The Visual Computer

Animating *soft* objects

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Soft objects change shape as they move. Specifying such changes is a complicated task which has received little attention in the literature largely because, until recently, we had no adequate way to represent such objects.
In order to look natural, any animation has to represent possible motion in the physical world. In this sense, the best animation is based on detailed simulation. Fairing in hand animation can be regarded as a crude attempt to use a few simple rules to do this.
Our *soft* objects are represented by a surface constructed around a set of key points. We use both mathematical descriptions and physical simulation to determine the motion of the key points and thus achieve convincing animation effects.

Key words: *Soft* objects – Geometric modelling – Computer animation

The distinguishing feature of a *soft* object is that its shape changes constantly because of the forces imposed on it by its surroundings. There are many examples: a liquid flows, moulding itself to the surroundings; a boiling liquid bubbles; a face changes its expression and a bouncing ball flattens as it strikes the ground. Our research focuses on the problem of describing the animation of *soft* objects.
The motion of a rigid object can be described as a sequence of geometric transformations which are applied uniformly to all the components of the object. This kind of description has proved very useful in engineering and it has been inherited by the discipline of computer animation, but it utterly fails with *soft* objects. We cannot conveniently separate the gross motion of an object from its changes of shape because some *soft* objects, liquids for example, actually break into separate parts during their motion. The separate parts can then move independently. The problem centres on the unsuitability of traditional modelling techniques to describe these objects.
We are using a modelling technique introduced independently by Jim Blinn (1982) and Oishi Omura (Nishimura 1985). We represent our *soft* objects as a surface of constant value in a scalar field. The field value at any point is a function of the distances from the point to members of a set of control points. Each control point has a position, radius, colour and other properties described by the user, and the surface is a smoothly curved envelope wrapped around the skeleton described by the control points. Details of our modelling and rendering techniques have already been described (Wyvill 1986a) and a revised version of that paper appears as a companion article in this issue of the Visual Computer (Wyvill 1986b).
In this paper we discuss the use of this technique for the representation of *soft* objects in motion, and compare it with traditional modelling methods. We illustrate the discussion with some practical examples and show how some complex motion may be specified.
Bill Reeves has used particle systems for modelling explosions and fire (Reeves 1983). Such objects do change shape over time and could be described as "fuzzy" *soft* objects. However this technique does not lend itself to the decription of non-fuzzy *soft* objects and we have not pursued it further.
The animation described in this paper has all been done using the Graphicsland system at the University of Calgary (Wyvill 1985a). Graphicsland consists of a collection of programs for describing animation which pass their output to a common mod-

elling program, and a number of rendering programs which may be driven by the modeller.

Building models for animation

It has been pointed out (Thalman 1985) that in the last ten years much research has been devoted to the development of rendering algorithms, but little to the equally difficult task of defining complex motion. One of the reasons is the lack of suitable modelling primitives. In modern animation systems the three most commonly used modelling primitives are: polygon mesh, spline surface patches and quadric surfaces. These techniques are not well suited to represent motion of objects which change shape over time.

Polygon meshes are a poor choice for representing curved surfaces anyway. Spline patches, in particular beta splines (Barsky 1982), provide an excellent method for defining curved surfaces. 3D objects consisting of a closed surface may be formed by joining such patches. But moving the object so that it changes shape requires careful management of a large number of control points to ensure that the patches remain as a closed surface and do not penetrate one another.

So *soft* objects may be represented by spline patches as still frames but often lose credibility when motion is attempted (Huitric 1985). Spline surfaces also require the animator to enter a large number of carefully chosen control points to model an object. This can become an immense task for large and complex closed surfaces. Bending could be achieved by moving the spline control points at different velocities and recalculating the spline surface at every frame.

Like a spline surface a *soft* object is also defined by a set of key points. However, unlike a spline surface, the *soft* object key points from a skeleton of the model which gives a better intuitive idea of the form of the object than can be given by the control points of many spline patches. Our initial experiments indicate that an equivalent model built using the iso-surface technique uses considerably fewer control points than are required to describe the same models by patches. This will, however, not be true in all cases.

Shape change can be achieved by moving the control points and adjusting the spatial relationship between the points in a controlled manner. Since *soft* objects can also change shape, motion specification for these models becomes more difficult to express than for rigid objects. To some extent this problem is offset, since our representation of these objects guarantees the formation of one or more closed surfaces, no matter how the control points are moved.

The *soft* object model

A detailed description of our modelling and rendering technique is given in the accompanying paper (Wyvill 1986b). Here, we give just enough explanation to allow this paper to be read independently.

A *soft* object, or collection of objects, is represented by a set of key points specified by the user. Each point has associated with it, a radius R, a colour, a force and possibly other information concerning textures. Each key point is considered to be the source of a potential or field value. The value of this field is proportional to the force and decreases as we move away from the key point. The field due to several key points is the sum of the field due to the individual key points. The radius R determines the rate at which the field due to the key point decays with distance. R is actually the distance at which the influence of the key point falls to zero.

The surface of our objects is defined by the infinite set of points in space for which the field value has some constant value, *magic*. This surface is guaranteed to be closed because the field is continuous. If we move from any point where the field value is greater than *magic* to a point where it is less, we must pass through a point where the field value is exactly *magic*. That is to say, we must cross the surface. This property, that the surface is always closed, is very important.

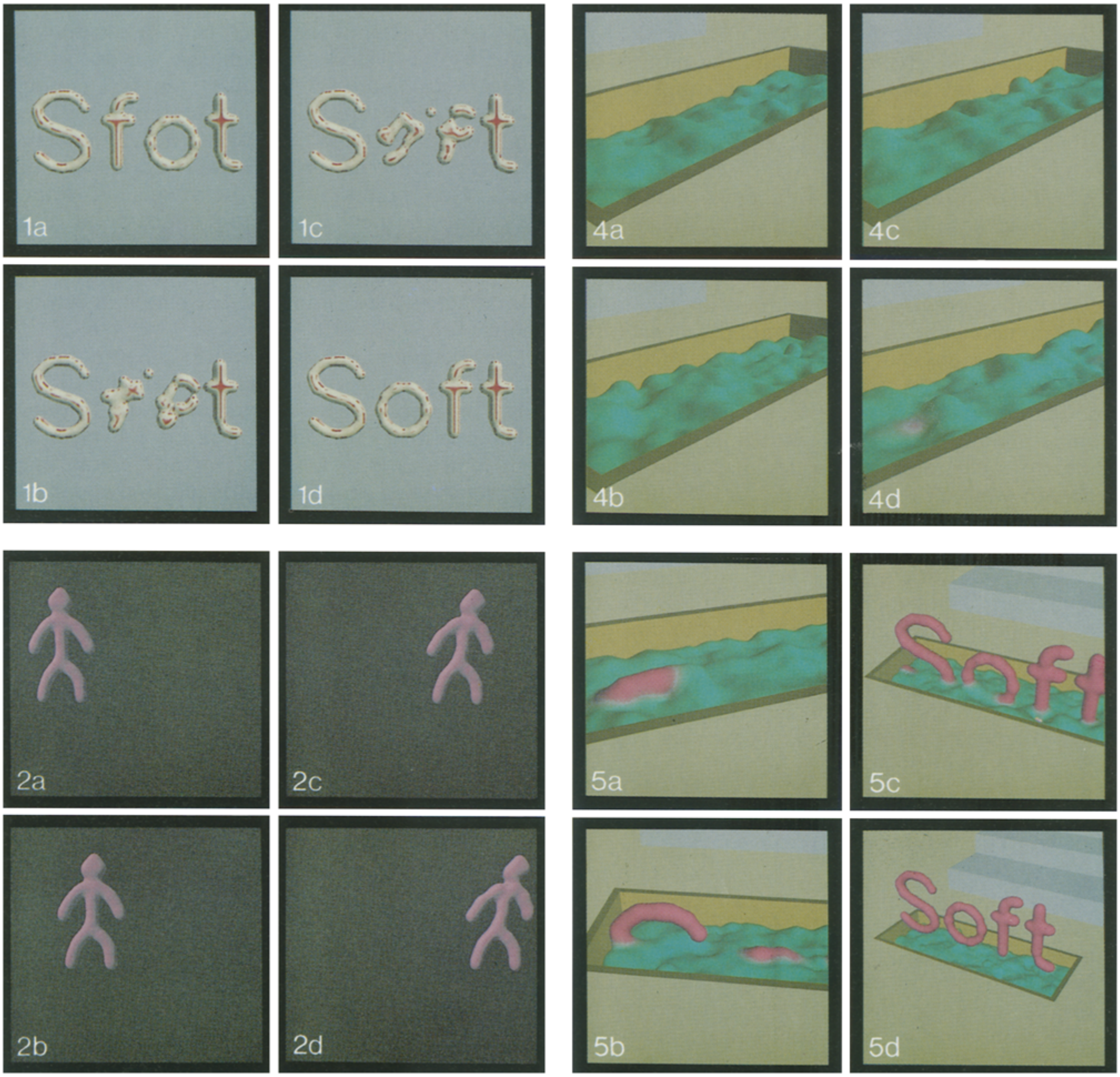
The colour at any point on the surface is defined as a weighted sum of the colours of those key points which influence the field at that point. This means that *soft* objects can exhibit smooth colour changes across their surface. Figures 5a–d show such a change as objects of different colours merge. We can alter the colour of key points as a function of time to produce special effects. For example, we can make a face blush.

The illusion of animation

In animation we wish to simulate the motion of real objects. This motion control falls roughly into two classes: simulation and illusion. In order to look natural, any animation has to represent possible motion in the physical world. In this sense, the best animation is based on detailed simulation which takes into account the physical laws which govern motion. In such a simulation, a mathematical model representing these laws, produces the desired effect automatically. In many applications, it is not necessary for an animation sequence to follow such a physical model. All that is required is to convince the human eye that the motion is one that would be seen in the real world. Fairing in hand animation can be regarded as a crude attempt to use a few simple rules to do this. Such techniques attempt to model the visual effect we refer to in this paper as illusion. In a sense, any approximation, however crude, can be thought of as simulation. Rather than invent new jargon, we use the term simulation in this paper to refer to an accurate physical model as opposed to illusion, where no attempt is made to understand the relevant physical laws, merely to produce a recognisable visual effect. So far, our experiments indicate that *soft* objects provide a very powerful way to represent both of these classes of animation.

Keyframe interpolation

In hand animation an animator draws a character in some position, makes a second drawing of the character in a new position and then fills in the inbetween frames. The digital version of this technique that has been used extensively to represent complex motion in 2D animation is generally known as "inbetweening". Technical difficulties, such as shape distortion and even loss of surface continuity, not to mention the expense of computation, encountered in this process are due primarily to the way in which the animated objects have been modelled. *Soft* objects remove, or at least mitigate, these problems. Moreover, *soft* objects are amenable to various techniques of inbetweening (see the discussion of parametric and key point interpolation, below). Best of all, they present a simpler model for the animator to work with.
A simple form of inbetweening, suitable for two-dimensional (cartoon) models, would have the character drawn on a vector oriented display in two positions, and the inbetween frames interpolated by the system. The simplest way to do this is to interpolate each point of the first (source) object to a corresponding point on the second (destination) object. Difficulties arise if the number of points is different on source and destination objects. New points have to be created or several points have to collapse onto a single point. Even if the number of points is the same on the two objects, if they are distributed in a different way the image will be scrambled as each point is interpolated.
Inbetweening is not only used to show motion of a character from one position to another, it can also be used to show metamorphosis from one character to another. If the characters are very different in shape and number of key points, then the scrambling problem is difficult to avoid. Peter Foldes uses software by Burtnyk and Wein (Burtnyk and Wein 1976) in the film, "La Faim" and exploits this technique to advantage. However to avoid scrambling is a difficult and tedious task which requires very careful design of the key points for inbetweening.
For inbetweening in 3D, two methods of solving these problems have been tried. Both solutions require the definition of a set of keyframes, with the objects in their correct orientations.
The first method uses interpolation of a set of keys which are defined for each object. The interpolation usually works on the geometric transformations, or the parameters of a parameterized model. Examples of this type of system would be BBOP or EM, both developed at the NYIT Graphics Laboratory (Sturman 84). More elaborate control of the motion is discussed in (Stekette 1985). This system guarantees continuous acceleration while still having local control of key points, and the ability to join motions. Most of the techniques offer the user different methods of interpolation, including linear, cubic, and cosine.
The second method uses interpolation of the actual objects. A set of key points are defined either by the artist or by the system, and these key points are interpolated. Theoretically, systems for doing inbetweening of this type in 2D can be extended to 3D, although this may often be impractical. The technique of using moving point constraints (Reeves 1981) may be unsuitable only because of the difficulty of specifying a natural user interface into the system, which would now extend over four



Figs. 1, 2, 4 and 5. For explanation see text

dimensions (3 space and time). In simple cases the problem of matching key points can be left to the system. More difficult cases arise when the objects change shape, or components are added or removed from the scene.

It is possible to combine the two types of system. The parameters of the objects could be interpolated to change location, and at the same time the source object could be inbetweened to the destination object to make some sort of shape change. Since the two systems work on different levels of detail this should not pose a problem.

The difficulty of inbetweening in 3D is influenced by the choice of modelling technique. In the case of polygons, for example, the polygons and their vertices must be carefully matched from source to destination object – a difficult task to automate. The use of B-spline patches reduces the number of points that have to be inbetweened, but to manufacture a complex object would require many patches, and maintaining a closed surface demands the management of complicated constraints on the inbetween positions of the patch control points. With the *soft* object technique, however, a continuous closed surface is guaranteed; some kind of closed volume will be produced whatever the shape of the object in the inbetween stage. This will always produce a more desirable result than allowing the objects to collapse incoherently.

Soft objects require the user to provide comparatively few control points compared with other modelling methods. When using keyframe animation the animator has a much better intuitive feel for what is going to happen and how to alter the motion since in a very real sense the key points form a skeleton of the 3D surface. Figures 1a–d show the letters of the word "Sfot" in various inbetween stages, changing to the word "Soft". The number of key points differs by one between the *O* and the *F*, and a sphere representing that key point moves from one letter to the other. The texture is mapped onto the surface using a method discussed in (Wyvill 1986c).

Physical simulation

The example of the bubbling bath (described below) and the use of techniques such as inbetweening and fairing are very crude methods which create a visual illusion of a desired motion avoiding the calculation necessary for an accurate physical simulation. *Soft* objects are also useful for modelling more accurate simulations of processes.

Figures 7a–d show the word "Soft" in various stages of a fall. The object reaches the ground, compresses and bounces back up again. In this simulation it is assumed that the object is made from some elastic substance that will deform when a force is applied to it, by an amount specified by some characteristic constant of the material (Young's Modulus). The object gains kinetic energy in the fall under gravity and this is used to deform the object which stores the energy and releases it as it bounces back up again. Some of the energy is lost (producing heat) and the second and subsequent bounces gradually damp out the motion.

In the example the object is compressed but does not flatten. That is, the local shape of the bottom

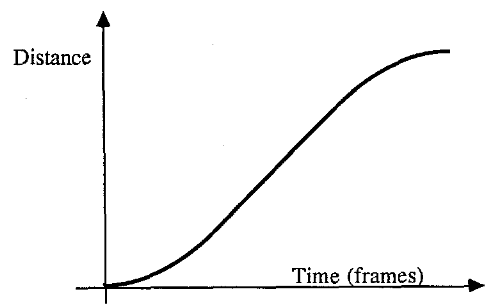


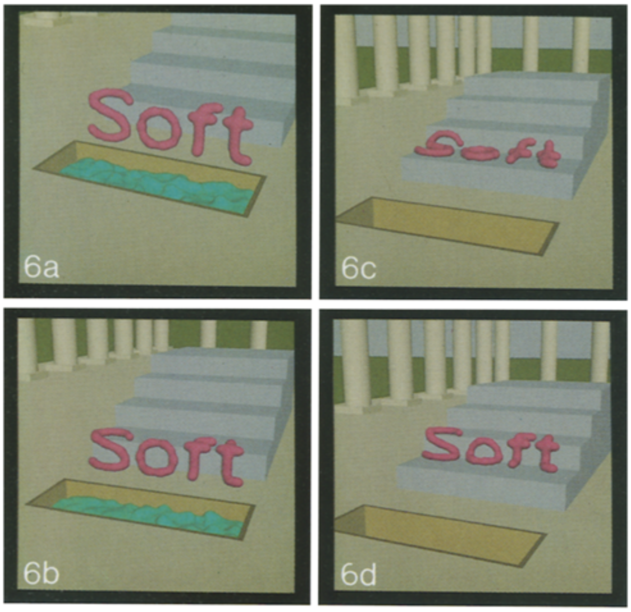
Fig. 3. For explanation see text

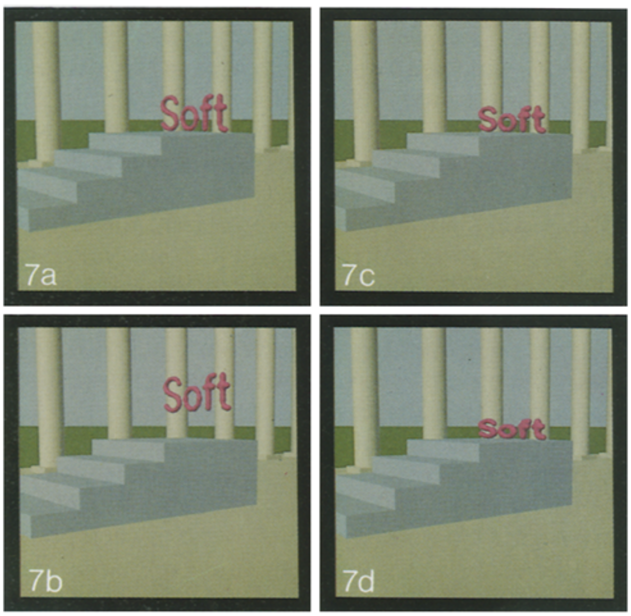
of the object remains undistorted. This is because the compression is achieved by applying dynamics to the key points without altering the shape of the field about a given point. We can also alter this field in two ways. One method is to represent the ground as a surface of constant potential in the field. Thus the surface of an approaching *soft* object would tend towards a constant value and the surface would flatten. This method has the disadvantage that it is difficult to provide a user with a general tool by which such surfaces may be defined.

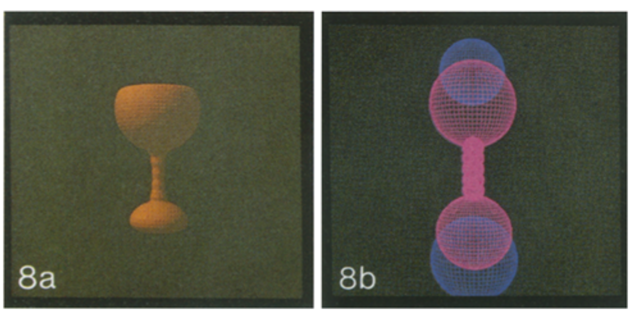
The second, more general technique, identifies a key point as making a negative contribution to the field. Blinn originally introduced this idea to create holes in an object (Blinn 1982). The model of the goblet in Fig. 8a demonstrates how key points with a negative force value may be used to flatten the surfaces. Figure 8b shows the key points used to describe the goblet. Each key point is represented by a sphere whose radius is proportional to its radius of influence. The blue spheres are negative points. The force value of such points can be changed with time to cause a gradual flattening of a surface.

The bubbling bath

Simulating very complex motion, such as a bubbling liquid, is a rather difficult task mathematically. However, a reasonable illusion is presented here using a very simple representation of the liquid. Figures 4a–d show some scenes from the film, "Soft" (Wyvill 1985c). The liquid surface is represented by distributing 140 key points in a regular 14 by 10 rectangular grid in the $x-z$ plane. Each







Figs. 6–8. For explanation see text

key point is moved in the positive y-direction to some maximum height, H, in F frames. The height increments follow a sine curve and thus the key point returns to its original position. New values of F and H are chosen at random within certain limits and the cycle repeated. To add to the random nature of the surface each key point was chosen with a different radius, again within certain limits. In the film "Soft" (Wyvill 1985c), the constraints on H were such that it was a rare event for a key point to rise more than the radius, R, above the surface. The minimum value of R was chosen so that holes did not form in the surface. The net effect was of a very mobile surface which always remained closed. An occasional bubble would break the surface and fall back again.

The following information was stored for each key point:

Current Position, xyz
Maximum Height for this cycle, H
Radius
Force
Number of frames to reach maximum height, F
Current Frame.

The liquid is contained within a box of height BOXY. At the end of each cycle, F and H were recalculated using:

H = meanrand (0.7 * BOXY);
F = meanrand (TIME);

TIME was set to one second (24 frames). Meanrand (j) returns a random number from a normal distribution with mean $= j/2$ standard deviation $=$ mean/2.

Controlling shape change

Soft objects provide a means of exploring combined motion and shape change which has not been practical with other modelling techniques. When animating *soft* objects, a change of shape will occur if the spatial relationship between key points is altered at any frame. To obtain a controlled change of shape, an object can be moved and the relationship of the key points altered as a function of time. For example, Figs. 2a–d show a stick man as he moves between two fixed points. To make him appear to bend forward as he moves, the mo-

tion of each key point differs from the normal faired motion. In this case, the difference is a function of the height of the key point. We start by defining the normal faired motion of the whole figure. Figure 3 shows a distance vs. time graph which is followed to create this motion. The stick man is moving in the $x-z$ plane and he has a certain height in the y-direction. To bend the stick man, the position of each key point is calculated from the graph at a particular frame number. The frame number is advanced more rapidly as a function of the y-coordinate of the key point until each point reaches its final destination. In this scheme some of the points will reach their final position before others. Here they could stop so that the stick man bends as he runs and straightens at the end of the motion. Provided the key points remain close enough to each other, then the object will remain as a coherent shape. If the bending is to be increased the radius of influence of some of the key points may need to be increased. This technique can be applied to any type of motion. All that is required is to define the fairing curve for the motion and a function to say how the *soft* object key points follow the curve.
In this case, the control function was:

for each point i, timex
 = current frame number + $(d[i] \cdot y * d[i] \cdot y)$;

where timex is the absolute frame number used to calculate the x coordinate of the inbetween object from the fairing curve of Fig. 3. In other words, the distance along the time axis varies as the square of the height of the stick man. $d[i] \cdot y$ are the y-coordinates of the stick man's key points. The function which controls the spatial relationship of the key points over time can be changed to achieve many effects. For example, we can make our objects stretch or compress in some direction. Currently, such functions are implemented in a programming language. What has yet to be done is to provide a consistent user interface which will allow the animator to experiment with this powerful method of changing the object's shape.

Bound motion

There has been quite a lot of work done in 2D, on using motion paths to control inbetweening, such as moving point constraints (Reeves 1981). In a paper by Kochanek, splines similiar to beta splines are used to generate a motion path in 3 space (Kochanek 1984). This work on motion paths can be easily and powerfully applied to *soft* objects. Whereas a rigid object can be made to follow the path in steps, a *soft* object can be made to bend round the path. Figures 6a–d show the letters "Soft" sliding up some steps. A single path was drawn round a profile of the steps. In this case, the key points forming the letters of "Soft" are defined in a plane and each key point effectively follows a translation of the path. Since the relative positions of the key points are displaced the object changes shape as it follows the path. A closed surface is guaranteed at each time interval and provided the key points are not allowed to drift too far apart, the object will remain coherent and bear some recognisable relation to the original object. Our system is currently unconstrained so that if key points move too far apart, pieces of the object will appear to break off. Conceivably, constraints to prevent this and control the amount of object distortion can be built into the system.

Conclusion and future work

We have discussed the use of *soft* objects in animation and demonstrated by example, how various complex motions can be defined without introducing complications inherent in other modelling methods. In particular, we have used direct physical simulation, inbetweening, and bound motion regulated by an empirical fairing curve. We have many experiments to do, including the testing of alternative field functions. One of the main problems is to provide the user with a consistent human interface which will allow the design of *soft* object models as well as the specification of complex motions. Currently we are working on both these problems as part of the Graphicsland research project at the University of Calgary.

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