Virtual Clay: A Real-time, Haptics-based Sculpting System

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1 Introduction and Motivation

In this research we systematically develop a novel, interactive sculpting framework founded upon subdivision solids [1] and physics-based modeling. In contrast with popular subdivision surfaces, subdivision solids have the unique advantage of offering both the boundary representation and the interior material of a solid object. We unify the geometry of subdivision solids with the principle of physics-based models and formulate *dynamic subdivision solids*. Dynamic subdivision solids respond to applied forces in a natural and predictable manner and give the user the illusion of manipulating semi-elastic *virtual clay*. We have developed a real-time sculpting system that provides the user with a wide array of intuitive sculpting toolkits. The flexibility of the subdivision solid approach allows users to easily modify the topology of sculpted objects, while the inherent physical properties are exploited to provide a natural interface for direct, force-based deformation. More importantly, our sculpting system is equipped with natural, haptic-based interaction to provide the user with a realistic sculpting experience.

Due to space constraints, only a brief discussion of this research is given. Interested readers can find more details in [2, 3].

2 Dynamic Subdivision Solids

Our dynamic subdivision solid model marries the geometric information and topological structure of subdivision solids with physical attributes and other relevant material quantities. After a user-specified number of subdivisions of the control lattice, the resulting subdivision solid is endowed with physical properties such as mass, damping and stiffness distributions. Specifically, each vertex in the subdivided geometry is assigned a mass and each edge is assigned a stiffness. Material attributes are assigned both on the inside and on the outside of the subdivided solid. Note that a surface-based approach could not represent heterogeneous interior attributes because the interior of a surface is empty. The control lattice is retained but is not assigned any physical parameters. It is required to maintain the geometric validity of the subdivided solid.

Like many subdivision surface algorithms, the subdivision solid representation can be expressed as a global matrix multiplication:

$$\mathbf{d} = \mathbf{A}\mathbf{p}. \tag{1}$$

$\mathbf{p}$ is a column vector of the positions of the control points; the matrix $\mathbf{A}$ is a sparse matrix that contains weights given by the subdivision rules; and the column vector $\mathbf{d}$ gives the positions of the points in the solid after subdivision has been performed. In our work, the $\mathbf{d}$ corresponds to a set of mass points.

3 Numerical Solvers

In order to simulate the dynamic behavior of a subdivision solid, the system must solve at run-time an equation of motion that describes the physical behavior of the object. This simulation process is driven by solving an integration at discrete time-steps. We have implemented both an explicit numerical solver for time integration and an implicit one. We describe only the implicit solver, which provides real-time update rates and is numerically stable.

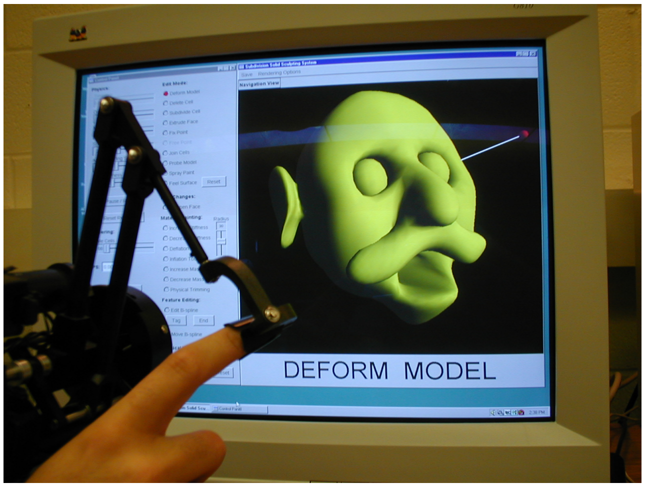

Figure 1: The user interface consists of a PHANToM haptic device, a standard 2D mouse, and on-screen GUI controls.

3.1 Implicit Time Integration

Our dynamic model is founded upon the energy-based Lagrangian equation of motion, which has the following discrete form:

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{D}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{f}_{\mathbf{x}} \tag{2}$$

The $\mathbf{M}$, $\mathbf{D}$ and $\mathbf{K}$ matrices represent the mass, damping and internal energy distributions of an object; $\mathbf{x}, \dot{\mathbf{x}}$ and $\ddot{\mathbf{x}}$ represent the discrete position, velocity and acceleration of an object; and $\mathbf{f}_{\mathbf{x}}$ contains the total external forces acting on an object.

We augment the discrete Lagrangian equation of motion with geometric and topological quantities related to the subdivision solid algorithm. Subject to the constraints defined by Equation 1, we augment the Equation of motion as follows. First, discrete derivatives are computed using backward differences:

$$\ddot{\mathbf{p}}_{i+1} = \frac{(\mathbf{p}_{i+1} - 2\mathbf{p}_i + \mathbf{p}_{i-1})}{\Delta t^2} \tag{3}$$

$$\dot{\mathbf{p}}_{i+1} = \frac{(\mathbf{p}_{i+1} - \mathbf{p}_{i-1})}{2\Delta t} \tag{4}$$

After substituting Equations 1, 3 and 4 into Equation 2 and after some algebraic manipulation (see [2, 3] for the derivation), we

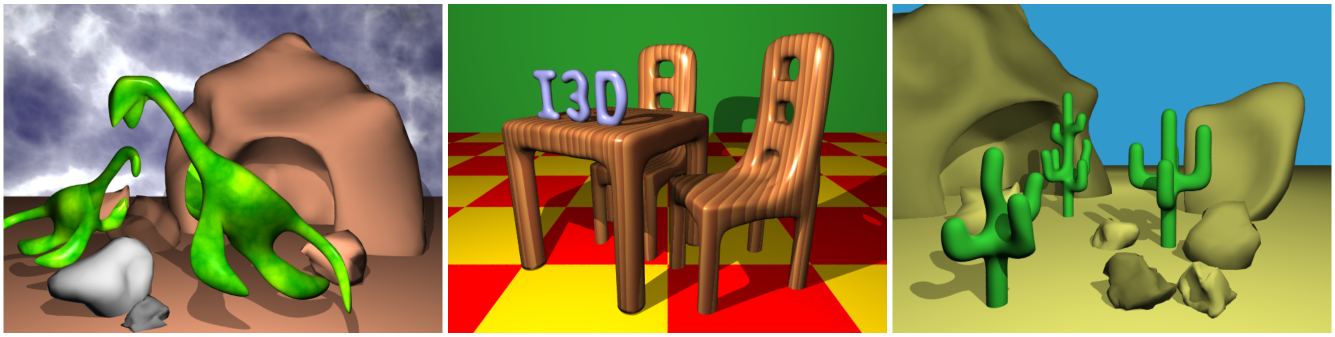

Figure 2: Several scenes created entirely with our system and then composed and rendered with POV-Ray (www.povray.org).

obtain the time integration formula

$$\begin{aligned}\left(2\mathbf{M}_\mathbf{p} + \Delta t\mathbf{D}_\mathbf{p} + 2\Delta t^2\mathbf{K}_\mathbf{p}\right)\mathbf{p}_{i+1} = \\ 2\Delta t^2\mathbf{f}_\mathbf{p} + 4\mathbf{M}_\mathbf{p}\mathbf{p}_i - (2\mathbf{M}_\mathbf{p} - \Delta t\mathbf{D}_\mathbf{p})\mathbf{p}_{i-1},\end{aligned} \qquad (5)$$

where

$$\mathbf{M}_\mathbf{p} = \mathbf{A}^\top\mathbf{M}\mathbf{A} \qquad \mathbf{D}_\mathbf{p} = \mathbf{A}^\top\mathbf{D}\mathbf{A} \qquad \mathbf{K}_\mathbf{p} = \mathbf{A}^\top\mathbf{K}\mathbf{A}$$

and the subscripts denote evaluation of the quantities at the indicated time-steps. This equation is solved repeatedly as time progresses during a sculpting session. It is straightforward to employ the conjugate gradient method [4] to obtain an iterative solution for $\mathbf{p}_{i+1}$.

4 Sculpting System

The user interface (see Figure 1) of our sculpting system consists of a Sensable Technologies PHANToM 1.0 3D haptic input/output device, a standard 2D mouse, and on-screen GUI controls. The PHANToM features a thimble for the user's index finger and can exert a real-world force in any 3D direction. The mouse is used to activate or enable over a dozen sculpting tools as well as control various simulation parameters through GUI sliders and check boxes. The entire system runs on a generic Microsoft Windows NT PC with an Intel Pentium III 550 Mhz CPU and 512 MB RAM.

Our sculpting system features three classes of tools: haptic tools, which exert real forces on the user's hand; geometric/topological tools, which cause geometric and/or topological changes in the subdivision structure; and physics-based tools, which evoke local or global changes in the physical properties of an object.

The haptic tools include:

- Bend and stretch material
- Probe the interior
- Feel the surface

Among the geometric and topological tools are:

- Cut material
- Extrude material
- Extrude material of a certain shape
- Drill hole
- Join disconnected parts
- Subdivide locally to create details
- Create sharp features

The physics-based tools include:

- Curve-based interaction
- Surface-based interaction
- Stiffness and mass "painting"
- Inflate / deflate part of object
- Perform local trimming
- Freeze / unfreeze part of object

Descriptions of these tools can be found in [2, 3]. Figure 2 shows several scenes containing objects that were created exclusively using our sculpting system.

5 Conclusions

We have presented a new dynamic solid modeling framework and an intuitive, natural haptic interface based on the novel integration of subdivision solids and physics-based techniques. Our sculpting system permits the user to create real-world, complicated models in real-time using an extensive suite of geometry-, topology-, physics- and haptic-based virtual sculpting tools. Within our sculpting environment, the virtual clay responds to direct, user-applied forces in a predictable and intuitive manner while the haptic feedback can significantly enhance the sense of realism. Our physical formulation of topologically complex subdivision solids frees users from the need to deal with abstract geometric quantities and esoteric topological structures that often hinder the extensive use of sophisticated solid models on a large scale. Future research involving dynamic subdivision solids includes data fitting applications, volumetric morphing, scientific visualization, physical simulation for flow dynamics and heat transfer, and others.

References

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