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Springs and Constraints for 3D Drawing

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ABSTRACT

In this paper we present examples of haptic sculpting mediated by a physical model or constraint. Most current work in haptic drawing and sculpting focuses on interacting with a static model and properly simulating contact forces. Our work proposes dynamic models for the creative process. These are based on physical models, but present physically impossible scenarios which allow new forms of expression. By focusing on models not realizable in the real world we show an expansion of the creative process through haptic feedback.

As example applications we present two prototypes. *Dynasculpt* allows 3D sculpting by attaching a sprung virtual mass to the Phantom position and creating a ribbon or tube along the path taken by the mass through space. *Griddraw* is used for constrained 3D drawing – a uniform 3D grid of detents is haptically superimposed over 3D space, allowing the easy production of straight lines and right angles. Both focus on dynamics as intrinsic to the creative process.

Our initial reflections and observations indicate that this paradigm is a fruitful one for haptically enhanced creation of static models. The standard problem of users comparing their experience to the superior real-world experience is circumvented in this work by presenting novel experiences impossible to feel or construct in the physical world. By presenting ourselves and naïve users with simple target tasks, we have informally analyzed the controllability of each tool. Our two prototypes seem to lie on extremes in a continuum of expressivity/controllability – Dynasculpt can become difficult to control – often at the edge of chaos, while Griddraw can be overly constraining. Active force feedback in both cases can serve to stabilize unstable or chaotic models.

INTRODUCTION

A natural and immediately apparent use for haptic feedback is in the area of three-dimensional modeling. Architecture, industrial design, and sculpting all benefit from natural haptic feedback. Real-world haptic feedback is present in scale models of works-in-progress: architectural models, sculptural maquettes and full-scale industrial prototypes. Haptic feedback is also present in tactile building materials such as clay, foam, wood, metal and plastic. Most current work in the haptic enhancement of sculpting, drawing and architectural design focuses on the first problem – haptic rendering of a rigid, usually static model via simulation of contact forces [1].

The majority of the work in haptic modeling has focused on the simulation of real-world materials – particularly hard geometric objects. This approach suffers from two problems based on comparison with the real world phenomena. First, only single-point contact forces are possible using the Phantom and users may find this manipulation weak in comparison to the full tactile/kinesthetic feedback provided by real materials. Second, the low refresh rate and smaller forces of the Phantom suffer in comparison to the real-world phenomena.

At Interval, we are exploring non-physically based dynamic models for haptic sculpting, sketching and drawing. We believe that providing experiences based in dynamic systems, but not directly reflecting real-world phenomena is a fruitful approach to creative expression with haptic devices. By using a model not based in reality, we provide the users with an experience otherwise impossible to achieve – giving them new creative potential. At the same time, the tools discourage comparison with the real world because the models are not based on real phenomena. Our initial experiments in this realm are described in this paper. A deeper exploration of this space and further applications will appear in a future publication.

PRIOR WORK

In the graphics community there are a number of examples of interactive sketching without haptic feedback, notably the 3D geometric sketching work done at Brown University [2], Paul Haeberli's image-based impressionistic painting algorithms [3] and the 2D non-photorealistic sketching at the University of Washington [4]. Passive haptic feedback in a sculpting application was attempted in the Sculpt application [5].

A strong inspiration for us is an application called *Dynadraw* by Paul Haeberli [6]. Dynadraw is a drawing program that connects a virtual mass to the cursor position via a damped spring. As the user draws, the path that the mass follows is stroked, instead of the mouse position. This creates smooth, calligraphic strokes (Figure 1). This application is the first example we know of which mediates

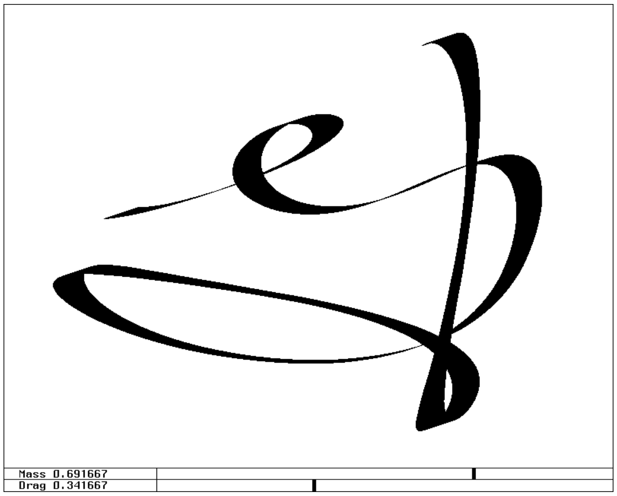

Figure 1. Paul Haeberli's Dynadraw.

a creative experience (drawing) through a physical model. Dynadraw involves no haptic feedback. Our first explorations in haptically mediated sculpting involve adding haptic feedback to a similar application.

APPLICATIONS FOR DYNAMIC SCULPTING

DYNASCULPT

Dynasculpt allows sculpting by attaching a virtual mass to the 3D Phantom position and constructing a ribbon or tube along the path taken by the mass through space. A linear, damped spring is used to attach the mass to the finger position (Figure 2). The spring force between the mass and finger is calculated using Hooke's law with a damping term:

$$\mathbf{f} = -k(\mathbf{x}_{\mathrm{m}} - \mathbf{x}_{\mathrm{f}}) - b\dot{\mathbf{x}}_{\mathrm{m}}$$

where k is the spring constant, b is the damping constant, $\mathbf{x}_{\mathrm{m}}$ is the virtual position of the mass and $\mathbf{x}_{\mathrm{f}}$ is the real-world finger position as measured by the Phantom. The position of the mass can be expressed as a Newtonian system:

$$m\ddot{\mathbf{x}}_{\mathrm{m}} = -k(\mathbf{x}_{\mathrm{m}} - \mathbf{x}_{\mathrm{f}}) - b\dot{\mathbf{x}}_{\mathrm{m}}$$

where m indicates the mass. We solve this second order differential equation using Euler's method. Continuous haptic feedback is provided to the user by applying the equal and opposite force -**f** to the user via the Phantom. The user is also provided with two "clutches". The first controls whether the pen leaves a stroke through space – controlled via the Phantom stylus button. The second is a spring-loaded force enable on the keyboard. Users can modify the mass, spring constant and damping via sliders.

Drawing is significantly altered by haptic feedback (**Error! Reference source not found.**). In purely physical terms, the user's hand is pulled towards the mass point. If only a modest force is applied, the Phantom cursor is drawn along behind the virtual mass and both soon come to a rest. Without haptic feedback, the dynamics are those of a fixed point attached to a moving mass - in the original Dynadraw and in Dynasculpt without haptic feedback, the finger position is in effect nailed rigidly to the virtual mass with no intervening dynamics. The simulation consists of, in the case of Dynasculpt, movements which are opposite but balanced; whereas with Dynadraw it reflects the movement of the mass alone. Dynasculpt demonstrates the distinction between real and virtual objects in a haptically enhanced environment. The position of the virtual mass is updated via discrete steps in a simulation, while the position of the real mass must be updated through a human user's reaction to real forces. By understanding implication of this difference, we can start to find the applications where haptic feedback presents valuable and novel experiences.

Via informal evaluation of our colleagues and our own experiences going back several years, we have observed other ways in which haptic feedback alters the sculpting experience. As users interact with the system, they can often build up quite a strong rotational inertia in the virtual mass. The kinesthetic feedback provided by the Phantom helps them to fine-tune their speed and inertia to create a desired periodic behavior. We find that removing the force feedback results in less controllability in these cases. When the damping constant is reduced in the original Dynadraw or in Dynasculpt, small changes tend to continually add energy into the system, resulting in wildly oscillating and sometimes exploding dynamics. As soon as haptic feedback is introduced into these under-damped systems the human operator's muscles and reflexes serve to naturally damp the system. This is one of our more important (if obvious) observations, that a human operator can serve to dampen chaotic or overly energetic systems. Thus, the dynamic system can operate closer to the limits of the system without becoming unstable.

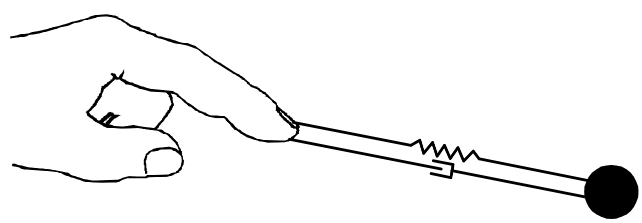

Figure 2. Dynamic model for Dynasculpt.

GRIDDRAW

A typical problem encountered in 3D sculpting applications is effectively navigating the 3D space [5]. Using 2D screens is an obvious cause of this problem, but even in experiments with stereo or immersive displays, users' movements tend to be uncoordinated and unsteady. These sculptors have trouble both maintaining and guiding their absolute position through space [7].

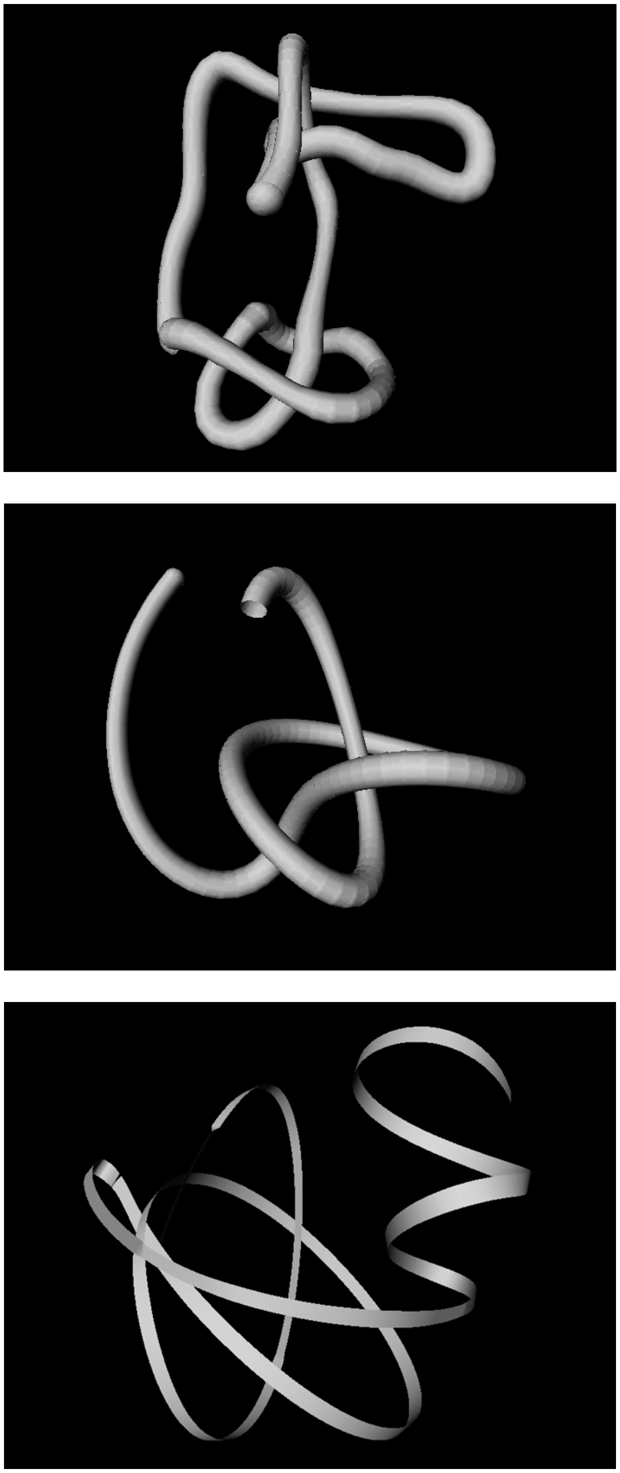

Figure 3. Dynasculpt. Different sculptural qualities can be achieved by varying the dynamic parameters. All three drawings used the same spring constant. With low damping and small mass, rapid oscillations induce wiggles in the shape (top). High damping and large mass result is smooth, slowly varying shapes (middle). High mass and moderate damping result in relatively quick variation while still smoothing the path (bottom).

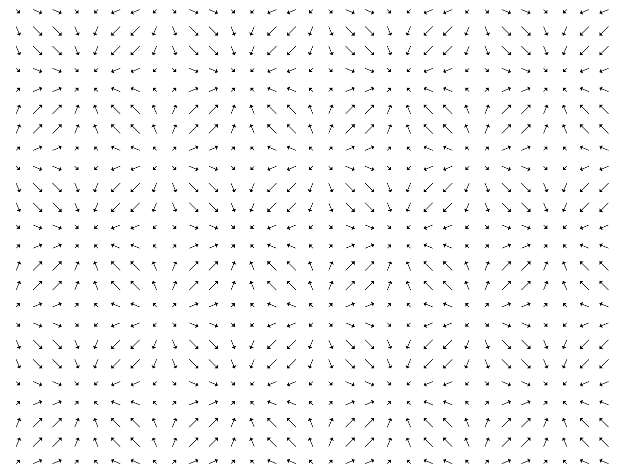

Figure 4. Griddraw force vectors (2D slice).

Griddraw is an experiment in constrained sculpting. We chose the simplest possible constraint we could think of – a 3D grid. This grid is created by haptically overlaying a sinusoidal force grid on top of the 3D Phantom workspace:

$$\mathbf{f} = k_s \sin(k_g \mathbf{x}_{\mathrm{f}})$$

where k_{s} is the strength of the grid force and k_{g} is the density of the grid spacing (Figure 4). This results in two qualitatively different constraints. First, motion is naturally constrained along the orthogonal X, Y, and Z-axes, easily enabling straight lines to be drawn (Figure 5). Second, the Phantom maintains its position when a user lets go of the stylus. Thus, work is more naturally picked up and put down, without the clumsy fumbling to locate a particular position in three-space.

We certainly found that our users could draw straight lines quite easily. Further, users were able to more easily complete drawing tasks, such as drawing a cube. Finally, users were more likely to move along the Z-axis, moving into the space of the screen. We experimented with two drawing methodologies. The first methodology actually constrained the on-screen sculpture to the grid-lines. Our second algorithm exactly stroked the path followed by the stylus, even when straining against the constraint, and we find the latter method more interesting. With normal constrained drawing in a non-haptic application using a mouse and a graphic display, the former method is the only one available – the on-screen object's movement or structure is modified by the constraint. With haptic feedback, the user has the choice to follow or diverge from the constraint. A continuum of behavior is possible without switching modes. Thus force feedback allows a constraint to be followed in degrees, rather than the binary constrained/unconstrained choice.

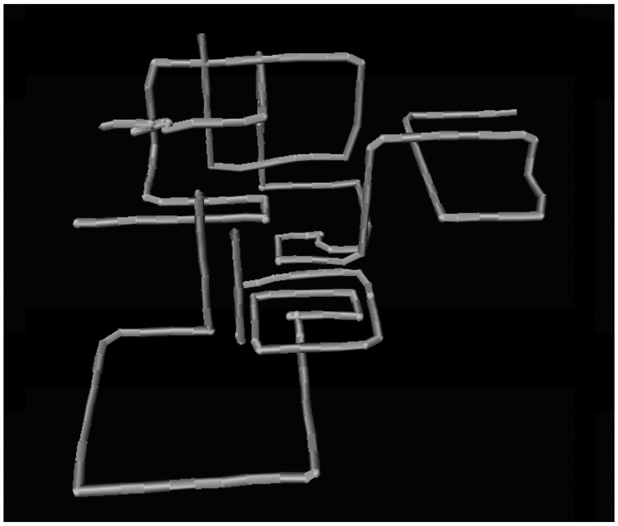

Figure 5. Griddraw. Lines do not travel along precisely straight lines, since the grid constraint is imposed haptically rather than graphically.

IMPLEMENTATION DETAILS

Both Dynasculpt and Griddraw are implemented on an SGI Indigo^2 R10K. We run in two separate processes which communicate through shared memory. The graphics process is implemented using Inventor and is refreshed at a constant rate of 30Hz (subject to degradation due to graphics performance). Our custom software updates the haptic process at a constant 2.5Khz using the real-time scheduling provided by the IRIX 6.5 OS and communicating directly with a Phantom SW Desktop model. Since our model is a simple one, we can update the mass/spring/damper system at the haptic refresh rate. The graphics process looks at the computed values for mass and finger position whenever a new frame is drawn. We have found real-time scheduling to be a reliable method for obtaining guaranteed haptic refresh rates using a single processor SGI machine. However, one must take care to insure that computation doesn't exceed the allocated time-slice. Models that have no constant or upper bound on time complexity are unsuited to this solution.

OBSERVATIONS AND REFLECTIONS

We believe our two applications lie near the extremes of a large space of dynamic sculpting applications. Dynadraw presents a near-chaotic model in which the system is fun to play with, but most users find it difficult to achieve any drawing goals. A seemingly simple task of drawing a knot was only successfully achieved by only a small percentage of our users. In contrast, Griddraw presents an over-constrained system – it is easy to achieve certain drawing goals, but the tool only allows a limited range of expression. Both applications are similar in that their dynamic models enforce a strong style on the works created.

We found that despite using a 3D input device, many users worked only in the plane parallel to the computer screen while sculpting. We are not certain if this is due to prior experience – being accustomed to mice, tablets and other 2D devices – or if this is a natural expression of human creativity. Do we tend to think and create in planes? Does our body geometry encourage movement in planes? Or is it the experience of seeing a 2D display that dominates the experience?

FUTURE WORK

As we further explore this space we would like to find applications in the middle ground between Dynadraw and Griddraw. More controllability is essential to a tool for real-world tasks. More sophisticated constraints might influence the users' style to a much lesser degree – for example constraints sensitive to specific orientations, speeds or positions.

We would like to administer more formal testing of our applications with a set of drawing tasks. We also would like to experiment with stereoscopic displays as a more natural 3D display. We also think that a comparison between stereoscopic and monoscopic displays will help us to understand the tendency to draw in planes.

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