between 0 and 1 are simply shape sequences between shapes A and B when the t-dimension value is fixed at zero. If, however, the t-dimension value is allowed to become positive as s varies from 0 to 1, then the intermediate shapes will take on some of the characteristics of shape C. In fact, the 5D implicit function actually captures an entire family of shapes that are various blends between the three shapes. Figure 8 illustrates some members of such a family of shapes.

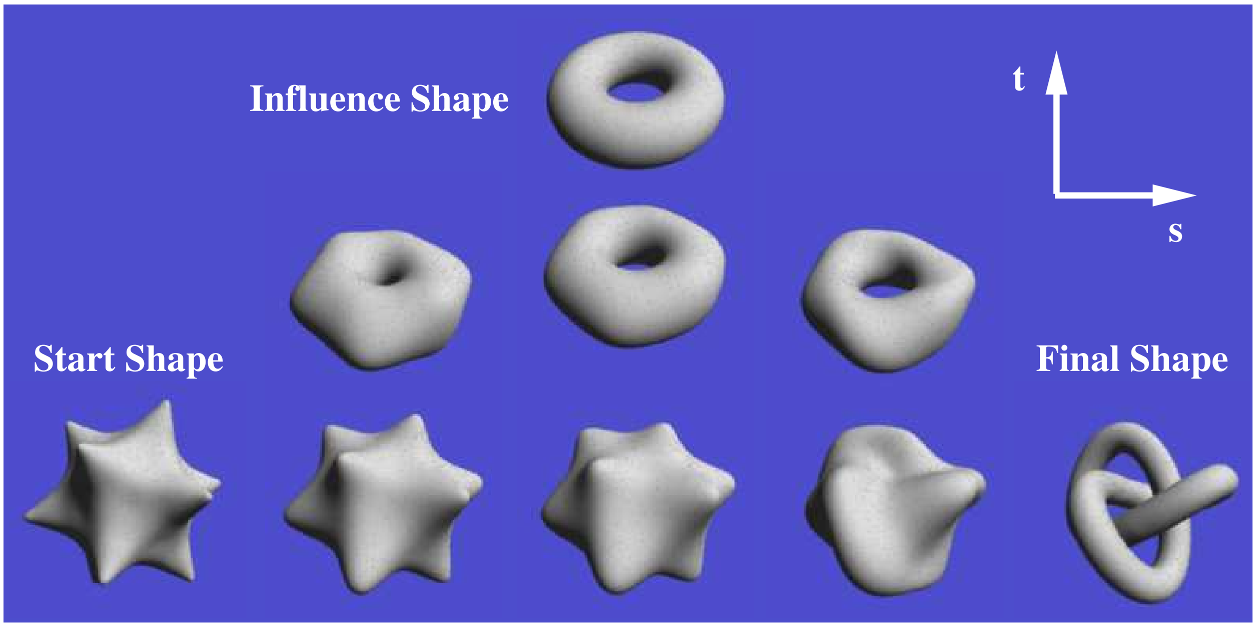

Figure 8: Sequence between star and knot can be influenced by a torus (the influence shape) if the path passes near the torus in the five-dimensional space.

There is no reason to stop at three shapes. It is possible to place four shapes at the corners of a quadrilateral, five shapes around a pentagon, and so on. If we wish to use four shapes, then placing the constraints at the corners of a quadrilateral using two additional dimensions would not allow us to produce a shape that was arbitrary mixtures between the shapes. In order to do so, we can place the constraints in yet a higher dimension, in effect placing the four shapes at the corners of a tetrahedron in $N+3$ dimensions, where N is the dimension of the given shapes.

There are two related themes that guide our technique for shape transformation. The first is that shape transformation should be thought of as a shape-creation problem in a higher dimension. The second theme is that better shape transformation sequences are produced when all of the problem constraints are solved simultaneously— in our case by using variational interpolation. Influence shapes are the result of taking these ideas to an extreme.

8 Conclusions and Future Work

Our new approach uses variational interpolation to produce one implicit function that describes an entire sequence of shapes. Specific characteristics of this approach include:

- Smooth intermediate shapes
- Shape transformation in any number of dimensions
- Analytic solutions that are free of polygon and voxel artifacts
- Continuous surface normals for contour interpolation
- Contour slices may be at any orientation, even intersecting

This approach provides two new controls for creating shape transformation sequences:

- Separation distance gives local/global interpolation tradeoff
- May use influence shapes to control a transformation

The approach we have presented in this paper re-formulates the shape interpolation problem as an interpolation problem in one higher dimension. In essence, we treat the “time” dimension just like another spatial dimension. We have found that using the variational interpolation method produces excellent results, but the mathematical literature abounds with other interpolation methods. An exciting avenue for future work is to investigate what other interpolation techniques can also be used to create implicit functions for shape transformation. Another issue is whether shape transformation methods can be made fast enough to allow a user interactive control. Finally, how might surface properties such as color and texture be carried through intermediate objects?

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10 Appendix: Warping

Warping is a commonly used method of providing user control of shape interpolation. Although warping is not a focus of our research, for the sake of completeness we describe below how warping may be used together with our shape transformation technique. Research on warping (sometimes called deformation) include [2, 26, 28, 3, 18, 7].

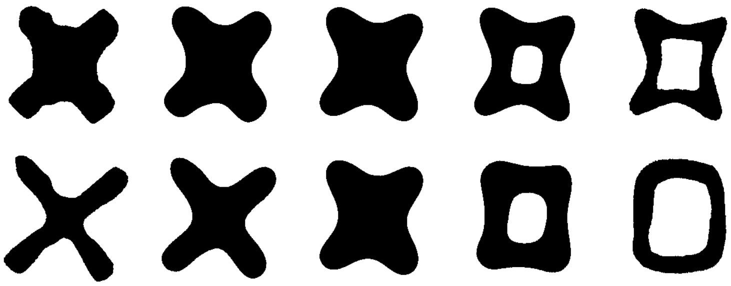

Figure 9: The extreme left and right shapes in the top row have been warped before creating the upper shape transformation sequence. The lower row is an un-warped version of this sequence that gives the final transformation from an X to O.

For symmetry, we choose to warp each shape "half-way" to the other shape. Given a set of user-supplied corresponding points between two shapes A and B, we construct two displacement warp functions $\mathbf{w}_A$ and $\mathbf{w}_B$. The function $\mathbf{w}_A$ specifies what values to add to locations on shape A in order to warp it half-way to shape B, and the warping function $\mathbf{w}_B$ warps B half of the way to A.

In what follows, we will describe the warping process for two-dimensional shapes. Let $\{\mathbf{a}_1, \mathbf{a}_2, \ldots, \mathbf{a}_k\}$ be a set of points on shape A, and let $\{\mathbf{b}_1, \mathbf{b}_2, \ldots, \mathbf{b}_k\}$ be the corresponding points on B. We construct the two functions w_A and w_B such that $w_A(\mathbf{a}_i) = (\mathbf{b}_i - \mathbf{a}_i)/2$ and $w_B(\mathbf{b}_i) = (\mathbf{a}_i - \mathbf{b}_i)/2$ hold for all i. Constructing these functions is another example of scattered data interpolation which we can solve using variational techniques. For 2D shapes, if $\mathbf{a}_i = (a_i^x, a_i^y)$ and $\mathbf{b}_i = (b_i^x, b_i^y)$, then the x component $w_A^x$of the displacement warp $\mathbf{w}_A$ has k constraints at the positions $\mathbf{a}_i$ with values $(b_i^x - a_i^x)/2$. We invoke variational interpolation to satisfy these constraints, and do the same to construct the y component of the warp. The function $\mathbf{w}_B$ is constructed similarly. This is not a new technique, and researchers who use thin-plate techniques to perform shape warping include [5, 20] and others.

In order to combine warping with shape transformation, we use these functions to displace all of the boundary constraints of the given shapes. These displaced boundary constraints are embedded in 3D (as described in Section 5) and then variational interpolation is used to create the implicit function that describes the entire shape transformation sequence. The result of this process is a three-dimensional implicit function, each slice of which is an intermediate shape between two warped shapes. The top row of Figure 9 shows such warped intermediate shapes. We can think of the two "ends" of this implicit function (at $t = 0$ and $t = t_{max}$) as being warped versions of our original shapes. In order to match the two original shapes, the surface of this 3D implicit function needs to be unwarped. To simplify the equations, assume that the value of t_{max} is 2. If $t \leq 1$ the unwarping function $u(x, y, t)$ is:

$$u(x,y,t) = (x + (1-t)w_A^x(x,y), y + (1-t)w_A^y(x,y), t) \qquad (4)$$

If $t > 1$ then the unwarping function is:

$$u(x,y,t) = (x + (t-1)w_B^x(x,y), y + (t-1)w_B^y(x,y), t) \qquad (5)$$

At the extreme of $t = 0$, the warp $u(x, y, t)$ un-does the warping we used for the first shape. At $t = 2$, the function $u(x, y, t)$ reverses the warping used for the second shape. When $t = 1$ (the middle shape in the sequence), no warp is performed. The bottom sequence of shapes in Figure 9 shows the result of the entire shape transformation process that includes warping. Both sequences in Figure 5 were created using warping in addition to shape transformation.

Although we have described the warping process for 2D shapes, the same method may be used for shape transformation between 3D shapes. For Figure 6 (right), warping was used to align the bunny ears to the points of the star.