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# Elastically Deformable 3D Organs for Haptic Surgical Simulation.

Roger Webster, Ph.D.[1], Randy Haluck, M.D.[2], Rob Ravenscroft, Ph.D.[1]
Betty Mohler [1], Eric Crouthamel [1], Tyson Frack [1], Steve Terlecki [1], Jeremy Sheaffer [1]

[1]*Department of Computer, Science School of Science and Mathematics, H. Justin Roddy Science and Technology Building, Millersville University Millersville, PA. USA 17551*
*webster@cs.millersville.edu*

[2] *Department of Minimally Invasive Surgery, Penn State University College of Medicine, Milton S. Hershey Medical Center, Hershey, PA USA 17033*

**Abstract.** This paper describes a technique for incorporating real-time elastically deformable 3D organs in haptic surgical simulators. Our system is a physically based particle model utilizing a mass-springs-damper connectivity with an implicit predictor to speed up calculations during each time step. The solution involves repeated application of Newton's 2nd Law of motion: F = ma using an implicit solver for numerically solving the differential equations.

## 1. Introduction.

Surgical simulators are currently being developed by many research institutions and corporations to train medical students and surgeons in minimally invasive surgery. Among the primary research topics is the notion of deformable virtual organs and soft tissue for use in haptic surgical simulators. During the past decade many graphics researchers have contributed to the forefront of deformable 3D objects research, see D. Terzopoulos, et.al. in [1,2], and in cloth animation systems, Baraff and Witkin in [4], and N. Thalmann, et.al, in [5]. Haptic surgical simulators have primarily used either physically based models [6,7,8] or finite element models [9,10,11]. Although many techniques have been proposed for deformable object animation (see [12] for an overview), few can provide the performance necessary for real-time applications. The fundamental trade off therefore is accuracy vs interactivity. In haptic surgical simulation this problem is especially acute, as the user must feel contact forces (and see the graphical deformations) that are accurate yet computed in real time.

Our system is a physically based particle model utilizing a mass-springs-damper connectivity with an implicit predictor to speed up calculations during each time step. This system consists of a set of point masses (nodes) connected to each other with a network of springs and dampers. Each vertex in the organ geometry has a mass and is connected to every other vertex with springs and dampers. The solution involves repeated application of Newton's 2nd Law of motion: F = ma using an implicit solver for numerically solving the differential equations. The dynamics equation for each mass point is $m_i x_i = -\gamma_i x_i + \Sigma g_{ij} + f_i$ where $m_i$ is the mass at point $x_i \in R^3$, $-\gamma_i x_i$ is the damping force to prevent instabilities, $g_{ij}$ is the linear Hookian force exerted on mass i by the spring between i and j, $f_i$ is the sum of the external forces acting on mass i (gravity, pushing and probing the 3D organ). Combining the vectors of all mass points produces: $Mx + Dx + Kx = f$, where M is the mass matrix, D is the damping matrix, K is the stiffness matrix, and f is the aggregate force vector. As the system progresses through time dt, the first order differential equations are: $v = M^{-1} (-Dv - Kx + f)$, $x = v$, where v is the velocity vector. Baraff and Witkin [4] have used a similar technique effectively in modeling cloth systems for special effects in the motion picture industry. The fundamental problem with these implicit solvers is that they need to solve a linear system at each time step, which is not practical with today's computers. To get around this computational expense, we incorporate a technique, based upon the work of Desbrun et.al. [13], with an approximate solver that pre computes the solution to a linear system. In addition, we have written a pre-processor that builds the matrices for the predictor for each organ and writes them out to a file. The matrix generation process may take considerable time to calculate (several minutes). The surgical simulation application, however, can simply load a file with the prediction matrices pre-built.

**Method and Tools.**

Our simulator uses the Sensable Technologies' PHANToM™ haptic device, the "Reachin Display"™ unit to provide the user with the ergonomic feel of actual surgery (see Figure 1). The Crystal Eyes™ stereo glasses are used to enhance the 3D effect. The graphics programming environment is EAI/Sense8's WorldToolkit™ API of OpenGL calls. The haptics programming environment is the Sensable Technologies' GHOST™ API calls. The control computer is a Pentium processor workstation running Windows2000™ with an Nvidia GeForce™ graphics OpenGl accelerator.

Our system has four basic forces. They are: (1) gravity, in which all masses are accelerated in the y-axis at 9.8 m/s/s. The collision forces (2) are calculated when the user pulls and probes the organs. All momentum being exerted is transferred back to the colliding mass points. The springs (3) are either stretched or compressed away from their initial resting length. Each spring is subject to the conventional Hooke's Law restoring force ($F = -kx$). To prevent numerical instabilities we use a damping coefficient (4) in which masses in motion will receive a small force opposite to their directional vector.

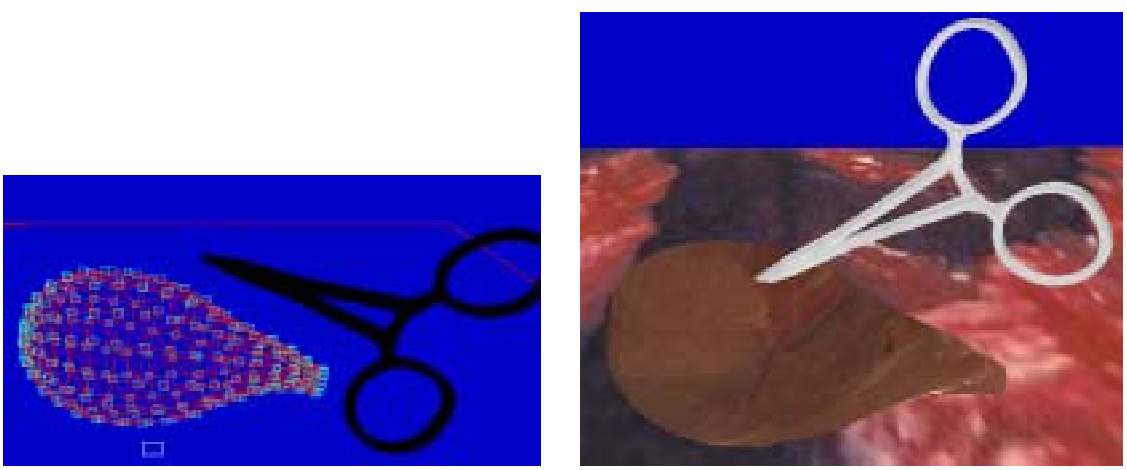

Figure 2. (a) Wire frame of gallbladder model showing mass points and (b) probing deformation.

## Conclusions/Results.

The goal of this project is to develop real-time elastically deformable 3D organs software for use in simulating a suite of surgical procedures. We have experimented using 3D organs with up to 1000 polygons with frame rates of 25 fps on a conventional intel 1.4 Ghz single processor PC with a GeForce OpenGL accelerator with no significant visual or haptic computational lag. The advantage of this technique is that the underlying physical model is simple, it uses well-understood dynamics, and interactive frame rates with modestly sized polygonal models are attainable. The downside is that the discretized mass-springs system is an approximation of the actual continuous real-world physics. In addition, proper values for the spring constants of non-isomorphic soft tissues are contrived and can cause instability problems as well as slow deformations. Further enhancements, testing and evaluation are in progress. See our web site http://cs.millersville.edu/~webster/haptics for updated information.

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