MAKING DIGITAL SHAPES BY HAND

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INTRODUCTION

We do many things with our hands, but when it comes to making digital shapes, we tend to use the mouse and the keyboard. The hand is the human's most versatile means of acting on the material world, yet we use a small fraction of its potential when we model using conventional interfaces. This presentation explores interfaces which translate properties of the hand into operations on digital geometry. In particular we focus on looking beyond the mouse to alternate forms of user input.

What does the hand offer? One might answer this question from an emotional point of view Hands are part of the body, they create a heightened sense of connection with a design space when richly connected to its constituents. There is a sense within our culture that the manual tradition is important, and vanishing. Objects carry a particular value when they absorb human touch during formation, and reflect that human touch in their completed form.

Alternately, we can view the hand from a technical perspective. The hand's skeleton has about 27 continuous degrees of freedom, and placed at the end of an arm there is a huge parameter space which can be expressed by the human hand. Mouse input is a continuous stream of two-dimensional coordinates punctuated by discrete events (clicks, double-clicks, and the like). Is there not a better interface which would allow users to control more simultaneous degrees of freedom?

There is a certain integration of mind and body that takes place when we intentionally move our bodies. A professional baseball player can reliably hit a baseball moving at a high velocity. Computing the bat position and velocity, as any first-year physics student can attest, is a non-trivial set of calculations. The player does this in a split second. Current modeling interfaces break 3-dimensional shape modeling into a series of disjoint displacements that users compute using high-level cognition. Can we not use the motor cortex as a kind of parallel processor, to facilitate the creation of models?

The ultimate challenge in shape creation is conceptual — linking motion and model conception into a paradigm that facilitates the creation of sophisticated forms.

CONTROL MAPS: BETWEEN THE BODY AND THE MODEL

As Axel Mulder [Mulder 1998] notes in his dissertation on sound control, many simultaneously sensed parameters do not necessarily afford rich control. Mulder considers controlling sound with a CyberGlove. This glove detects 18 DOF of the human hand. Consider an interface where joint angles are mapped to properties of sound — the angle of the first finger joint is pitch, the thumb controls volume, etc., for several simultaneous sounds. While a performer technically has control of many parameters, there is a mental difficulty in realistically controlling them.

In digital interface design, input devices offer a general, abstract access to parameters. The relationship between an input device and a digital model is a *control map*. A control map (also known as transfer function) is a mathematical relationship established between body/input device position and model state.

We will consider three classes of interface, each with a distinct flavor of control map.

MATERIAL — The model consists of atomic units which are arranged and manipulated by the user. Input directly manipulates this structure. The virtual clay interface presented by Marie-Paule Cani, earlier in this course, is an example. In this interface, a 2-dimensional mouse controls a sculpting tool which, on a monitor, affects the shape of a 3-dimensional virtual clay model. In material interfaces, there is a continuous map between motion of the input device and deformations of the model.

Many systems implemented in the virtual world are also material [Deering 1995, Keefe 2001]. In these interfaces, 3-dimensional direct manipulation creates shapes. Shapes made of discrete entities can also be made in this manner. Block-based systems (such as a child's toy blocks, or [Frazer 1980]) present a number of physical objects which are manually arranged to make a form.

MARK INTERPRETATION — Continuous paths in two or three dimensions are mapped to 3-dimensional geometry. These paths either add to, or modify an existing shape. In Takeo Igarashi's Teddy interface, also presented earlier in the course, strokes are used as input to an algorithm which produces 3-dimensional form.

In these methods, hand motions are captured, but do not directly affect form. Hand motion creates strokes which are inputs to functions which produce 3-dimensional geometry. The effectiveness of the control map is highly dependent on the design of these functions.

THINKING THROUGH STRUCTURE — In these interfaces, parameters of an underlying data structure are exposed to the user. The user edits parameters (often continuously), and views the resulting change in the data structure. In the subdivision modeling described by Denis Zorin, users pull control vertices. These modifications of single points cause a surface to deform. Before the information age, engineers used technical diagrams to numerically describe processes which, after manufacture, resulted in a three-dimensional form.

MATERIAL METAPHORS

We will consider material interfaces based on input devices ranging from mice to cameras. The mouse-driven ZBrush toolsuite allows modelers to add details to subdivision surfaces in a material manner. Dragging the mouse cursor across an area causes a region to be deformed along the surface normal (or other vector). By changing the method of calculating the deformation vector, users can tune the creation of detail.

The grooves in this character's skin were formed by ZBrush

The Free-Form modeler, which utilizes the Phantom haptic device, adds a sense of touch to this process. The user is able to specify the normal vector of the deformation interactively by rotating the phantom around its pentip. The user can also more accurately depress the form due to the force feedback. This is especially useful for creating features which trace surface curvature lines.

The phantom input device controls the deformation of the onscreen model. Through haptic feedback, the user can feel the surface as it is deformed.

Note the phantom keeps the pen in front of a flat screen. There is a mapping from the 3-dimensional input space to the 2-dimensional display surface across some distance. While the input control map is between 3-dimensional spaces, and the haptic display is 3d, the visual display is lower-dimensional and across some distance. Thus it is not quite as immediate as the physical carving of clay where the mapping to the surface is direct.

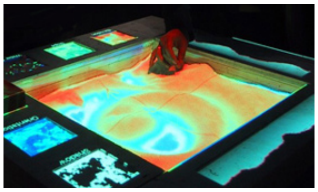
While Free-Form offers haptic feedback & 6-DOF deformation, it does not allow users to fully grasp objects. Haptic devices that control the human skeleton to such a degree that grasping can be enforced are (sadly, but inevitably) bulky and awkward. There is another paradigm, one where instead of simulating material we use the material properties that already exist in nature.

These sensed blocks are manipulated in Frazer's interface.

Sensed material interfaces detect physical objects and use this information to update a digital structure. The earliest known work is that of John Frazer et al., which was realized in the early 1980's [Frazer 1980, Frazer 1994]. These innovative physical/digital interfaces comprised of an array of cubic blocks. Each cube was the same size, and wired to a computer that detected the spatial configuration of the blocks (based on block topology). Frazer came from the architectural tradition, and was interested in designing tools to allow the quick evaluation of building programs. In some implementations, computations occurring on the CPU, such as the results of thermal analysis, were displayed on a screen as the user interacted.

One limitation of this approach is that the blocks themselves are not visually sophisticated. Anderson et al. developed a system [Anderson 2000] that displays a stylized rendition of the physical model on a 2d display. This sensed-block approach cannot create detailed geometry, as the resolution of the form is bounded by the resolution of the building blocks.

The SandScape system [Piper 2002] uses particles of sand as its building block. The user creates a form in a small sand box. A camera detects the shape, while a projector displays information on the sand surface. This increases model resolution, although users are limited to height fields, such as landscape models.



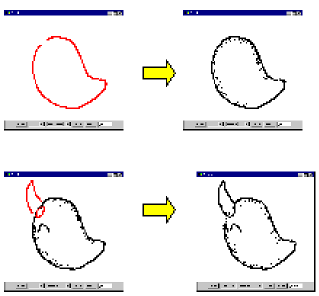
A user manipulates a landscape visualization with the SandScape interface.

These physical, tangible interfaces have many advantages. They are bimanual and multiuser, and they mimic the physical world, so interaction is immediate. The hand manipulates many degrees of freedom simultaneously. However, they are limited in the types of models they can create. As we will see elsewhere in this presentation, there is typically a trade-off between the simplicity of a metaphor and the sophistication of the results it produces.

MARK-INTERPRETATION

Tracing interfaces, based on the act of making a stroke, have their roots in traditional drawing. Computers interpret these strokes in a variety of manners to create shapes.

The Teddy interface [Igarashi 1999], described earlier in this course, creates 3-dimensional information from 2-dimensional strokes.



The Teddy system converts strokes, shown in red, into 3d geometry.

In Teddy, the control map is not a mathematical surface representation but a set of algorithms which takes 2d strokes as input. It is very challenging to make these algorithms so clear that a child can understand them (which is the case with Teddy).

Systems which interpret marks are a rare augmentation of material with algorithmic properties. The current challenge with this style of interface is to make the algorithms capable of very precise, expert-class surface modifications.

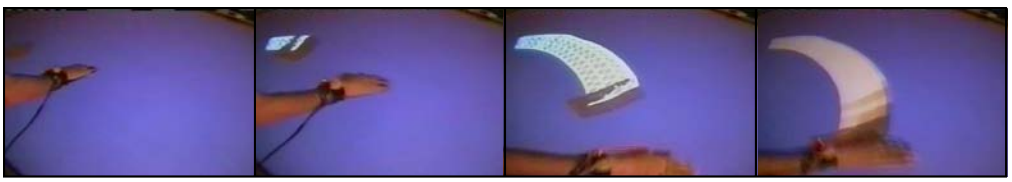
SURFACE DRAWING

As a case study we look at the surface drawing system, which I built with Michael Pruett and Peter Schröder [Schkolne 1999, 2001, 2003]. In this system, which utilizes 6-DOF electromagnetic trackers and a stereoscopic display, hand motions create 3-dimensional shapes in free space. This direct creation is material, although the strokes are merged to one another to form a coherent surface. This last step of mark interpretation makes it easier for users to build coherent surfaces.

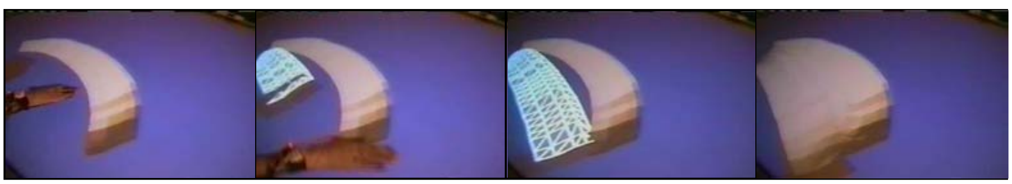
The path of the hand in space is rendered as a geometric object. The curvature of the hand defines the curvature of the stroke: a large amount of data is specified in each sweep of the hand.

Surface drawing is very hand-centric. The produced marks directly reflect the curvature of the hand as it bends. The resulting shapes reflect this organic nature. This interface also has limitations, and by studying it we can understand the shortcomings of transparent (so-called 'natural') control maps.

The images below show an implementation of this interaction. The second row shows strokes merging together to form a larger continuous surface due to a stroke-merging algorithm.



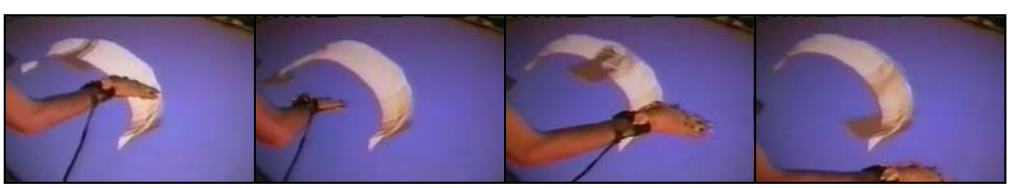
The hand paints a stroke in space.



Two strokes automatically merge to make a continuous surface.

The tangent plane can be used as a variable to control a smoothing operation (where the surface moves closer to a flat surface whose normal is dictated by the hand's normal) and a deform operation (where the surface moves in the direction of the hand's normal).

Smooth: A surface is polished by rubbing the hand over it.



Deform: The surface is slightly altered by rubbing the hand over it.

These three-dimensional digital tongs contain a 6-DOF sensor in their base. A contact switch detects when they are closed. These tongs are used to move and stretch shapes in the surface drawing system.

Objects are moved with sensed tongs. The act of closing the tongs is a natural signal to begin moving a virtual object with the tongs themselves. Two sets of tongs used together stretch an object, increasing or decreasing its scale.

RESULTS

The shapes that can be produced with the system have an intrinsic roughness to them. This is a reflection of the wavering of the body, combined with sampling error introduced by sensors. Note how well the organic qualities of the leaves and petals below are modeled by this shakiness. While the final roughness can be removed by known methods [Desbrun 1999], it is more difficult to add such a meaningful roughness to surfaces. Although this process is non-haptic, the element of touch has significance. While not volumetric, surface drawing has many of the tactile elements of clay sculpture.

A variety of shapes created with the surface drawing system.

The two versions of a head model (above, at right) show the effects of the smoothing operation. Shown at left is an early model of the head. At right, the smooth/deform tool has been used to correct the proportions of the face and smooth the head's surface.

There is a level of spatial understanding which is unique to 3-dimensional interfaces. The images below are of the same shape. It is difficult to see this as one shape through 2d views. Working directly in three dimensions allows one to create highly artificial structures that are not easily made with 2d tools.

Three views of an interwoven form

one-minute gesture drawings

The gesture drawings shown above were created by an experienced user. Even for a user new to 3-dimensional interfaces, it is easy to produce a quick gestural rendering of a person.

An artist created this shape in 20 minutes, after 10 minutes of training.

Users responded enthusiastically to this system, making assessments such as the following:

> *I was completely amazed at how quickly I interpreted and understood the canvas and model to be existing in space. It was immediate.*
>
> *To see abstract images pour like water from my fingertips is sensational... Even more amazing is to see what touch looks like!*

We can clearly see the emotional connection that such an interface enables. However, we must note the difference between enthusiasm and incorporation of a method into professional practice. It is one thing to feel connected to a form, and another to actually have a fine degree of control over a surface. Interfaces such as surface drawing are rich examples of bodily interfaces, yet they miss something crucial: the data-centric, structural view of digital models. The optimal modeling interfaces mixes the physical (motor cortex) thought of surface drawing with the data-driven (frontal lobe) analysis required by interfaces that expose their data structures more directly.

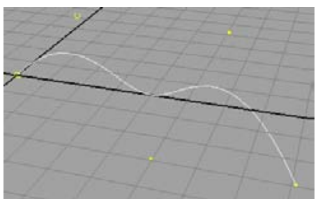
THINKING THROUGH STRUCTURE

The key component that is missing from both the material and mark-interpreting interfaces presented above is a close relationship between the user and the underlying data structure. The majority of these works aim to liberate users from having to worry about data structures. However, these material interfaces are not very popular commercially. Even the methods that do not require specialized hardware have failed to become standards for digital modeling. Why is this the case?

I believe the root of this to be the utility of data structures. There is a level of control that can be achieved by being close to the data. In the most useful systems, users actually think in terms of a data structure that they are presented with. This is as unintuitive as it is powerful. This type of control is rarely afforded by material input mappings. In structural interfaces, networks of control points, curves, and interpolating surfaces/volumes are used to control objects. Users will put in a large amount of work for a high quality result, even if the interface is unpleasant

A subdivision model is controlled by placing vertices in a control mesh which is subdivided to produce a continuous surface.

and counter-intuitive. Traditional Computer-Aided Design (CAD) has long been criticized as unintuitive. In many of these systems, users place points on screen space planes which weight basis functions to form a 3d object. For example, the curve below is created by five coplanar control points which are interpolated by a spline. In typical CAD interfaces there are several steps to create curves, as users must specify three dimensions with a 2d input device.



A curve and its control points

Perhaps the first system to allow the direct input of 3d spatial data, 3-Draw [Sachs 1991] tries to make the process more straightforward by using a 3d stylus to place control points in space. 3-Draw can build points with constraints and interpolating curves. While it is similar to other stylus-based systems (such as HoloSketch [Deering 1995]) in outward appearance, its control map is fundamentally different. HoloSketch is a material interface where the path of the stylus creates strokes directly in 3-dimensional space. There is a continuous relationship between hand and form. In 3-Draw, users place points, and the form is decided by spline basis functions. More recently, Wesche and Seidel [Wesche 2001] have presented further developments 3d interfaces for the creation of spline surfaces.

The 2d metaphors required by mouse-based CAD applications are sometimes an advantage, not a limitation. Planes are essential constructs in engineering applications where the tools used for manufacture work in terms of planes and sweep directions. However, for freeform modeling this is more of a limitation than a feature.

CONCLUSION

We have covered a variety of input devices and output scenarios, in the hopes that the reader (and the author!) will begin to understand the control maps that tie the input to the output. Between mind and model, the hand plays a crucial role in delivering input to this control map. We have seen how some maps provide a level of direct control. These come closest to replicating the sense of touch. While haptics is a nice addition, it is the link between hand motion and model deformation which most strongly establishes this connection.

Other interfaces place a level of interpretation between user action and the resulting change in the model. In these interfaces, the challenge is to allow the hand to most readily manipulate and/or create elements (such as strokes or control vertices) of geometric data structures. A flexible, versatile, intuitive structure that can be richly manipulated by the hand has yet to be discovered. Currently, we see either rich structures which can only be manipulated awkwardly, or overly simple structures which can be richly manipulated. Satisfying both goals simultaneously is a major challenge for modeling interface research.

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