A System’s Architecture for Warping and Morphing of Graphical Objects

Abstract
This paper describes a system architecture that enables the use of different techniques of warping and morphing applied to various classes of graphical objects (images, surfaces, plane curves, volumetric data, implicit surfaces etc.) Combinations of warping and morphing techniques can lead to more powerful and expressive results. The possibility of experimenting with alternative techniques for distinct classes of graphical objects creates a very flexible and robust warping and morphing system.


Additional Keywords: Metamorphosis; Shape deformation;

1 Introduction
Metamorphosis is a fundamental characteristic of the constant evolution of nature [37]. In computer graphics, the presence of warping and morphing is ubiquitous, ranging from the projective warping of the camera transformation to more complex transformations of shape and motion.

These operations encompass a broad range of applications in different areas, including shape design, rendering, image and volumetric data registration, and special effects for the video, television and the movie industry. In fact, warping and morphing constitute an intrinsic part of a rendering or animation system.

1.1 Previous Work
The importance of warping and morphing is reflected in the large number of publications from different research fields. The literature covers a wide range of warping and morphing techniques for different graphical objects.

Image warping has been addressed in computer graphics since the original work of Ed Catmull [8] on texture mapping (see also [9]). Since then, research in this area has constantly increased. An overview of the field can be found in [19], and specially in [39]. Several techniques have appeared in the literature, including [36, 4, 28, 1]. More recent work includes [25] and [34]. Also, image warping techniques have been studied separately related with the problem of image registration, in the areas of photogrametry [17], and medical images [14].

Curve warping and morphing have been studied in [33, 32, 35, 40, 7]. This topic has a wide range of applications, specially in the areas of shape design and animation [38, 30]. Surface warping techniques date back to the beginning of the use of free-form surfaces for surface design [11, 5]. In fact changing the control parameters is a flexible form of defining intrinsic warps of surfaces. There are several papers on warping and morphing of surfaces [31, 24, 23, 12, 6, 13]; for a survey see [3].

Volume metamorphosis has been addressed in [26, 22, 18]. This topic has applications in the area of medical images.

There is a number of commercial software available to compute warps and morphings of graphical objects [2, 29]. These packages have a high degree of functionality, but they are targeted at specific classes of graphical objects. There exists commercial graphical packages that offer solutions for warping and morphing of images as well as for surfaces, but they are usually not integrated.

1.2 Contribution
Certainly, the overview of the field cited above represents only a percentage of the work that has been published concerning warping and morphing. A few remarks about the existing literature are in order:

1. Morphing and warping research has covered particular classes of graphical objects.
2. There has been no attempt to obtain an integrated approach to warping and morphing;
3. There exists no flexible software architecture that enables us to experiment with warping and morphing of distinct graphical objects, using different techniques.

Certainly, problems 1 and 2 above are fundamental in addressing problem 3. Problems 1 and 2 have been addressed in [16] (see also [15]). This paper focuses on problem 3. More precisely, we describe a software architecture we have developed which has the following characteristics:

1. Allows for warping and morphing of different graphical objects (images, surfaces, plane curves and volume data);
2. Allows the use of different warping and morphing techniques, which are shared among various types of graphical objects;
3. Allows the inclusion of new graphical objects in the system;
4. Allows the development of plug-ins using different warping and morphing techniques;
5. Provides a uniform and coherent interface, across different graphical objects and techniques.
1.3 Structure of the Paper

The structure of the paper is as follows: Section 2 discusses the concept of graphical objects, and warping and morphing operations; Section 3 gives an overall description of the system’s architecture; sections 4, 5 and 6 describe in detail the architecture; section 8 presents examples of using the system in several situations; section 9 concludes the paper summarizing the results and describing future work.

2 Warping and Morphing

In this section we will bring into the stage the two major actors in the study of warping and morphing: graphical objects and transformations.

2.1 Graphical Objects

A graphical object [16] is characterized by its shape and attributes. The shape describes the topology and geometry of the graphical object, and the attributes carry information about its different properties: color, material, etc.

Mathematically, the shape of a graphical object is a subset \( U \subset \mathbb{R}^n \) of some \( n \)-dimensional euclidean space, and the attributes are defined by a function \( f: U \subset \mathbb{R}^n \rightarrow \mathbb{R}^m \) (we are encapsulating all of the attributes in one function). A graphical object \( O \) is denoted by \( O = O(U, f) \). The dimension of \( U \) defines the dimension of the graphical object. \( \mathbb{R}^n \) is the space where the object is embedded.

The most common examples are:

- A curve is a 1-dimensional graphical object embedded in \( \mathbb{R}^n \). For \( n = 2 \), we have a plane curve.
- A planar region is a 2-dimensional graphical object embedded in the plane, typically with a constant attribute color;
- An image is a 2-dimensional graphical object embedded in the plane. A planar region corresponds to a binary image.
- A surface is a 2-dimensional object embedded in \( \mathbb{R}^3 \);
- A solid is a 3D graphical object embedded in \( \mathbb{R}^3 \).

Some graphical objects (e.g. an image) have a very simple shape and complex attributes, while other objects (e.g. a surface) might have complicated shapes and simple attributes.

2.1.1 Computing with Graphical Objects

The concept of a graphical object allows us to obtain a unified computational pipeline. In fact, when dealing with graphical objects, we are faced with the following problems:

- Description of graphical objects;
- Representation of graphical objects;
- Reconstruction of graphical objects.

The description of graphical objects accounts for the creation of objects, and it is closely related to the user interface. The representation of graphical objects accounts for the discretization of the shape and attributes. We should emphasize the importance of representation and reconstruction techniques. In general, the user describes a discrete object that has to be reconstructed in order to perform operations with them. On the other hand, continuous graphical objects must be discretized to obtain a computational representation. The interplay between reconstruction and discretization techniques constitute a fundamental problem when dealing with graphical objects. The computational framework for graphical objects is shown in Figure 1.

![Figure 1: Graphical objects computational pipeline.](image)

In general, a graphical object is described by functions (either parametrically or implicitly). On the other hand, the attribute is also defined by a function. Therefore, in the computational pipeline of Figure 1, we are dealing with functions. That is, we must devise techniques and interfaces to describe functions, sample and reconstruct them. This unified view is one of the contributions of the concept of graphical objects.

2.2 Transformations of Graphical Objects

A transformation of a set \( U \subset \mathbb{R}^n \) is a function \( T: U \subset \mathbb{R}^n \rightarrow \mathbb{R}^m \). When \( T = L|U \) is the restriction of a function \( L: \mathbb{R}^n \rightarrow \mathbb{R}^m \), defined on the whole space, we say that \( T \) is a global or extrinsic transformation. Otherwise, \( T \) is called an intrinsic transformation. \( T \) is called a local transformation if for any point \( p \in U \), \( T \) does not move points outside a small neighborhood of \( p \).

A transformation of a graphical object \( O = O(U, f_1) \) is achieved by transforming both the shape \( U \) and the attribute function \( f_1 \), as illustrated in Figure 2: \( T(O(U, f_1)) = O(T(U), f_2) \), where \( f_2(T(p)) = f_1(p) \).

![Figure 2: Graphical object transformation.](image)
2.2.1 Computing with Transformations

The computational pipeline for dealing with transformations is shown in Figure 3. This pipeline is very natural:

- Devise techniques to specify transformations. This is closely related to the user interface.
- Devise techniques to discretize transformations.
- Devise techniques to reconstruct transformations.

We should notice that the specification of a transformation by the user either produces a continuous transformation or a discretized one. The techniques of discretization and reconstruction play a very important role when computing with transformations.

The reader may have noticed the similarity between the computational pipeline in Figures 1 and 3. The reason is that the natural habitat of both graphical objects and transformations is a space of functions. Therefore, those computational pipelines are indeed computational pipelines for functions.

2.3 Warping and Morphing Transformations

In order to define warping and morphing of a graphical objects, we need to introduce the concept of family of transformations.

A continuous k-parameter family of transformations of a graphical object $O = O(U,f), U \subset \mathbb{R}^n$, is a continuous transformation $T : \mathbb{R}^k \times O \rightarrow \Omega$, where $\Omega$ is a space of graphical objects. Thus, for each $v \in \mathbb{R}^k$, we obtain a transformation $T(v,O)$ of the graphical object $O$. As $v$ varies on the parameter space $\mathbb{R}^k$, the object changes continuously.

Suppose that $T(v_0(O)) = O$ for some $v_0 \in \mathbb{R}^k$, and take a continuous path $\alpha : [0,1] \rightarrow \mathbb{R}^k$, such that $\alpha(0) = v_0$. We obtain a 1-parameter family of transformations $T : [0,1] \times O \rightarrow \Omega$, defined by $T(t,O) = T(\alpha(t),O)$. By interpreting $t$ as time, this family represents an animation that describes a continuous deformation of the object $O$. This is called a warping of the object $O$.

Consider a continuous k-parameter family of transformation $T : \mathbb{R}^k \times O \rightarrow \Omega$, defined on some space of graphical objects $\Omega$. Let $v_0, v_1 \in \mathbb{R}^k$ and $O_1, O_2 \in \Omega$ such that $T(v_0,O_1) = O_1$ and $T(v_1,O_1) = O_2$. If $\alpha : [0,1] \rightarrow \mathbb{R}^k$ is a continuous curve satisfying $\alpha(0) = v_0$ and $\alpha(1) = v_1$, the 1-parameter family $T : [0,1] \times O_1 \rightarrow \Omega$ defined by $T(t,O_1) = T(\alpha(t),O_1)$ is a metamorphosis (or a morphing) from $O_1$ to $O_2$. This metamorphosis is an animation that produces a continuous deformation from object $O_1$ to object $O_2$. $O_1$ is called the source object and $O_2$ is called the target object.

For each point $p \in O_1$, the curve $\gamma(t) = T(t,p), t \in [0,1]$ describes a path in $\mathbb{R}^n$ from $p$ to $q = T(1,p) \in O_2$. This is called an animation path of the point $p$. Notice that the knowledge of the animation path for all points of the source graphical object characterizes the morphing completely.

The operations of warping and morphing result from a clever coupling of the concepts and techniques used to study graphical objects and their transformations. The computational framework for the operations of warping and morphing is shown in the diagram of Figure 4. This diagram is a merging of the diagrams of the computational pipeline for graphical objects (Fig. 1) with the computational pipeline for transformations (Fig. 3). The symmetry of the diagram well illustrates the interplay between graphical objects and transformations to accomplish the operations of warping and morphing.

According to the diagram in Figure 4, a warping of a graphical object is obtained in three major steps:

- Creation of the graphical objects;
- Specification of the transformation family;
- Computation of the transformation applied to the graphical object.

In the next section, we will see how this conceptual pipeline provides the elements for a computational framework.

2.4 Computational Elements

The design of a computational framework for the warping and morphing system can be based on six fundamental elements:

- Graphical object creation/representation;
- Transformation specification/representation;
- Warping reconstruction;
- Mapped object computation;
- Shape combination;
- Attribute combination.

Graphical Object Creation/Representation. The representation of a graphical object associates a data structure to a discretization of the object, encapsulating the description of its shape and attributes. A typical application may handle only a specific type of graphical object, for example, an image represented by a matrix of pixel values. The representation is closely related with the specification: in general the user specifies a representation of the object.

Transformation Specification/Representation. The specification of the transformation consists in a discrete representation of the transformation, that is usually manipulated by the user. In a typical situation, the user specifies values of the warp at a discrete set of points at initial and final states. In some key-frame systems, these values are specified at different intermediate key states.
Warping Reconstruction. The warping reconstruction uses the discrete representation of the transformation, computing the transformation values at any point of the spatial and time domains of interest. This includes interpolating the key states in time, and extending the transformation values to all points of the object shape. This is equivalent to computing a state of the warp along the animation paths for different time values.

Mapped Object Computation. This step of the technique enumerates the elements of the representation of the graphical object, traversing its structure. This is necessary in order to apply the warping to the object. The computation of the mapped object is closely related to the reconstruction of the transformation, and in some cases both elements are intermixed in actual implementations.

Shape Combination. This operation is, in general, necessary because we do not have a perfect alignment between the geometry of the two objects. When computing an image metamorphosis the shape combination in general is not present because we have perfect alignment of the image boundaries (also all of the emphasis on an image morphing is in the pixel colors). Nevertheless, shape combination is of fundamental importance when computing morphing of other graphical objects such as curves and surfaces. When the objects have different topologies, it is necessary to use topological surgery in order to proceed the shape combination operation. An example is given in [13].

Attribute Combination. The operation of combining attributes is used in the morphing transformation to compute the resulting attribute function from the attributes of the source and target graphical objects. The method of combination will vary according to the attribute nature. A typical example is a linear cross-dissolve performed on a pixel-by-pixel basis between two images.

A morphing technique is a combination of the six above elements, but the essence of the methods is contained in the specification and reconstruction of the transformation and the graphical objects.

The most common specification techniques are based on points, oriented line segments or meshes. In general, the problem of reconstructing the transformation reduces to the computation using scattered data interpolation techniques. Some of them are affine interpolation, inverse distance weighted functions, radial basis functions and thin-plates splines.

Two well-known image morphing methods are [4] and [36]. In [4], the described morphing method uses oriented line segment specification, field-based reconstruction (inverse distance weighted interpolation) and cross-dissolve for color combination. In [36], a two-pass warping is specified with spline meshes. The warping reconstruction and the mapped object computation in this case are not completely separated. The technique constructs the transformation for each scan-line and scan-column, in two consecutive passes. For a description of different warping and morphing techniques the reader should consult [15].

2.4.1 Hybrid Techniques

Usually, morphing techniques offer complete solutions to each of the steps of the morphing problem. The solutions of these subproblems can be potentially detached from each other, and recombined to produce different techniques.

The use of a particular warping method may induce the use of a type of specification that is not practical to manipulate from the user point of view (e.g., mesh-based interfaces). On the other hand, some specification techniques have very good user interfaces, but are associated with costly reconstruction techniques. In both cases, intermediate specifications can be introduced, yielding hybrid techniques.

For instance, a point specification can be very convenient for the user, while a two-pass spline mesh warping method is generally much faster to compute. Allowing the user to work on the point specification, which is then used to deform a spline mesh, which in turn is used to deform the graphical object, is an alternative solution.

3 System’s Architecture

We will now give a description of an architecture of a general morphing system, which addresses the problems stated in section 1.2.

A morphing system has to manage the computational elements of warping and morphing described in section 2.4, and orchestrate their interactions. Although these elements are not necessarily clearly identified and isolated in a given implementation, this separation can bring several benefits to the design and functionality of a system. As an example, the separation of the elements in a system makes it easy to experiment with hybrid techniques. Nevertheless, not all combinations are possible, and the set of specification techniques that suits a particular warping reconstruction technique has to be limited by the system.

One of the primary objectives of the morphing system we developed is to serve as a testbed for experimentation. To attain this, the system design tried to accomplish for the following features:
• extensibility;
• portability;
• flexibility.

Extensibility provides entry points to make the addition of new implementations of computational elements, such as graphical objects and warping reconstruction techniques, an easy task. Portability allows the system to run on various platforms with little implementation effort. Flexibility has the purpose of making it easy to use the system with different types of graphical objects and warping and morphing techniques. Accomplishing these goals is a very difficult task, specially the last one, because of the rich diversity of existing graphical objects (image, curves, surfaces, volumetric objects etc.) and techniques to warp and morph them.

3.1 System Components

The architecture of the system is based on a separation into three different levels: kernel, platform and support levels, as shown in the diagram in Figure 5.

Kernel level. This constitutes the core of the warping and morphing system. It is responsible for managing all the computational elements from section 2.4. Each type of element will be implemented in several different ways, corresponding to different techniques for performing the computation relative to that element. This level should be independent of platform.

Support level. This module is responsible for the utility libraries, such as container classes, safe object sharing mechanisms, geometry and math libraries. It is also responsible for the input and output of graphical objects, supporting various standard and custom file formats for each type of graphical object. Portability of this level is one of the goals in the implementation of the system.

Platform level. This module is responsible for the entire interface with the operating system. This includes in particular user interface and memory management. This is the level where all the platform dependencies are concentrated.

Figure 5 also shows the internal structure of each block of the system architecture. Each of these blocks will ultimately correspond to classes. In the following sections, we will give more details about each of the system levels, and their components.

4 Kernel Level

The kernel level performs the operations necessary to compute warpings and morphings of graphical objects. In this level, the implementation notably benefits from the warping and morphing concepts introduced in section 2.

The kernel level is basically divided in three parts, which encompass all the computational elements:

• graphical objects: graphical object representation;
• specification of transformations: transformation specification and representation;
• computation of transformations: warping reconstruction, mapped object computation, shape combination and attribute combination.

Each of these parts will be controlled by a manager, which is responsible for keeping track of all the available computational element implementations, or techniques. It also defines the basic interface for each element, which provides all the operations and information needed for using those elements in computations, so that they are managed independently of their implementation.

Example (Reusing techniques). Suppose the system contains a vector-based specification among its specification techniques. Assume it also has a field-based warping reconstruction technique [4] that uses the vector specification. Implementing a second warping method that also uses vector specification amounts to actually implementing just the warping reconstruction part: given a set of corresponding vectors, reconstruct the transformation to the entire domain using an appropriate interpolation. This new warping reconstruction technique should be dropped into the system, and the computation manager will automatically make it available to the other layers, and use it when requested.

Note that no user interface will have to be implemented, because the new warping reconstruction technique shares an existing form of specification. This makes the experimentation with new warping and morphing techniques very enticing, once some basic specification techniques are implemented.

4.1 Graphical Objects

The implementation of graphical objects naturally follows object oriented concepts, with each type of graphical object being derived from a generic graphical object. The object
interface will have to adapt to the graphical object class, and to the dimension of the space the graphical object is embedded.

The graphical objects classes are organized in a hierarchy of abstract data types, starting from a very generic root level. A simplified example of such a hierarchy is represented in Figure 6. Each technique that manipulates graphical objects will attempt to plug into this hierarchy at the highest level possible, so that it encompasses the largest group of graphical object types. For instance, the inverse mapping object computation technique can be applied to any implicit discrete graphical object, so this technique should be implemented at this level, and not for some specific class of graphical objects, such as images.

4.2 Specification of Transformations

The specification of a warping or morphing has a strong relationship with the user interface, as the transformations are usually specified graphically through the use of geometric primitives in two states, resulting in a discrete representation of the transformation.

4.2.1 Manipulators

All the specification techniques in our system are built upon basic interface building blocks, which we call manipulators. They are high-level geometric and interactive entities, similar in essence to widgets [10]. Manipulators provide both the semantics and the appearance of the components that allow the handling and modification of the specification of a transformation. Manipulators can be either 2D or 3D, depending on the dimension of the space where the graphical object is embedded. The implementation of the manipulators is portable, using the high-level input and output graphics primitives from the platform level.

Manipulators can be of two types: basic and composite. Basic manipulators are very simple geometric primitives, including points, squares, lines etc., with some basic interaction capabilities, such as hit testing and dragging. The composite manipulators are more complex, and are constructed from basic manipulators. The composite manipulators are container classes that have to process messages, and appropriately propagate them to their children. Examples of messages include drawing, dragging, selection and deselection.

There are several types of composite manipulators, including basic and composite groups, which are ordered collections of basic and composite manipulators, respectively. Figure 7(a) shows some nodes of a basic manipulator, and Figure 7(b) illustrates a composite manipulator class hierarchy.

As composite manipulators are collections of other manipulators, manipulators have a hierarchical instantiation structure.

Example (Curve set manipulator). Take, for instance, the curve set composite manipulator, whose structure is shown in Figure 8: the curve set manipulator is a composite group, constituted by curve manipulators. The curve manipulators derive from the basic group manipulators, and contain a number of square manipulators. The curves are manipulated via these square handles. The curve manipulator just overrides the rendering routine of the basic group manipulator to draw the spline connecting its control points. All the other operations of the composite manipulator are performed by the basic group and square manipulator base classes.
4.2.2 Specification Techniques

The specification manager offers a set of manipulators for the specification techniques. The specification techniques can choose manipulators from this set, or can derive even more complex manipulators from the existing ones, with modified appearance, or imposing technique specific constraints, priorities and relationships among manipulators. In this way, the specification techniques can share and reutilize the provided graphical elements.

The specification manager defines the interface of a generic specification technique, i.e., the operations that a given specification technique will have to perform. It also requires that the specification techniques provide methods to extract the geometric and topological parameters from the manipulators which will be needed by the warping reconstruction techniques.

The specification manager defines the syntax of the specification and the implementation of the technique defines its semantics. In this way, the addition of a new specification technique does not involve tracking of user state or any system-dependent graphics, just the implementation of the meaning of the graphical manipulators.

4.3 Computation of Transformations

The separation between the computation manager and the computation techniques makes the process of adding a new computation technique straightforward. The parts that are common to any computation technique, such as the generation of a series of frames of a transformation by varying the time parameter, are factored out to the computation manager level. The computation manager is also able to handle families of transformations and generate animations from them. The implementation of the computation techniques have to deal with just the computation, at a given point in time, of the specific operation: mapping object computation, warping reconstruction, attribute combination or shape combination. Examples of computation modules are shown in Figure 9.

<table>
<thead>
<tr>
<th>Object Traversal</th>
<th>Warping Reconstruction</th>
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<tr>
<td>Inverse mapping</td>
<td>Field-based</td>
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<td>Direct mapping</td>
<td>Radial functions</td>
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<td>Attribute</td>
<td>Shape Combinations</td>
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<td>Combination</td>
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<td>Cross-dissolve</td>
<td>Exponential blend</td>
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<td>z-buffering</td>
<td>Linear interpolation</td>
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Figure 9: Computation Modules.

4.3.1 Transformations Schedulers

The computation manager is also responsible for controlling the flow of the transformations, i.e., controlling the rate of change for different parts and attributes of the graphical objects. This control is offered by the schedulers, that determine the schedule according to which, different parts of the graphical object will be transformed. The schedulers can be interpreted as unidimensional functions that warp the time parameter, and have the identity transformation as their default state.

Schedulers can be applied to modify the effect of a transformation globally, or modify some elements of the morphing technique (warping reconstruction, attribute or shape combination). The use of different functions for different parts of the domain of the graphical object undergoing the transformation has the effect of localizing the transformation. As an example, consider the image in Figure 10(a). The attribute combination schedulers for the nose and hair specification elements are shown in Figure 10(b). The warping is controlled simply by a global scheduler with ease-in and ease-out. It is interesting to note that the schedulers themselves are specified using a derivation of the Curve composite manipulator, constrained to be a function in the domain of interest.

5 Support Level

This module of the system (Figure 5) manages input and output of graphical objects, and provides several utility libraries.

Input and output of graphical objects is performed by filters managed by an external object format manager, in much the same way as the warping techniques are managed by the computation manager. The addition of new filters is also a well defined process, limited to implementing a module that performs the operations defined by the file format manager, and adding the new module into the system. The file format manager provides mechanisms for the user to select preferred formats (according to the graphical object type), configure format specific options, and for automatically identifying the
format of input files so that the appropriate graphical objects can be created and loaded.

The support level is also responsible for providing all the functionality of commonly used classes, such as vectors, matrices, hash tables, lists etc., which will facilitate the sharing of code throughout the system.

6 Platform Level

The main goal of the platform level (Figure 5) is to concentrate all the information related to the operating system and user interface. Besides allowing an easier port of the morphing system, the separation between the platform level and the rest of the software allows the implementation of different front ends for the same kernel level, in the same platform. For instance, it is possible to have two different applications, one using a graphical interface and the other using a command line or scripting interface, using the same kernel and support levels.

6.1 User Interface Host

The simple mapping of calls to the operating system does not solve completely the problem of portability of the morphing system. The user interface host, besides providing this “driver” functionality, is responsible for making the morphing application seem native to the system it is being ported to. This obviously implies that semantics of the graphical user interface of the operating system has to be embedded into the morphing system at some stage. The goal here is to confine that knowledge to the system dependent part of the code, so that it can be properly adjusted when porting the system.

In this way, the user interface host provides both event handling and output drawing methods at a high level used in the implementation of the manipulators (section 4.2.1). If the interface functionality were designed at a lower level, this could imply in code redundancy: for example, both point and line manipulators would receive mouse events, and might have to duplicate the implementation of rubber banding.

The color and pattern management is an integrated part of the user interface host. Rather than directly requesting a particular color or pattern to be used in a drawing operation, the manipulators select representation types according to the idea conveyed to their states. Examples include hot spot and selected manipulator representation. These can be mapped to monochrome patterns or to the user’s color scheme.

6.2 System Host

The system host manages the platform-dependent resources used by the application, such as memory, interprocess communication and error handling. As the usage of the standard libraries is recommended to maximize portability, the importance of the system host tends to be reduced. For instance, the use of C/C++ standard I/O library is usually enough to process file I/O.

The system host is also responsible for providing simple user interfaces for asking questions and notifying the user of errors, and also for exceptional situation handling to be used in the kernel and support levels. It also provides services for saving and retrieving persistent configuration options in the system, that can be implemented, for instance, through environment variables.

6.3 Application

Given the kernel level, the support level and the core modules of the platform level, an application can be built by making use of the parts of the system that are of interest.

In a command-line application, the specification of the warping or morphing transformation would not be given interactively, but by files. These specification files could be generated by using a separate specification-only software. This kind of separation would enable the user to compute transformations previously specified in an off-line fashion, to split up the work in a farm of workstations. This kind of application can be made portable by providing appropriate user interface and system hosts.

More commonly, the application will use system dependent features, and graphical interfaces. The use of application frameworks to automate the construction of most of the user interface of the software is a relatively simple approach.

7 The System

The Morphos warping and morphing system has been implemented in C++. The application and the platform level are currently implemented for the Windows family of operating systems, using OpenGL for the 3D interface and for real-time previews of image warpings.

As stated before, the fundamental operations of the system are concentrated in the kernel level. An user-friendly interface, project management, intelligent file format usage and configurability are important aspects of an actual system that must be taken into consideration when designing the architecture. We have concentrated most of the system development effort in designing the kernel level, the support level, and the relation of these parts with the user interface.

7.0.1 Objects and Transformations

Morphos currently supports three types of graphical objects: images, polygonal curves, and surfaces. It has several techniques implemented, including: mesh, features and point specifications; linear and exponential dissolve attribute combination; field-based, radial basis functions, two-pass spline mesh warping, projective mapping etc.

A snapshot of the plug-in modules linked to the system is shown in Figure 11. Note that, as the managers are responsible for keeping track of the techniques and graphical objects under their control, none of the dialogs showing plug-ins has to be modified when adding new modules. Also, all the plug-ins can be configured regardless of their type.

7.0.2 User Interface

For metamorphosis the system uses a “side-by-side” interface: the user interacts with the source and the target objects in order to specify the animation path for corresponding points. The transformation is specified by giving elements of the specification in two states (constraints). Figure 12 illustrates the side-by-side interface for curve metamorphosis. As our system allows the use of different specification types, several different specifications can be placed over the same graphical object, as illustrated in Figure 13 for images.

Side-by-side interface can also be used for specifying warping operations, specially for graphical objects embedded on the plane (curves and images). This interface is useful when we need to specify precisely the handlers constraints, referencing them to the graphical object shape. Another warping specification is achieved by letting the user specify values for
the constrained handlers (points, vectors, etc.). Morphos has an interface for displacement vectors in tridimensional space which uses constrained arcball (see Figure 14). This interface is very effective for interactive warping of surfaces and volumes using point or vector specification.

8 Examples

In this section we give some examples that demonstrate the extensibility and flexibility of our unified architecture for warping and morphing systems. They try to illustrate situations that require the ability to use many different specification and computation techniques for the warping and morphing of distinct types of graphical objects. We stress that it will be very difficult, or even impossible, to deal with these situations in the current warping and morphing systems, because they don’t implement techniques and representations in an integrated way.

8.1 Adapted Image Warping Specification

This example reveals the importance of having several specifications techniques for the same type of graphical object and computation method. This makes it possible to use a specification that best adapts to the problem at hand.

Take the specification of a warping for two different purposes: the first, for correcting distortions, and the second, for real-time registration.

In Figure 15(a), we show the image of a grid that was obtained through a scanning process. The grid is distorted in this image due to problems in the acquisition process. For this reason, we want to determine a morphing specification that will correct the distortion of the input device. The best specification technique for the above problem is a grid-based specification, shown in Figure 15(b). The one-to-one correspondence between the specification primitives and the image makes the task very simple.

In Figure 16(a) we show the image of a texture that needs to be aligned with features of the geometric model shown in Figure 16(b). The best specification technique, in this case, is a feature-based technique. The technique allows the direct indication of features in the image of correspondence with the geometry.

The above examples clearly demonstrate that the effectiveness of a specification technique depends on its adequacy to the task at hand. Therefore, a warping and morphing system should provide a variety of specification techniques, as well as the possibility of adding new ones to the system.
8.2 Integration of Warping and Morphing of Different Types of Graphical Objects

The example of this section illustrates the importance of integrated warping and morphing operation for different types of graphical objects. Such a system is well suited to deal with the problem of registering when texture mapping a warped surface, as described in [27].

As an example, consider the problem of applying the clown texture from Figure 16(a) onto the cylindrical mask shown in Figure 17.

In order to get good results, we must align the features of the clown face (eyes and mouth) to the corresponding features of the mask. This alignment is attained with a warping operation of the clown image to align the eyes and mouth of the clown to the eye and mouth of the mask on the 2D parameter space of the cylindrical mask (See Figure 16). Figure 18(a) shows the warped clown, and Figure 18(b) shows the texture mapping result.

Now we must accomplish the second warping operation: Deform the geometry of the mesh in order to modify its shape. Figure 18(c) shows the warping of the geometric mesh used in the previous example, where the texture is deformed with the mesh. It is clear that when one operation is performed, the object representation should remain consistent. In particular, the correspondence of the texture image with the mesh geometry should be maintained at all times. Also, the user should be able to intermix these two operations in any order using the system.

The system could be able to handle even more complicated versions of the problem above. For instance, consider the case of a morphing between two textured parametric surfaces, in which both the textures and the meshes are being warped and the correspondence needs to be maintained so that the representations can be combined. Complex transformations involving the various aspects of several graphical objects, such as the case described above, can be handled by the integrated architecture of our system.
8.3 Incorporating New Techniques

This example illustrates the usefulness of an extensible architecture that allows incorporating new techniques into the system, showing how a recent image-based rendering method can be easily added to the system. In [20] a technique, called Tour Into the Picture (TIP), is described. This technique uses a spidery mesh interface to specify a projective warping of some image. In that way, the 3D scene depicted in the image can be approximately reconstructed, and re-rendered from different points of view.

Since our system already has a projective warping reconstruction technique, the only component that needs to be added to incorporate the TIP method is the spidery mesh specification technique. Figure 19 shows the interface that we developed for the spidery mesh. The specification consists of a composite manipulator based on:

- a rectangle indicating the back plane. The rectangle is derived from the quadrilateral manipulator, with an added constraint;
- a square, derived from the punctual manipulator, is used to indicate the vanishing point.

The drawing of the composite manipulator is augmented to draw the perspective lines converging to the vanishing point, and passing through the rectangle.

This specification implicitly defines five regions that will be warped using a projective transformation, corresponding to the planes of a cube, with the back plane indicated by the rectangle. The implementation of this specification technique was done in a few hours and all of the functionality of the TIP technique was made available to the system.

8.4 Comparison of Computational Methods

An important feature is to use Morphos as a warping and morphing testbed system, with the ability to compare different methods and techniques, as well as the possibility to experiment with various comparison schemes and metrics.

In this example we illustrate the comparison of two different warping computation methods: two-pass warping and piecewise affine warping. In order to compare these two methods, we are going to measure the RMS error of warped images using each method with a reference warped image using exact computation.

Figure 20 shows the original image and the warping specification. Figure 21(a) depicts the warped image using the two-pass spline mesh warping, and Figure 21(b) shows the warped image using piecewise linear computation technique. Figure 22 shows RMS error between the two warped images.

![Figure 20: Original image.](image-url)

![Figure 21: (a) Two-pass spline mesh warp; (b) Piecewise linear warp.](image-url)

![Figure 22: RMS difference.](image-url)
9 Conclusion and Future Work

We have presented a new architecture for a warping and morphing system. The architecture is based on the fundamental unifying concepts of graphical objects and transformations of graphical objects. These two concepts allow us to create an integrated framework that encompasses all warping and morphing techniques, as well as all types of graphical objects, such as curves, images, surfaces and volumes.

The framework clearly separates the representation from the computational aspects, allowing any transformation to be applied to any object in the system.

Also, a warping/morphing scheme is decomposed into several computational elements. This decomposition is very important because it greatly enhances the expressive power of the system and allows the definition of customized warping and morphing schemes that best match the problem at hand.

The system architecture is structured in three levels: kernel, support and platform level. The kernel level encapsulates the operations of warping and morphing. The support level encompasses the file I/O and utilities and the platform level provides services to implement the user interface.

The above structure makes the system highly portable and, at the same time, makes the task of incorporating new technologies very easy.

We demonstrated the capabilities of the system with some examples that include:

- The use of different warping and specification techniques for the same type of graphical object and computation method.
- The integrated use of warping and morphing in the different aspects of a graphical object, such as its shape and color attributes.
- The design of a new warping technique using the basic functionality of the system.
- The application of the system as a test bed comparison of various warping and morphing techniques.

Future work in the system includes: Addition of volumetric data into the system, which can be implemented in a straightforward manner. The main difficulty is the development of efficient methods for visualization and feedback. Use of side-by-side interface for surface metamorphosis. Include some automatic feature detection techniques as an alternative form of warping specification. Hierarchical correspondence schemes for schedule control of the transformations. These mechanisms will allow a more precise specification of the evolution of the morphing transformation. Capability to handle time-varying graphical objects (motion, video and audio warping and morphing). This requires the tracking of the evolution through time of features associated with graphical objects. Also we intend to port the system to the UNIX operating system.

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References


