Eurographics Italian Chapter Conference (2006)
G. Gallo and S. Battiato and F. Stanco (Editors)

Real-time Cataract Surgery Simulation for Training

M. Agus, E. Gobbetti, G. Pintore, G. Zanetti, A. Zorcolo

CRS4
Center of Advanced Research and Development in Sardinia
Cagliari, Italy

Abstract

Cataract is a clouding of the eye's natural lens, normally due to natural aging changes, and involving at least half of the population over 65 years. Cataract extraction is the only solution for restoring a clear vision, and nowadays is probably the most frequently practiced surgical procedure. This paper describes a novel virtual reality simulation system for cataract surgery training, involving the capsulorhexis and phacoemulsification tasks. The simulator runs on a multiprocessing PC platform and provides realistic physically-based visual simulations of tools interactions. The current setup employs SensAble PHANToM for simulating the interaction devices, and a binocular display for presenting images to the user.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Three-Dimensional Graphics and Realism]: Virtual Reality I.6 [Computing Methodologies]: Simulation and Modeling

---

Keywords: [Surgical simulation] [Real-time rendering] [Physically-based modeling]

1. Introduction

The word cataract is used to describe the natural lens that has turned cloudy. Cataracts are not a disease, but rather a condition affecting the eye. This causes gradual impairment of vision. If left untreated, cataracts can cause needless blindness. The development of cataracts is a normal part of the aging process, but they can result from a number of other reasons.

The more efficient solution for restoring vision consists of extracting the cataract and substituting it with an **intraocular lens**, or IOL. Modern advances in micro-surgical techniques permit cataracts to be removed safely and are very successful in restoring vision. Nowadays, they are probably the most frequently performed surgery in the world.

Considering the diffusion and the complexity of the specialty, training is considered very important. In this context, the usage of Virtual Reality based training systems would greatly help in improving the learning curves and the quality of apprenticeship. In fact, analogously with aerospatial technology, where simulators are currently used as fundamental training and certification instruments, the employment of surgical simulation technology would allow:

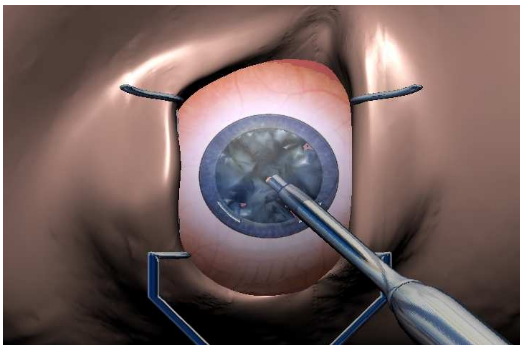


Figure 1: *A snapshot of our cataract simulator prototype.*

- a great flexibility in training sessions;
- to gradually modify the training difficulties;
- to expose trainees to rare events, that can be very dangerous for patient;
- to quantify *performance* and surgical skills.

That's why a number of research groups are working towards the goal of VR simulator systems realistically mimicking a patient-specific operating environment [WSM02a].

In this short paper, we describe our preliminary results in the realization of a virtual reality cataract surgery simulator. The system contains physically-based simulations of the capsulorhexis and phacoemulsification tasks as well as a simple geometric simulation of corneal incision. The simulator runs on a multiprocessing PC platform and provides realistic visual feedback with real-time interaction. The current setup employs SensAble PHANToMs for simulating the interaction devices, and a binocular display for presenting images to the user.

Figure 1 shows a snapshot of our prototype simulation system. The rest of the paper is organized as follows: section 2 describes the phases of the intervention, while section 3 provides a brief description of the architecture of the prototype simulator, with details on the principal tasks (subsection 3.4 for capsulorhexis and subsection 3.5 for phacoemulsification). We conclude with a discussion of the first results obtained insofar and a view of our future work.

2. Application area

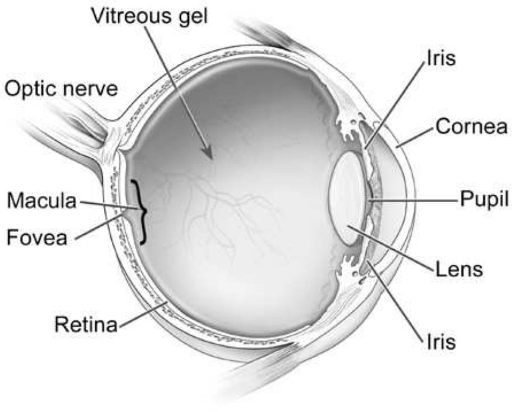


Figure 2: *Complete eye diagram with labels. Courtesy of U.S. National Eye Institute.*

Phacoemulsification consists of breaking the hardened crystalline lens into very minute fragments by employing localized high frequency waves (figure 2 shows a complete eye diagram indicating the lens position and shape). The lens fragments are then easily removed out with a small sucker. Both the ultrasound generator and the sucker are combined into a single thin instrument: the phacoemulsificator. The most common way of fracturing the lens nucleus consists of sculpting a ditch at 6 o'clock direction and repeating the same operation after a 90 degrees rotation, in order to obtain four arms of a smoothly deep cross. In order to open the way to the phacoemulsificator, first a small incision (the right port or tunnel) of about 3 mm, has to be performed on the cornea at about 5 o' clock with a lance knife. The corneal tunnel section should be Z-shaped in order to limit the outgoing liquid flow and maintain the internal pressure. Subsequently, a capsulorhexis is performed in order to uncover the upper surface of the crystalline. The capsulorhexis procedure consists of removing the anterior capsule, by first creating a small flap (a L-shaped incision) in the central area of the capsule with a hook, then engaging the flap by forceps and pulling it in a circular manner to create a regular round opening on the membrane. A second tunnel (the left port) is often performed on the cornea at about 8 o' clock. It is used to perform auxiliary tasks, such as controlling eye globe movements or holding and moving the crystalline lens during the phacoemulsification stage. It is also used to introduce an irrigator attached to a balanced salt solution with bottle height of 90-95 cm above eye level, necessary to stabilize the anterior chamber pressure during all intervention phases.

3. Methods and Tools

3.1. Decoupled simulation

The analysis of the intervention revealed that, in order to provide realistic images to the user, the system needs to simulate very different interactions. We have exploited this difference by modeling the simulator as a collection of loosely coupled concurrent components. Logically, the system is divided in a fast subsystem, responsible for the surgical instrument tracking (100 Hz), and a slower one, essentially dedicated to the production of data for visual feedback. The slow subsystem is responsible for the global simulation of the eye, and for the interaction of the devices with the cornea, the anterior camera membrane and the crystalline lens. The algorithms used to control the simulations are local in character, leading naturally to a further break-up of the slow subsystem in components, each dedicated to the generation of a specific visual effect, and thus possibly to a parallel implementation on a multiprocessor architecture.

The system runs on two multiprocessor machines connected with a 100 Mbit Ethernet link. The first machine is dedicated to the high-frequency devices tracking tasks (100 Hz), while the second machine concurrently runs the low-frequency task (20-25 Hz): eye simulation, anterior camera simulation, and crystalline lens simulation. Since the low-frequency tasks do not influence high-frequency ones, the two machines are synchronized using one-way message passing, employing the VRPN library [RMTHS*01].

3.2. Tool-eye interaction simulation

Since force feedback returned by surgical instruments is nearly imperceptible, the main way the surgeon have to understand the effort really exerted on the patient eye is the visual feedback provided by the tool position related to the environment and the eye globe displacement.

To evaluate tool-eye interaction, we use a two-step algorithm. In the first step, a simple conjugate gradient descent is employed to minimize the total deformation energy of the following constraints: the corneal tunnels (both translational and rotational constraint), the internal cornea surface, and the external crystalline surface (unidirectional radial interaction) which bound the tool working area. The result is an equilibrium position, to be visualized during simulation. In the second step, the eye globe is rotated in order to reduce the deformation of the tunnel. The new globe position is thus the resultant of the force applied to the tunnel borders by the tool and the globe muscles reaction. All constraints are simply modeled as linear springs.

3.3. Corneal tunnel simulation

At the moment the cutting feature is intended as a geometric tool to select the corneal insertion point and the port geometric features, such us orientation and width. Tunnel section profile control is currently not implemented. The cut is modeled as a circular arc and stored as its extrema radial versors. During the cutting stage, the extrema are constantly recomputed, in order to perform the cut enlargement and its partial reorientation.

3.4. Capsulorhexis simulation

For the capsulorhexis procedure, we geometrically model the anterior camera as a mesh composed of triangular facets. This model is used for the physical simulation as well as the rendering stage. The physical simulation is obtained by mapping a mass-spring network over the triangular mesh [WSM02b, HPH96], where mass particles are mapped over the mesh vertices, and linear springs are mapped over the mesh edges. Mass particles are tagged as **anchored particles** (they cannot change their position), **scripted particles** (with position and velocity externally imposed), and **free particles** (with position and velocity derived from a second order dynamic simulation). Tools are implemented through collision detection and scripting routines, moving particles freely in the space together with tracked devices (hook and forceps). For each particle, the accumulated acceleration includes gravity, environment viscosity, and spring contributions. Weak positional springs are also employed in order to simulate a light glue effect between the membrane and the crystalline lens. The time integration is obtained by employing a semi FSAL formula for mildly stiff problems [AT94, Ver67]. The algorithm is fairly stable because the velocity is computed using an implicit method and has a feedback on the position which is computed explicitly. At the end of each step a correction routine is applied to each particle in order to correct position and velocity according to the environment physical constraints. Tearing is obtained by breaking the spring exerting largest force on a vertex if it is overextended, and by propagating cuts along the most stressed directions. All these physical effects rely on a number of parameters, that need to be adequately tuned in order to get a membrane physically similar to a real anterior camera.

3.5. Phacoemulsification simulation

For the phacoemulsification task, we model the eye lens as a collection of simplices, built from a tetrahedron mesh, with mass particles placed in tetrahedrons barycenters. Links connecting particles are maintained in order to provide geometrical information for deriving the external triangular mesh for rendering, and for recognizing crystalline lens independent fragments when phacoemulsification is performed. The phacoemulsificator device is modeled by eroding particles, in a zone of influence. We employ a Russian roulette scheme, that keeps into account the ultrasound effect and the lens nucleus hardness. The hook tool is modeled by scripting particle positions, similarly to what happens in the capsulorhexis simulation. When particle masses are removed, the simplicial mesh topology is updated. For the dynamic simulation we employ a shape matching approach [MHTG05]. The main idea is to replace energies by geometric constraints and forces by distances from current positions to goal positions. These goal positions are determined via a generalized shape matching of an undeformed rest state with the current deformed state of a point cloud. A different point cloud is associated to each topologically connected subset. Since points are always drawn towards well-defined locations, the overshooting problem of explicit integration schemes is eliminated. Similarly to capsulorhexis simulation, phacoemulsification simulation relies on a number of parameters, that are adequately tuned in order to get realistic effects.

4. Results

The prototype cataract extraction training simulation system was developed in C++ on top of the OpenSceneGraph toolkit [ope05]. A complete and detailed eye model was built according to the indications of [LCRB03].

Our current configuration is the following:

- a single-processor PIV/1.5 GHz for the high-frequency device tracking task; two threads run in parallel: one for the tracking loop (100 Hz), and one for sending instruments position updates to the other machine;
- a dual-processor PIV/2.2 GHz with 2 GB RAM and a NVIDIA GeForce 6800 and running a 4.4 linux kernel, for the low frequency tasks (25 Hz). Two threads are continuously running on this machine: one to receive position updates, one for simulations and visual rendering;
- a Phantom Desktop haptic device for the dominant hand; the device is connected to the single processor PC. It provides 6DOF tracking;
- a Phantom 1.0 haptic device for the non-dominant hand;

the device is connected to the single processor PC. It provides 6DOF tracking;
- a N-vision VB30 binocular display for presenting images to the user. The VB-30 contains a small high-resolution LCD display and is connected to the S-VGA output of the dual processor PC.

A number of training sessions have been performed, and videos recorded. The performance of the prototype is sufficient to meet the timing constraints for display, even though the computational and visualization platform is made only of affordable and accessible components. The overall realism of the simulation is considered sufficient for training purposes. Subjective input is currently being used to tune the parameters that control capsulorhexis and phacoemulsification simulations. Figure 3 shows a sequence of a real capsulorhexis [aTDaPS05], while figure 4 shows selected frames of a virtual capsulorhexis. Figure 5 shows a sequence from a virtual phacoemulsification, where the cross-shaped incision is clearly visible.

5. Conclusions and future work

We have described our preliminary results in developing a virtual reality simulation system for cataract surgery training. The system includes all principal phases of cataract extraction: corneal tunnel, the capsulorhexis and phacoemulsification tasks. The simulator runs on a multiprocessing PC platform and provides realistic physically-based visual simulations of tools interactions. Our current setup employs SensAble PHANToM for simulating the interaction devices, and a binocular display for presenting images to the user.

The overall realism of the simulation has been judged sufficient for training purposes. Subjective input is currently being used to tune the parameters that control capsulorhexis and phacoemulsification simulations. Our current work is concentrating on improving the quality and speed of simulations.

Acknowledgments

We acknowledge the NIH National Research Resource in Molecular Graphics and Microscopy at the University of North Carolina at Chapel Hill for the VRPN library.

References

[AT94] Allen M. P., Tildesley D. J.: *Computer Simulation of Liquids*. Oxford Science Publications, 1994. 3

[aTDaPS05] adn Tanuj Dada H. S., amd Prabhpreet Sethi H. R.: Closed chamber globe stabilization and needle capsulorhexis using irrigation hand piece of bimanual irrigation and aspiration system. *BMC Ophtalmology 5*, 21 (2005). 4, 5

[HPH96] Hutchinson D., Preston M., Hewitt T.: Adaptive refinement for mass/spring simulations. In *Proceedings of the Eurographics workshop on Computer animation and simulation '96* (New York, NY, USA, 1996), Springer-Verlag New York, Inc., pp. 31–45. 3

[LCRB03] Lefohn A., Caruso R., Reinhard E., Badge B.: An ocularistś approach to human iris synthesis. *IEEE Computer Graphics and Applications 23*, 6 (November-December 2003). 3

[MHTG05] Muller M., Heidelberger B., Teschner M., Gross M.: Meshless deformations based on shape matching. *ACM Trans. Graph. 24*, 3 (2005), 471–478. 3

[ope05] Openscenegraph, 2005. Available from http://www.openscenegraph.org. 3

[RMTHS*01] Russell M. Taylor I., Hudson T. C., Seeger A., Weber H., Juliano J., Helser A. T.: Vrpn: a device-independent, network-transparent vr peripheral system. In *VRST '01: Proceedings of the ACM symposium on Virtual reality software and technology* (New York, NY, USA, 2001), ACM Press, pp. 55–61. 2

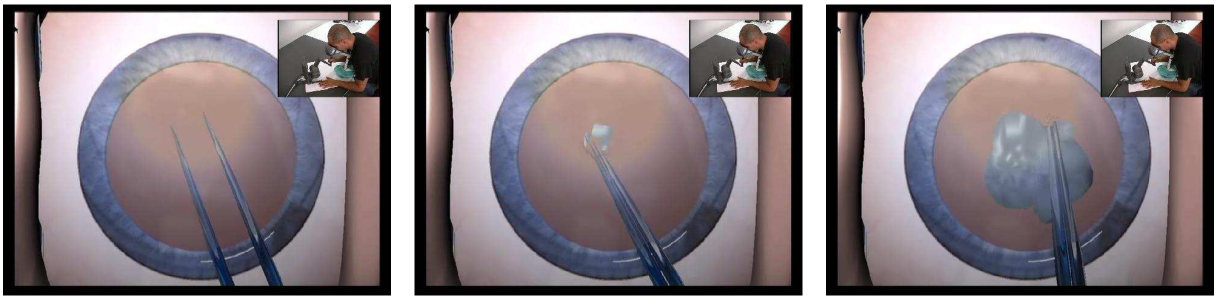
[Ver67] Verlet L.: Computer experiments on classical fluids. i. thermodynamical properties of lennard-jones molecules. *Physics Review 159* (1967), 98–103. 3

[WSM02a] Wagner C., Schill M., Manner R.: Intraocular surgery on a virtual eye. *Communicactions of the ACM 45*, 7 (2002), 45–49. 2

[WSM02b] Wagner C., Schill M. A., Manner R.: Collision detection and tissue modeling in a vr-simulator for eye surgery. In *EGVE '02: Proceedings of the workshop on Virtual environments 2002* (Aire-la-Ville, Switzerland, Switzerland, 2002), Eurographics Association, pp. 27–36. 3

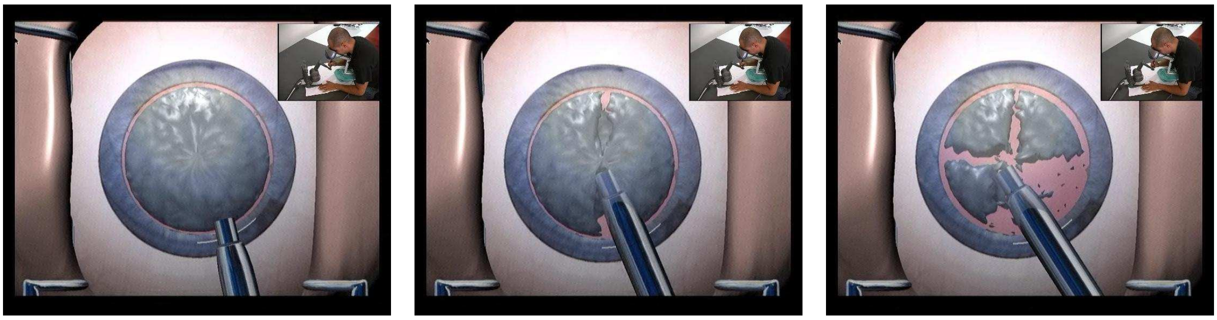
(a) (b) (c)

Figure 3: *A real capsulorhexis snapshot from [aTDaPS05].*



(a) (b) (c)

Figure 4: *Here we show a typical capsulorhexis sequence performed by virtual forceps.*



(a) (b) (c)

Figure 5: *A virtual phacoemulsification sequence. Here we show a typical lens rupture and extraction performed by a phacoemulsificator tool. The typical cross-shaped cut is clearly visible.*