Representing Fluid with Smoothed Particle Hydrodynamics in a Cranial Base Simulator

Wen LIU [a], Christopher SEWELL [b], Nikolas BLEVINS [c], Kenneth SALISBURY [b], Kenneth BODIN [d], Nils HJELTE [d]
[a] *Department of Electrical Engineering, Stanford University*
[b] *Department of Computer Science, Stanford University*
[c] *Department of Otolaryngology, Stanford University*
[d] *Department of Computer Science and HPC2N/VRlab, Umeå University*

Abstract. We describe the implementation of irrigation and blood simulation using Smoothed Particle Hydrodynamics (SPH) in a cranial base surgical simulator. Graphical accuracy of virtual surgery is a significant goal for improving the realism and immersive experience of computerized training environments. For temporal bone micro-surgery fluids contribute not only to the visual integrity of the surgical field but provide relevant anatomic cues as well. The skill of 3-D sensory and navigation has become increasingly viable in surgery with the rising popularity of laparoscopic, catheter angiography and other minimally invasive approaches. The introduction of realistic simulated blood and irrigation enables the practice and coordination of two-handed microdissection techniques and the timing needed for safe bone removal and cautery.

Keywords. Surgical simulation, fluid, Smoothed particle Hydrodynamics, Cranial Base Simulator

Introduction

Surgical simulators have addressed the importance of fluids using many different approaches including Eulerian, spring and damper or particle-based models, though most have limitations in fidelity. The Stanford SPRING project, for example, recognizes the need for including smoke and blood in their laparoscopic open source surgery simulator [2]. Implemented with an uncoupled particle system, its smoke composition, however, does not detect any environmental collisions. Interactivity of its blood modeling is also limited because fluids are drawn in strips constrained to the sides of anatomic structures. Blood trails are either rendered flat in a two-dimensional visualization technique, or appear as a tubular polygon in an alternative three-dimensional technique. Our SPH methodology provides a more dynamic interaction with the surgical environment, enabling a potential gain in surgical training realism as championed by M. Mueller, et al in their proposal of an interactive modeling of fluid also using SPH [3]. The cranial base simulation system being described here had already been developed at Stanford University mainly as a mastoidectomy simulator [1].

Smoothed Particle Hydrodynamics

SPH - Smoothed Particle Hydrodynamics is a mesh-free particle-based method in which discrete particle properties are smoothed by a kernel function [4]. For our incompressible viscous fluids representing irrigation and blood we continuously calculate force density fields as the sum of pressure, viscosity, and external forces such as gravity, collisions, and boundary conditions. The computational complexity of SPH is dominated by computing these forces, and by constructing neighbor lists for the interacting particles. The latter is typically accelerated by means of spatial decomposition. The pressure force penalizes fluid compression with a strength proportional to the squared speed of sound in the fluid. For e.g. water with a sound speed of 1500 m/s this would require time steps at least two orders of magnitudes shorter than what is practical in a real-time simulator, and therefore the sound speed is usually chosen much smaller than the real value, but large enough to avoid compressibility on the time and length scales relevant for the simulator.

Method

Previously within the mastoidectomy simulator we have implemented two different sized drills and a suction device. As the drill mills away bone voxels, represented by a hybrid voxel triangular mesh, smaller bone particles collect in the removed region. The suction device should then be used to clear the bone dust to retain a clear visual field. Using the same device, blue irrigation particles are emitted from the tip of a suction irrigator when a button on the haptic interface is actuated. Intraoperatively, this is used to wash away bone dust and blood, and to prevent excessive heat from being generated by the surgical drill. Blood particles, colored red, are emitted at points of contact between dissection instruments and surface meshes representing vascularized structures. Another designated button on the haptic interface activates the suction, which clears adjacent blood and irrigation particles as well as bone dust. Customizable particle parameters that we have explored include mass, viscosity, interactive damping factor and volume as well as a configurable probability of introduction of blood on a voxel to mesh collision. We can process approximately 10-15k particles in a stand-alone application on a 3GHz Pentium 4, and 50-100k particles on more specialized hardware e.g. Cell [5] and the GPU [6]. In practice, on our simulator, with a 3GHz Pentium 4, we are able to introduce the probability of blood at a rate of 1% of all collisions.

With the integration of SPH into our voxelized mesh temporal bone, each iteration of visual rendering calculates not only force field quantities created by particle-to-particle collisions but particle-to-voxelized mesh as well. Additional collisions can also result between particles and the bounding environment. Force updates include vectors from SPH collisions as well as a gravitational source. We also have the option of adding an explicit external force. Velocity of each particle can then be calculated and updated before handling environmental boundary conditions. The default anatomic data load of our surgical simulator is a set of hybrid polygonal and volumetric models representing the posterolateral skull base. Thus the surfaces derived from these models provide the locality limits for particle repositioning within the surgical environment. That is in each rendering loop we calculate,

```
for each blood/ irrigation particle p1 {
    Find its 3D vector position in the local reference frame of the temporal bone
    for a configurable number of incremental steps {
        if p1 traveling from previous position to the current position at this step
        passes through a valid bone voxel. {
            Create a temporary particle p0 at this position to force a
            collision with p1 to push p1 back to this collision point
        }
    }
}
```

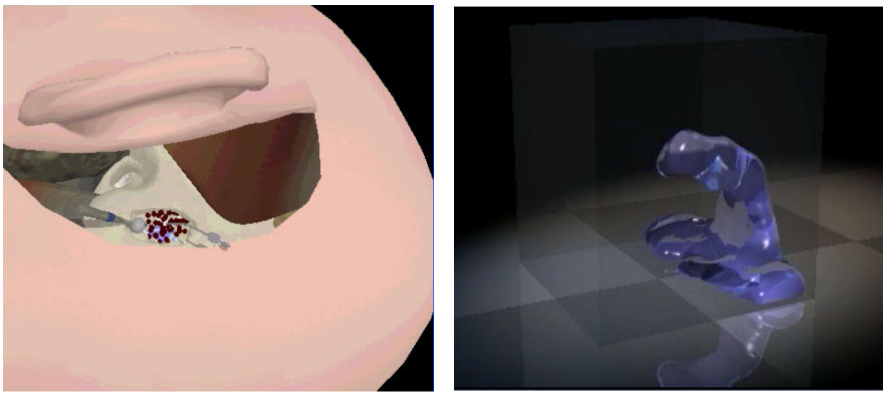

Figure 1. At left, a screenshot of a run in mastoidectomy simulator paused at a partially drilled temporal bone and showing irrigation and blood sph particles, of which resulted from collisions of tool with the sigmoid sinus beneath.. At right, sph modeling of fluid in a cube with smoothed surface reconstruction.

We have successfully integrated an initial SPH system into our virtual surgical environment. Our ongoing efforts include fine-tuning SPH parameters, and adding surface reconstruction for improved efficiency and greater visual realism. Based on this experience, we intend to explore the potential of SPH to represent deformable objects in surgical simulation.

References

[1] Morris D, Sewell C, Barbagli F, Blevins NH, Girod S, Salisbury K: Visuohaptic simulation of bone surgery for training and evaluation. IEEE Tran. on Comp. Graph. & App, Nov 2006.

[2] Daenzer S, Montgomery K, Dillmann R, Unterhiinninghofen, R. Real-Time Smoke and Bleeding Simulation in Virtual Surgery. Proceedings of MMVR (Medicine Meets Virtual Reality), January 2007

[3] M. Mueller, S. Schirm, M. Teschner. Interative Blood Simulation for Virtual Surgery Based on SPH. Journal of Technology and Health Care Volume 12. February 2004

[4] J.J. Monaghan, Smoothed Particle Hydridynamics, Rep. Prog. Phys 68 (2005)

[5] N. Hjelte, MSc thesis, Department of Computing Science, Umeå university (2006). To be published.

[6] Takahiro Harada, Seiichi Seiichi Koshizuka, Yoichiro Kawaguchi, Smoothed Particle Hydrodynamics on GPUs, Proc. Computer Graphics International, June 2007.