A Tangible Goal for 3D Modeling

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This article discusses applying touch feedback systems to 3D modeling. To achieve a high interactivity level requires novel rendering techniques such as volume-based rendering algorithms.

Although the speed of computers increases exponentially, the amount and quality of useful work that we perform on them seems to increase linearly at best. Faster processors are not enough—to significantly increase the utility of computers requires new computer interfaces. The keyboard was adequate for text-based applications, but the advent of the desktop metaphor and windows computing environment demanded a new mechanical interface—the mouse. As we progress into applications that incorporate interactive life-like 3D computer graphics, the mouse falls short as a user interface device, and it becomes obvious that 3D computer graphics could achieve much more with a more intuitive user interface mechanism.

Haptic interfaces, or force-feedback devices, promise to increase the quality of human-computer interaction by accommodating our sense of touch. Of all the senses, only touch is bidirectional—allowing us to perceive and change objects simultaneously in the same location. Because the sense of touch is so compelling, researchers have studied it for some time.[1,2] (Refer to the annual proceedings of the Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, published by the American Society of Mechanical Engineers, New York.) Various commercial devices are now available that can accommodate[1] even seven degrees of freedom. I used the three degrees-of-freedom Phantom haptic interface for most of the interactions described in this article. Users interact with the Phantom interface with their finger in a thimble or by holding a stylus (see Figure 1). By exerting a precise 3D force vector on the user's finger or on the stylus, the Phantom device can create compelling illusions of solid, palpable objects.[3,4]

To envision applications for digital-touch technology, simply think of physical-world experiences that do not translate to the digital world because the sense of touch is absent. For instance, consider the ease with which artists and designers can express themselves with familiar physical media, and compare that with the frustration they often encounter when using existing CAD and modeling packages to create within a 3D digital domain. Now imagine a 3D computer modeling system that uses the sense of touch and is as intuitive and interactive as using modeler's clay.

A tangible application

Imagine pushing the keyboard and mouse aside, and reaching into a truly 3D modeling environment with both your hands. As your left hand manipulates the workpiece, your right hand is free to touch, mold, and form the shape at any location. Select a gouging tool in your right hand, change the workpiece material to "clay," and create large grooves in the surface. Pick up a hot-wire tool, change the workpiece material to "blue foam," and cut expressive curves in the material. Then, choose a fine grit sanding block and gently round sharp edges from the blue foam model. Finally, set the modeling material to wood and paint the 3D surface with a pressure-sensitive paintbrush. Because you're in a digital domain, you can undo mistakes, save variations on your design, and even e-mail the model to another designer. Each combination of tool and material behaves as it would in a physical environment, but more importantly, each tool-material combination gives sensitive feedback to your hands, allowing you to instantly estimate and modulate the extent of your changes. Combining 3D touch technology and interactive 3D graphics makes this application possible.

Today's untouchable reality

Unfortunately, today's commercial systems do not provide the interactive and intuitive interface to 3D modeling described above. Many 3D design and modeling

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1 Deforming digital clay with the Phantom haptic interface.

systems build on nonuniform rational B-splines (NURBS), and the programs require users to move "control points" that only roughly correspond to the shape of the model's surface. (Granted, they correspond exactly if you can solve multiple high-order polynomial equations in your head!) Moving these control points in three dimensions with a 2D mouse or keyboard is difficult at best, and the response of the model to a control point's movement can occasionally be counterintuitive. Furthermore, without touch feedback, users often have difficulty estimating the extent of the changes they're making when the only cues come from a 2D computer screen. The effective interaction rate with these systems is, therefore, much lower than the interaction rate with physical models. Other approaches to 3D modeling systems exist (constructive solid geometry, various parametric descriptions, implicit surface definitions, and so on), but the interactivity of these digital systems still can not begin to match that of the real world.

The disparity between interactivity in the physical and digital worlds has motivated several animators and industrial designers to remain in the physical world, modeling shapes from clay and other familiar materials, and deferring conversion to the digital domain until the expressive aspects of the design have been completed. Even for *Toy Story*—the movie touted as the first feature film created entirely by computer animation—modelers actually developed several of the more detailed characters in clay before digitizing. Similarly, much of the industrial design for sleek consumer products still occurs in a modeling shop and not on a workstation.

While some design shops like it this way, others recognize the bottleneck imposed when models must be passed from the physical world to the digital world. First, the digitizing process is not automatic, but rather tedious and time consuming. Second, the digitizing process can be prone to errors, and can often misrepresent subtle points of the designer's intent, like curvature and fillets. Third, if some aspect of the model must be changed later in the process (due to manufacturing constraints or animation of a model), the designer who operates solely in the physical domain may have little influence over the modifications that ultimately affect the artistic result. For these reasons, designers desire a more intuitive modeling system.

Progress toward the goal

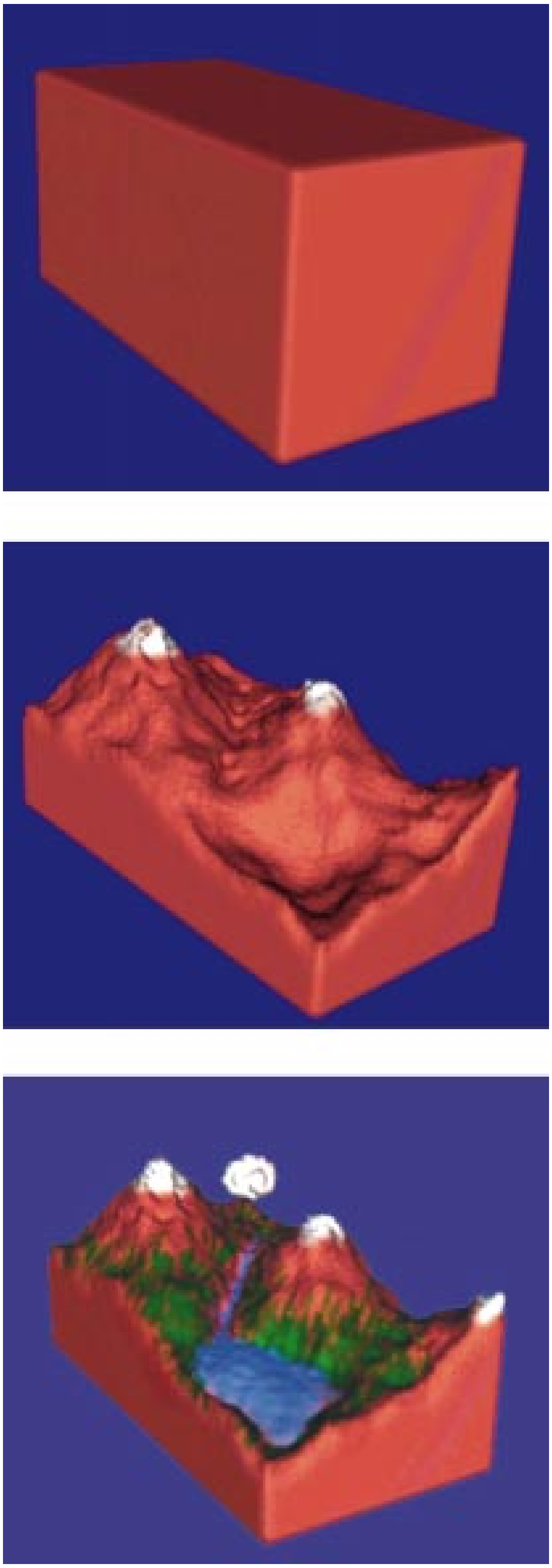
Initial efforts to sculpt digital clay with a Phantom haptic interface were very encouraging. Figure 2 shows a screen shot of an early demonstration that my colleagues and I wrote at the Massachussets Institute of Technology's Artificial Intelligence Lab, which allowed users to deform a virtual terrain. If the user exerted force above a threshold, the terrain would deform, and continuing pressure would result in larger deformations.

Although the implementation was simplistic, we discovered some important results. Users found that cutting straight lines and circular grooves in the surface was very intuitive. In fact, hemispheres could be cut from a flat surface by carefully tracing a circle while exerting some pressure on the surface. After making the initial groove, completing the hemisphere was trivial and could be done quickly even without visual feedback. As the user's finger traced the groove to complete each deeper cut, we found that the groove left from the previous groove guided each subsequent cut. A natural property of real clay, this could not be duplicated without haptic feedback.

At SensAble Technologies, we developed a noncommercial plug-in to Alias|Wavefront's Power Animator software package. Among the touch-enabled features we implemented were the ability to feel Alias|Wavefront models while building them and interactively shape

2 Deformations in virtual clay.

NURBS models by touching them. The ability to feel existing objects in the models, while placing new objects, proved useful in guiding model generation. For instance, when building a virtual scene using the sense of touch, it was possible to place a tree directly on the ground, without having to explicitly define the relationship between the tree and the ground. However, topological constraints of the NURBS geometry and lower than desired update rates prevented us from achieving a 3D free-form modeling system as compelling as clay.



3 Model sculpted from a block of virtual clay.

Image courtesy of General Electric, CRD

Whereas surfaces modeled with polygons and other surface representations encounter difficult topology problems when molded, folded over on themselves, and cut in two, voxel-based volume models encounter none of these problems when modified. Avila and Sobierajski[5] of General Electric, Gibson[6] of Mitsubishi Electric Research Labs, and Hughes and Galyean[7] have worked independently on voxel techniques for haptic and visual rendering. Avila and Sobierajski developed a robust method using a 3D rectilinear array of voxels, each specifying a set of scalar properties at a discrete location. Because the voxels represent discrete points, Avila and Sobierajski used an interpolating function to derive a smooth, touchable iso-surface from the voxels. This method works extremely well, and naturally fits volume sculpting applications. Figure 3 shows one of the models sculpted from a block of virtual clay.

The GE system imports 3D voxel data from existing models or even from a magnetic resonance imaging (MRI) machine, and lets users touch and deform 3D volumes with a "melting tool." The system also lets users add extruded material with a "toothpaste" tool and provides a paintbrush for coloring the 3D models directly on their surfaces. Feedback from users of the early system was positive but indicated that it could be improved by letting users rotate the workpiece with the nondominant hand.

Imageware (www.iware.com), a company that specializes in transferring 3D models between digitizers and various 3D modeling packages, has started integrating touch technology into their software as well. Historically, after solid physical objects have been digitized into computer models, modifications and corrections to the model were extremely difficult. The new capability from Imageware will let users "touch up" the digital models intuitively.

Limitations

Although surprisingly realistic to casual users, my colleagues and I must concede that current haptic interfaces are limited in their ability to faithfully reproduce all the subtle sensations you feel when interacting with the real world. For instance, the Phantom haptic interface can only produce a force vector at a single point. (We have expanded this basic approach to allow multiple points of contact between the user and the virtual environment, but any system with more than four points of contact becomes mechanically clumsy.) Realistically, this means that designers using one of the proposed touch-enabled modeling systems could not have the sensation of clay touching their palms or feel subtle texture variations across their fingertips. Given this fundamental limitation, a very useful modeling system can still be built. In fact, most physical modeling interactions occur through a tool, and even today's haptic interfaces can accurately duplicate the feel of a tool tip interacting with a model.

Reaching beyond

Touch provides many benefits to users for interacting in both physical and digital 3D environments, including

1. providing feedback to help position objects accurately in 3D space,
2. resolving visual ambiguities by letting users feel the models,
3. communicating physical properties of objects, and
4. letting users naturally and continuously manipulate models.

For these reasons, 3D modeling packages that incorporate even limited touch systems should have many benefits over classic modeling software. Most importantly, incorporating the sense of touch into model generation programs will let designers, stylists, and animators work more creatively in the digital domain. A combination of 3D computer graphics, 3D touch technology, and recently developed 3D rapid printing technology could enable 3D modeling applications that prove as revolutionary to design and animation as desktop publishing has been to the printing industry. ■

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