Towards Immersive Clay Modeling: Interactive Modeling with Octrees

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ABSTRACT

The described virtual clay modeling project explores the use of virtual environments (VEs) for the simulation of two-handed clay modeling and sculpting tasks. Traditional clay modeling concepts are implemented and enhanced with new digital design tools leveraging from virtual reality (VR) and new input device technology. In particular, the creation of an intuitive and natural work environment for comfortable and unconstrained modeling is emphasized. VR projection devices, such as the *Immersive WorkBench*, shutter glasses, and pinch gloves, equipped with six-degree-of-freedom (6DOF) trackers, are used to apply various virtual cutting tools to a volumetric data structure (octree). The employment of an octree as underlying data structure for volume representation and manipulation in immersive environments allows real-time modeling of solids utilizing a suite of either geometrically or mathematically defined cutting and modeling tools.

A virtual clay model is encoded as an octree, preserving its volumetric and physical properties and design history. Incremental undo/redo functionality for rapid transitions between different modeling states increases the efficiency and flexibility, while advanced features of the primitive and wire cutting tools, such as the removal of single layers from a clay model, enhance the modeling procedure to a level of precision hardly achievable at this level of detail in real clay modeling. Models can be passed to a raytracer or exported as either triangular or tetrahedral meshes. The resulting work environment can be utilized beyond the targeted application of virtual clay modeling, for example for the visualization and analysis of medical data.

Keywords: Virtual Reality, Virtual and Immersive Environments, Computer-Aided Design, Solid Modeling, Clay Modeling, Octree, Spatial Data Structures

1. INTRODUCTION

VEs have finally matured from proof-of-concept studies performed at university laboratories into fully featured applications. They are now applied to engineering design, research and development, manufacturing, medicine, architecture, marketing, geophysical explorations, and a variety of other fields. VEs have the potential to revolutionize traditional industrial product design by enabling the transition from conventional keyboard and mouse-based computer-aided design (CAD) to fully virtual product design. A car design, for example, traditionally originates from a clay model that forms the basis for a numerical CAD description in Bézier, B-spline, or NURBS format [1,2] after digitization. Furthermore, physical conceptual models, so called mock-ups, still play a key role in the otherwise CAD-centered development cycles. Our clay modeling project aims at closing this technology gap by merging classical design concepts with state-of-the-art visualization and interaction device technology, while emphasizing the creation of an intuitive and natural work environment.

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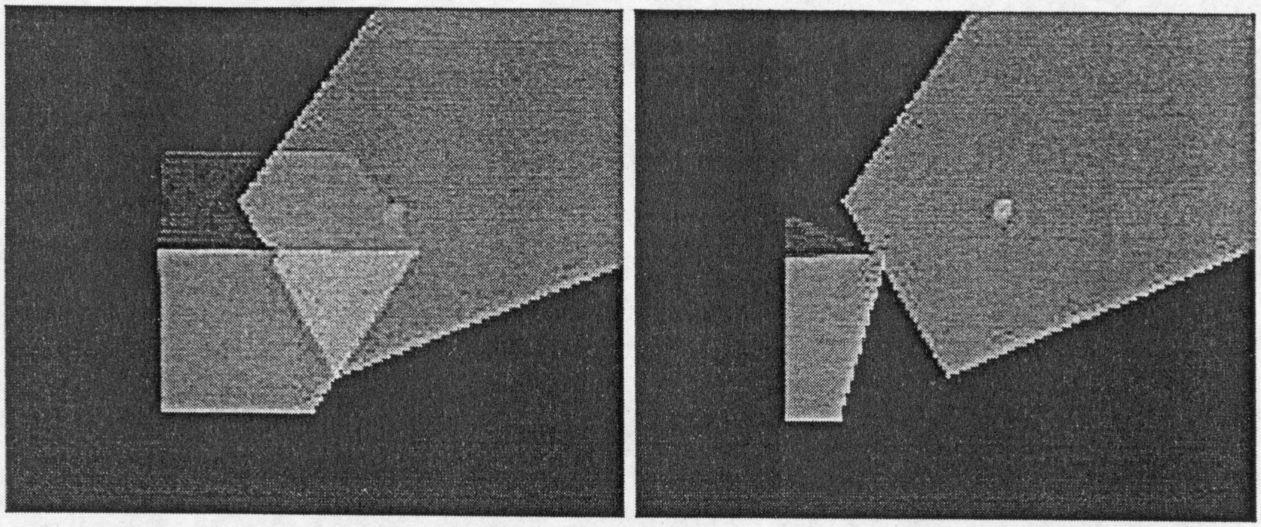

Figure 1. Initial "clay cube" with cutting plane tool (before and after cutting).

2. IMPLEMENTATION

The project realization followed two fundamental ideas. First, a designer should feel comfortable and unconstrained when interacting with the environment and have access to traditional and new virtual technology for the creation of new design paradigms. Second, a natural environment should be offered in the form of traditional design tools, augmented by new virtual gadgets.

A potter or clay modeling artist usually cuts the clay with a wire. This wire is, besides the fingers of the artist, the most important and often the only tool used for modeling. Other tools are used for basic modeling tasks like cutting away clay parts or cutting holes in the volume. To be as close as possible to the art- and design-driven process of shaping with one's hands, the gestures necessary for navigation and modeling have been kept as intuitive as possible. Since the pinch gloves in the provided hardware setup do not permit tracking of the exact finger positions, the development of auxilary tools was emphasized. These tools support the common modeling operations from the real-world environments and are accessible through a user-friendly virtual toolbox. This toolbox, combined with the hands-on user interface, allows unconstrained interaction with the clay in three dimensional (3D) space.

2.1. Related Work

Basic clay sculpting has been explored in [3], and with the introduction of the *Responsive Workbench* [4], new strategies for the visualization and manipulation of volume data sets in 3D space were developed. Complex 3D medical data sets, such as MRI or CT scans, can be displayed [5] and manipulated with single- and two-handed tasks [6,7] by using pinch gloves or a stylus. Cutler et al. [6] have explored navigation methods and menu usage in user interfaces, and several types of real-life oriented tools have been tested as well [8]. Selection in 3D space and 3D manipulation have been explored.

2.2. The Virtual Toolbox

The virtual toolbox containing various easy-to-use cutting tools enables the designer to perform a variety of manipulations of virtual clay. Three groups of tools are currently available:

A. Primitive Cutting Tools

- **Cutting Plane**
  This is an infinite plane, that allows to cut away parts of a clay model behind the plane, considering the direction defined by the plane normal.

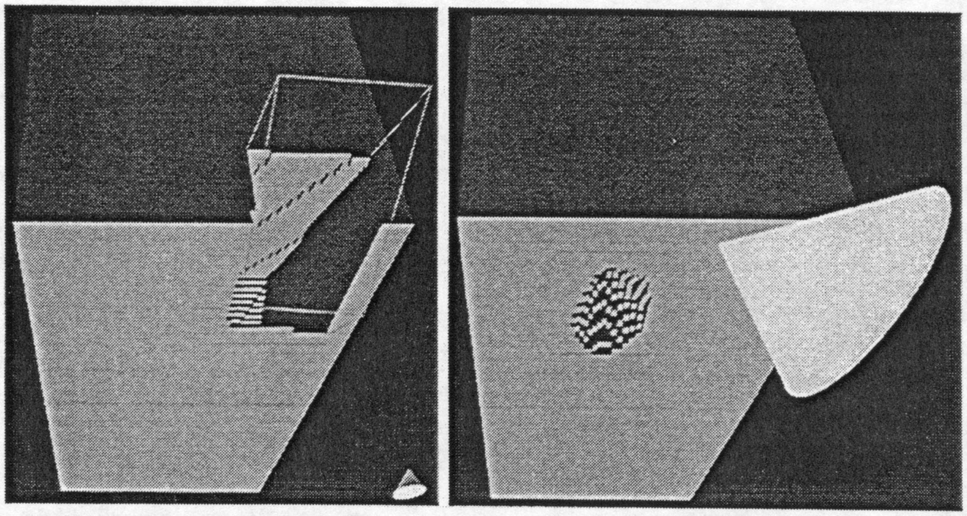

Figure 2. "Clay cube" and cone cutting tool.

- **Cutting Sphere**
  This is a sphere with user-specifiable radius, represented by its radius and origin.

- **Cutting Cube**
  This is a cube whose height, depth, and width are freely re-sizable. Together with the origin, intersections with the clay model are calculated via several coordinate tests.

- **Cutting Cone**
  This is a cone whose radius and height are re-sizable, and intersections are tested via angle calculation. If the clay model resolution is too low, the cut is rounded off at the tip of the cone.

B. Wire Cutting Tools

- **Hotwire**
  This is a VR implementation of a potter's wire for cutting clay. Held between thumbs and index fingers of the left and the right hands, the wire can be moved freely in 3D space to cut the clay. If the cut divides the model into two parts, the user gets to pick the part he/she wants to discard. Real-time modeling is still a problem due to the amount of necessary calculations for ruled surface implementation.

- **Lightsaber**
  This is a modified hotwire that is held in one hand and has a user-specifiable cutting depth.

C. Simple Boolean Functions for Adding Clay

- **OR**
  This function allows for a second, user-defined clay cube to be merged with the existing clay model (union).

- **AND**
  This function allows for a second, user-defined clay cube to be intersected with the existing clay model, where the non-overlapping areas are discarded (intersection).

- **XOR**
  This function is the same as AND, except that the overlapping areas are discarded.

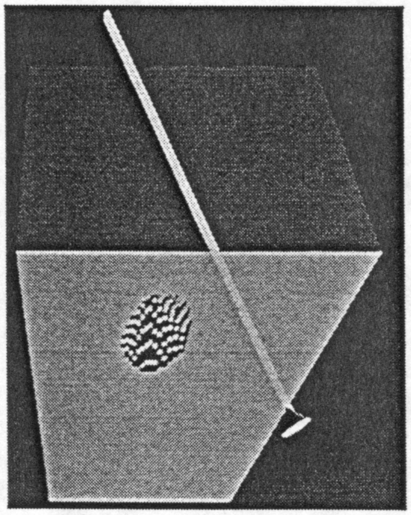

Figure 3. Lightsaber.

Since in our hardware setup the exact positions of fingers are not trackable, we employed cone-shaped cursors to represent the position and orientation of the left and right hands. All cutting tools are therefore virtually attached to a user's hand for modeling and interaction. The origin of the tools, which is needed for the cut calculation, is always the origin of the coordinate system of the hand that applies the tools. This defines the position of the cutting tools relative to the position of the operating hand, thus allowing cutting operations from every position and angle.

2.3. User Interface and Menu

Pop-up menues have proven to be flexible and appropriate for interaction in 3D space, since they do not obstrude the user. We chose cascading pop-up menues that can be placed anywhere and at any user-prefered orientation in the 3D workspace. The tools and functions are represented via intuitive icons and labeling for fast tool selection.

Various ways of scene navigation have been explored in related work, such as the use of virtual ropes for scene navigation, allowing the user to literally pull himself/herself through the scene. The most intuitive way to simulate movement in 3D space for virtual clay modeling is to grab the virtual clay with the hand and then move the hand, and with it the clay, in the desired direction. Using this principle, every movement of the hand is applied to the clay model. This mechanism allows to arbitrarily place the model in space by defining its location and orientation using the available 6DOF environment.

In the VE, a user wears shutter glasses and two pinch gloves whose positions are tracked. When a pinch between thumb and middle finger is recorded, the clay cube follows the movement of the hand, and the scene is drawn according to the current view direction. The most commonly used modeling functions are directly accessible through ten distinct pinch gesture combinations and can adapt to particular modeling tasks. By default, movement is recorded for both hands, allowing to move the object with one hand while applying cutting operations with the other hand.

We distinguish between one-handed and two-handed tasks. Navigation and cutting operations are possible with a single-handed gesture, while re-sizing the cutting tools requires both hands. The only exception is the hotwire, which has to be held between both hands to be pulled through the clay. The lightsaber can be re-sized, for example, by holding it with one hand and pushing or pulling the blade to the required length. In combination with the user-customizable menu, enabling access to other functions such as the selection of a new tool or starting I/O operations, these gesture short cuts allow rapid and intuitive virtual clay modeling.

2.4. Octree

A solid representation was chosen as the underlying geometric description for a virtual clay model, allowing us to store volumetric information. Since a data structure that allows fast and efficient access is crucial for solid geometric modeling in immersive environments, we chose an octree as underlying data structure. The implementation of the octree, nodes, and node attributes in seperate modules allows us to add more properties and functions as need arises.

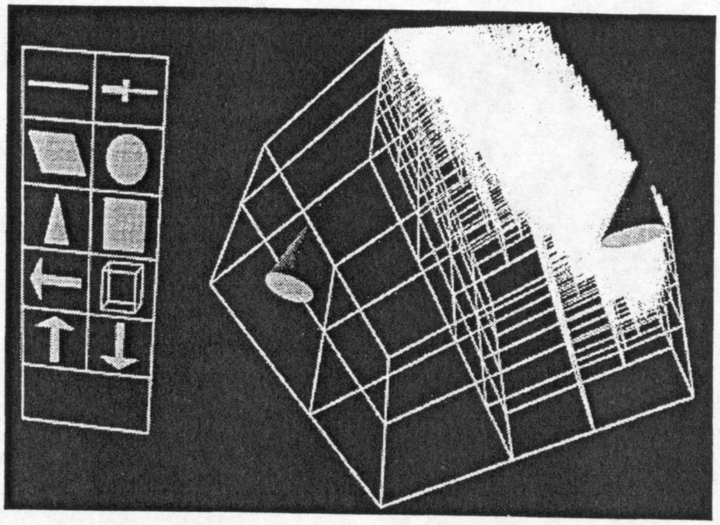

Figure 4. Virtual user interface.

Color and material information for each voxel are stored, allowing utmost flexibility in representing a clay model. One advantage of the octree data structure is that the exact position of each voxel can easily be calculated and does not need to be stored explicitly.

The octree also allows fast intersection calculation of the voxels with the mathematical representations of the cutting tools. These tools can be applied to single layers of virtual material for very exact modeling or can cut holes, even inside the volume, which is not possible at all at this level of detail in real clay modeling.

A special display function has been added to change the solid clay representation to a wire frame representation, which provides a view of an underlying octree, and allows a user to see each voxel. When no specific data set is used, the simulation starts with an "undivided" clay cube, which is divided subsequently when cutting tools are applied.

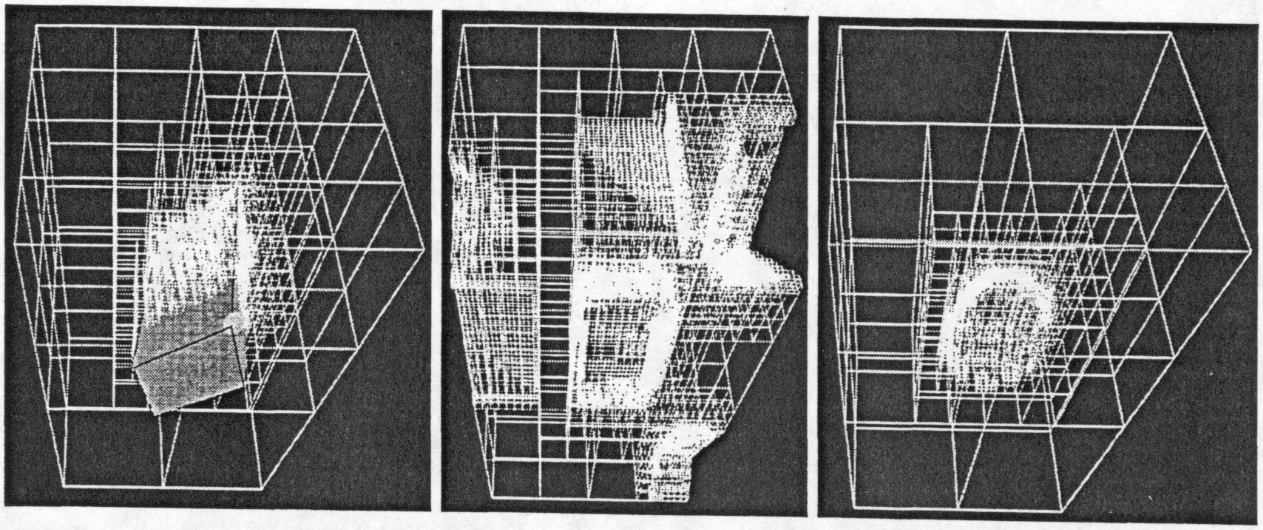

Figure 5. Wireframe model after single box cut, after several box cuts, and after a single sphere cut.

2.5. Design History

During the development of the system, undo and redo operations were added to increase modeling efficiency. Incorrect or unwanted operations can be undone with a simple finger movement, thus making this operation much easier than in the real-life modeling environment. Due to the fact that the entire design history is tracked, any number of undo/redo operations is possible, allowing rapid transition between different modeling states.

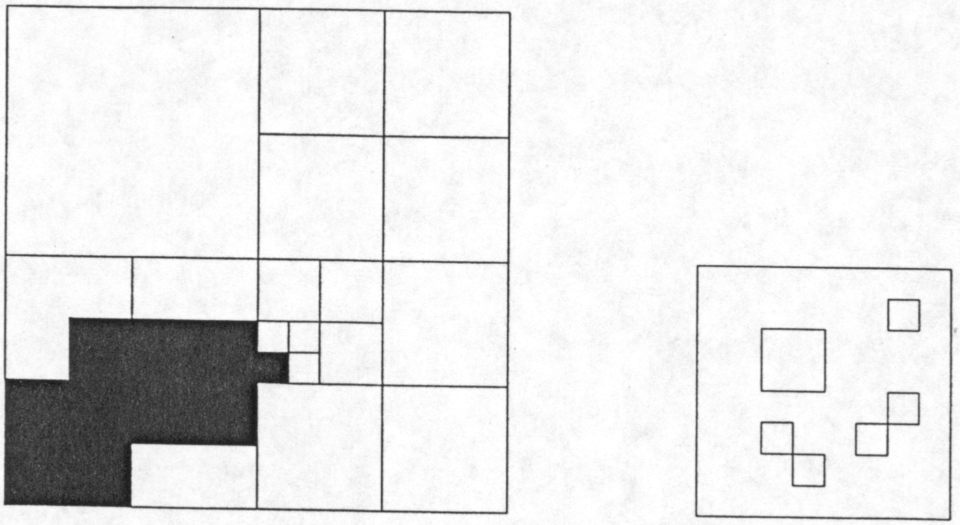

Figure 6. Two-dimensional view of subdivided surface.

2.6. Input/Output Function

The system supports read and write routines for storing a clay model or reading one from file. The clay data structure nicely supports the creation of triangular surface or tetrahedral volume meshes and ray-traced images of clay models.

Besides its originally intended purpose for clay modeling, the system supports the visualization of most volumetric data sets. Data sets consisting of n^3 voxels, including color or material information, can be loaded into the octree, displayed and modified. For example, MRI data sets of 64^3 voxels can be manipulated in real time. At higher resolutions, performance decreases, although working on 128^3 or 256^3 voxel data sets is still possible at interactive speeds. For larger data sets, the use of optimized view-dependent rendering becomes particularly important.

2.6.1. Surface extraction

Although we chose a volume representation for virtual clay models, it is sometimes necessary to generate a triangular mesh of the outside surface of a model. This is rather time-consuming for the often very complex 3D models, especially since a variety of tests have to be applied to extract the surface. Only the faces of those voxels that actually are on the boundary of a model contribute to the triangular surface mesh, which can then be exported for further use with applications supporting the OpenInventor or VRML file formats.

In order to define the triangular faces of a clay model, a three-level surface extraction algorithm has been added to the system. The octree is traversed, and each voxel is tested. Every voxel that is part of the outer layers of a clay model contributes at least the faces to the clay model surface that are already facing the outside of the octree (level 1). Then, each face of a boundary layer voxel is checked against the shared face of the corresponding sibling (level 2, inside neighbor test). If the corresponding sibling is not part of the clay model volume, the face of the tested voxel lies on the clay model surface.

To test the outside neighbors (level 3) of a boundary layer voxel, it is currently necessary that the tested voxel face and its corresponding neighbor are of the same size and therefore same division level (see Figure 6). Otherwise, more elaborate tests would be needed to decide which parts of the tested voxel face belong to the surface and which not. When two boundary voxels are neighbors but belong to different resolution levels, we must subdivide the larger voxel to ensure equal voxel size. Dealing with outside neighbors still takes a significant amount of time, since dividing the tree and traversing it up and down requires many calculations.

2.7. Transformation Matrices and Coordinate Systems

The *Fastrak* tracking driver generates a transformation matrix for each of the three trackers mounted on the shutter glasses and the back of the two pinch gloves. This transformation matrix includes information on the position of the corresponding tracker. Each tracker can be regarded as having its own coordinate system with the current

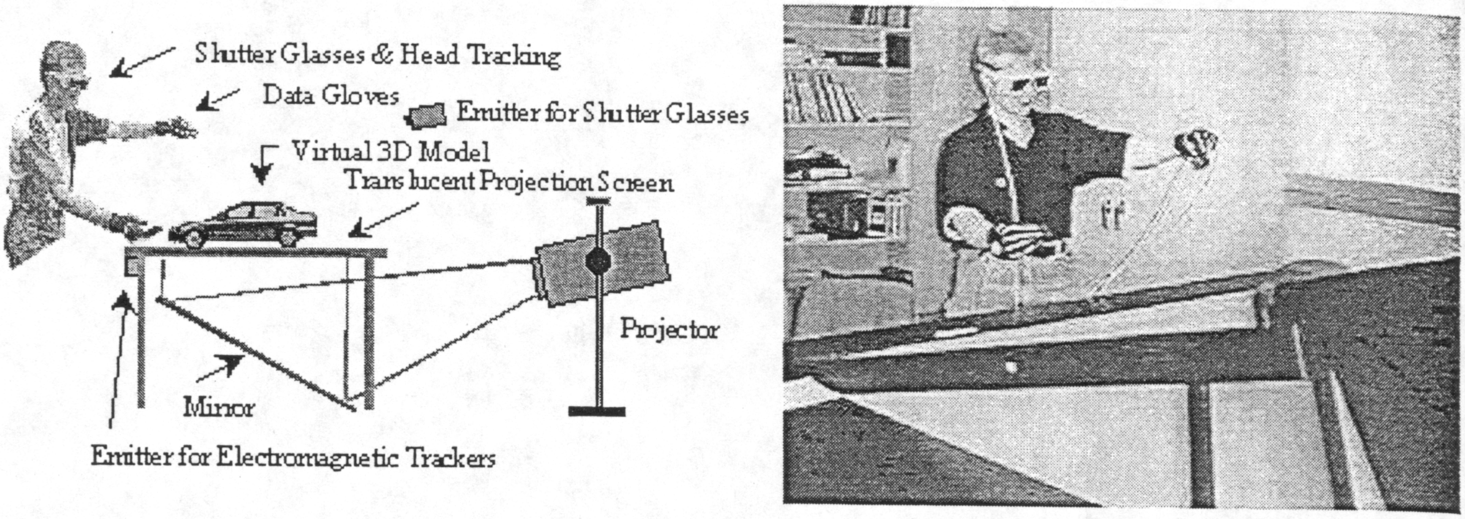
Shutter Glasses & Head Tracking
Data Gloves
Emitter for Shutter Glasses
Virtual 3D Model
Translucent Projection Screen
Projector
Mirror
Emitter for Electromagnetic Trackers

Figure 7. Hardware setup.

position being the origin. The matrix also yields information on scaling, translation, and rotation, as well as the three normals.

Thus, we can refer to the coordinate systems as the coordinate systems of the head, the left hand, and the right hand. They must be transformed into world coordinates. The virtual clay cube uses two transformation matrices (local-to-model and model-to-world) to enable an efficient and fast calculation of its current location in space. The origin of the head tracker matrix is used as the eye position to determine which sides of the clay cube can be seen by a user and therefore have to be drawn. The transformation matrices of the left and right hands are needed to calculate the positions of the hands as well as the positions of the menues and the cutting tools.

3. HARDWARE SETUP

The environment was specifically designed for a new generation of stereo projection systems, currently marketed under names such as *Immersive WorkBench*, *Responsive Workbench*, and *ImmersaDesk*. An Immersive WorkBench, used in our project, supports stereo projections of 3D computer-generated images onto an approximately 2m*1.5m-wide projection area. The necessary graphics performance was provided through a 4-processor SGI *Onyx2 InfiniteReality* system (225MHz, R10000 processor, 512 MB RAM) as rendering engine. The basic hardware setup is illustrated in Figure 7. The user is wearing shutter glasses with integrated head tracking for stereoscopic viewing and uses a set of pinch gloves for interaction with the VE. The spatial data describing the user's head position and hand movements is fully integrated.

4. CONCLUSIONS

The described virtual clay modeling system currently supports real-time user interaction. Using a "clay size" of 64^3 voxels, a vast number of cutting operations is possible without experiencing a significant performance hit. We have successfully worked with resolutions of up to 256^3 voxels. At higher resolutions, the memory requirements of the current implementation become the constraining factor. Considering the growth rate of available memory and processing speed and the falling market prices, this should not be a problem in the near future.

For a VE to simulate real clay modeling as well as possible, gloves with exact gesture tracking are required. Currently, we are using pinch gloves equipped with electro-magnetic 6DOF tracking. The used tracking devices exhibited calibration problems when working in large design spaces. Wireless technology would be usefull to avoid constantly tangled tracker cables. Overall, our virtual clay modeling environment allows easy and intuitive virtual clay modeling.

5. FUTURE WORK

More tools have to be implemented to allow better and more creative modeling. Besides the already implemented primitives cone, box, and sphere the implementation of a cylinder might be useful. Our ultimate goal is to model the clay without using tools except the fingers. One step in reaching this goal would be to generalize and adapt freeform modeling methods to virtual clay modeling and allow picking of a point on the surface of the clay and pulling it out, or even twisting it while doing so. This is not possible with our current hardware setup, but will be with more advanced gloves that allow tracking exact finger positions.

Common CAD modeling tools will be included and the existing tools enhanced. For example, in addition to holding the hot wire as a straight line, it will be possible to use the wire in a curved form to cut the virtual clay with an arbitrary curve. The optical representation of the clay and the user interface will be re-designed, and various color modes for painting the model and enabling detail modeling will be added.

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REFERENCES

1. L. Piegl and W. Tiller, *The NURBS Book*, Springer, New York, NY, 1997.
2. G. Farin, *Curves and Surfaces for Computer Aided Geometric Design*, Academic Press, San Diego, 1996.
3. T. A. Galyean and J. F. Hughes, "Sculpting: An interactive volumentric modeling technique," *Computer Graphics (Proc. ACM SIGGRAPH '91)* **25**, pp. 267–274, July 1991.
4. W. Krueger and B. Froehlich, "Visualization blackboard: The Responsive Workbench (virtual work environment)," *IEEE Computer Graphics and Applications* **14**, pp. 12–15, May 1994.
5. U. Obeysekare, C. Williams, J. Durbin, L. Rosenblum, R. Rosenberg, F. Grinstein, R. Ramamurthi, A. Landsberg, and W. Sandberg, "Virtual workbench: A non-immersive virtual environment for visualizing and interacting with 3D objects for scientific visualization," in *Proceedings of the Conference on Visualization*, R. Yagel and G. M. Nielson, eds., pp. 345–349, IEEE, (Los Alamitos), Oct. 27–Nov. 1 1996.
6. L. D. Cutler, B. Fröhlich, and P. Hanrahan, "Two-handed direct manipulation on the responsive workbench (color plate S. 191)," in *Proceedings of the Symposium on Interactive 3D Graphics*, pp. 107–114, ACM Press, (New York), Apr. 27–30 1997.
7. D. S. Ebert, C. D. Shaw, A. Zwa, and C. Starr, "Two-handed interactive stereoscopic visualization," in *Proceedings of the Conference on Visualization*, R. Yagel and G. M. Nielson, eds., pp. 205–210, IEEE, (Los Alamitos), Oct. 27–Nov. 1 1996.
8. L. Rosenblum, J. Durbin, R. Doyle, and D. Tate, "Projects in VR: Situational awareness using the Responsive Workbench," *IEEE Computer Graphics and Applications* **17**, pp. 12–13, July/Aug. 1997.
9. M. Agrawala, A. C. Beers, B. Fröhlich, P. Hanrahan, I. McDowall, and M. Bolas, "The two-user responsive workbench: Support for collaboration through independent views of a shared space," in *SIGGRAPH 97 Conference Proceedings*, T. Whitted, ed., Annual Conference Series, pp. 327–332, ACM SIGGRAPH, Addison Wesley, Aug. 1997. ISBN 0-89791-896-7.
10. B. M. Blumberg and T. A. Galyean, "Multi-level direction of autonomous creatures for real-time virtual environments," *Computer Graphics* **29**(Annual Conference Series), pp. 47–54, 1995.

11. B. Fröhlich, M. Fischer, M. Agrawala, A. Beers, and P. Hanrahan, "Projects in VR: Collaborative production modeling and planning," *IEEE Computer Graphics and Applications* **17**, pp. 13–15, July/Aug. 1997.

12. T. A. Galyean, "Guided navigation of virtual environments," in *1995 Symposium on Interactive 3D Graphics*, P. Hanrahan and J. Winget, eds., pp. 103–104, ACM SIGGRAPH, Apr. 1995. ISBN 0-89791-736-7.

13. M. Green and S. Halliday, "A geometric modeling and animation system for virtual reality," *Communications of the ACM* **39**, pp. 46–53, May 1996.

14. M. Green, "Shared virtual environments: The implications for tool builders," *Computers and Graphics* **20**, pp. 185–189, Mar.–Apr. 1996.

15. Y. Guiard, "Asymmetric division of labor in human skilled bimanual action: The kinematic chain as model," *Journal of Motor Behaviour* **19**(4), pp. 486–517, 1987.

16. Y. Guiard and T. Ferrand, "Asymmetry in bimanual skills," in *Manual asymmetries in motor performance*, D. Elliott and E. A. Roy, eds., Boca Raton, FL: CRC Press, (In press as of Sept. 21) 1995.

17. K. C. Hui and M. C. Ma, "Deforming virtual objects with an instrumented glove," in *Proceedings of the Conference on Computer Graphics International 1998 (CGI-98)*, F.-E. Wolter and N. M. Patrikalakis, eds., pp. 393–395, IEEE Computer Society, (Los Alamitos, California), June 22–26 1998.

18. F. Kuester, A. Uva, B. Hamann, and G. Monno, "3DIVS: 3-dimensional immersive visual sketching," in *Proc. 12th International Conference on Engineering Design (ICED '99)*, U. Lindemann, H. Birkhofer, H. Meerkamm, and S. Vajna, eds., vol. 3, pp. 1407–1412, 1999.

19. R. A. Noble and G. J. Clapworthy, "Sculpting and animating in a desktop VR environment," in *Proceedings of the Conference on Computer Graphics International 1998 (CGI-98)*, F.-E. Wolter and N. M. Patrikalakis, eds., pp. 187–197, IEEE Computer Society, (Los Alamitos, California), June 22–26 1998.

20. R. Rabätje, "Integration of basic CAD functions into a VR environment," in *Proceedings of the Conference on Computer Graphics International 1998 (CGI-98)*, F.-E. Wolter and N. M. Patrikalakis, eds., pp. 238–241, IEEE Computer Society, (Los Alamitos, California), June 22–26 1998.

21. C. Shaw and M. Green, "Two-handed polygonal surface design," in *Proceedings of the ACM Symposium on User Interface Software and Technology*, Two Hands and Three Dimensions, pp. 205–212, 1994.

22. C. D. Shaw, "Two-handed 3D editing," 1997.

23. J. P. Y. Wong, R. W. H. Lau, and L. Ma, "Virtual 3D sculpturing with a parametric hand surface," in *Proceedings of the Conference on Computer Graphics International 1998 (CGI-98)*, F.-E. Wolter and N. M. Patrikalakis, eds., pp. 178–186, IEEE Computer Society, (Los Alamitos, California), June 22–26 1998.