Virtual Reality Vitrectomy Simulator

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Abstract. In this study, a virtual reality vitrectomy simulator is being developed to assist Ophthalmolgy residents in correcting retinal detachments. To simulate this type of surgery, a three dimensional computer eye model was constructed and coupled with a mass-spring system for elastic deformations. Five surgical instruments are simulated including: a pick, blade, suction cutter, laser, and drainage needle. The simulator will be evaluated by a group of fellows and retinal surgeons with a subjective Cooper-Harper survey commonly used for flight simulators.

1 Background

1.1 Retinal Detachments

Ophthalmology programs generally follow four stages: clinical introduction, researching subspecialities, treating patients, and an optional subspecialty fellowship. Introductory training begins with lectures, surgical texts, prerecorded surgical video tapes, and practice on animal cadavers and sometimes fruits. Participation in surgery is similar to an apprenticeship where residents gradually perform more complex procedures under a surgeon's supervision. Modern vitreous surgery is categorized as a closed divided system in which an operative instrument and a light probe are inserted into the vitreous chamber to repair any abnormalities such as retinal detachments. To correct detachments, a vitrectomy is performed to reattach the retina, stop any bleeding and remove any fibrovascular tissue. Operative instruments range from simple forceps and picks, vitreoretinal scissors and cutting blades, blunt drainage needles, suction cutters; to more complex instruments such as lasers and cryoprobes.

1.2 Virtual Reality Surgical Simulators

Virtual reality surgical simulators generally consist of five components: anatomical models, a physics system, an abnormality simulation, a VR interface, and virtual surgical instruments. Anatomical models are computer representations such as surfaces or volumes which approximate the form of the human body. Models can be constructed from sequential cross-sectional images, physical cadavers slices, or from population statistics. A physics system couples anatomical models with physical properties so they can respond to external and internal forces much like their real world counterparts. Current physics systems range from mass-spring networks to finite element analysis to simulate deformation and fracture. An abnormality simulation is the anomaly or pathology that needs to be corrected through the surgical procedure. The VR interface is the real-world devices of the simulator. Lastly, virtual instruments allow the resident to interact with the anatomical models through the VR interface. Figure 1 shows a possible schematic diagram for a virtual reality surgical simulators.

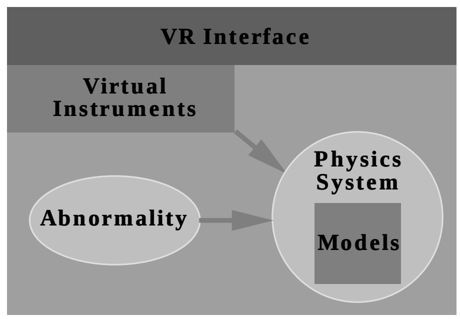

Fig. 1. Surgical simulator schematic diagram

Theoretically, a virtual reality simulator can assist in the surgical training process in a variety of ways such as reinforcing hand-eye coordination, the formation of a 3D mental model, finetuning a resident's performance, providing access to a variety of diseases, and ultimately supporting a uniform accreditation procedure [3]. The expense of a VR simulator could be offset by the surgical time reduction currently needed to train residents and recover from their initial complications. In addition, funding from the federal government to supplement surgical training may be reduced or discontinued in the future to cap health care costs.

1.3 Previous Research

The eye's small size and fine structures make it difficult to reconstruct using standard imaging modalities. An early eye reconstruction with an ocular tumor was created by segmenting and stacking ultra-sound images to visualize a radiation treatment plan [5]. Another model was developed to train surgeons in performing radial keratotomy on a cornea model using finite element analysis [12]. At the Interactive Media Technology Center, an eye simulator was prototyped with a tactile stylus that controlled several virtual instruments [13]. Their software program demonstrated a user cutting the sclera and inserting a phacoemulsifier to remove a cataract.

Of all of surgical instruments functionalities, cutting presents the greatest challenge for simulators. An early related method proposed by [16] propagated fractures by inserting positional discontinuities in regions with the largest elastic displacement. [15] demonstrated a cutting technique using a constrained particle system, but the method appeared to lose surface area when particle bonds were broken. Another method developed by [11] for plastic surgery radially projected a screen based cutting path onto a finite element mesh attached to a laser scanned facial model. Another finite element method by [14] moved a template over a 2D surface to define the cutting incision. In addition, the user's force vector from the input stylus had to overcome the shear strength of the virtual surface for cutting to occur. A more recent method by [6] used a single bilinear reference plane to cut into a voxel array of tetrahedral finite element substructures derived from CT and MRI images. Unfortunately, the algorithm was not within interactive frame rates needed by simulators. Another approach was taken by [2] who used boolean operations on 3D surface geometry, but did not included any underlying physics system. Other researchers have demonstrated cutting techniques but have not published their algorithms [12, 13]. One novel proposal incorporates fuzzy logic to quantitatively evaluate a user's cutting performance within a simulator [8].

1.4 Training Issues

Much of the purported potential attributed to medical simulators is based upon the training success achieved by flight simulators [4]. Correspondingly, a number of performance and training assessment techniques developed for flight simulators can be applied to medical simulators. A trainee's performance is a ranking of their decision-making process and motor skills compared to another session. Training assessment is the amount of skills that trainee has achieved from the simulator that can be applied to real-world tasks. One transference rate measurement is the Transfer Effectiveness Ratio which is the difference between the transfer performance of a control group to a simulator-based group [1]. Imperfections in a simulator may lead to negative transfer or counterproductive behavior that is reinforced by the simulator. Since simulators can only approximate their real-world tasks, they must be judged on their training effectiveness. One subjective method, the Cooper-Harper characteristic scale, allows pilots to determine if a flight simulator is unsatisfactory, needs improvements, or is sufficient for training. Another important aspect of a simulator is its workload which is the amount of mental ability required by the trainee to perform a task. As workload increases, the trainee can initially compensate but with further increases, performance drops rapidly until the trainee is overloaded [7]. Workload assessment can be done subjectively, based on performance measurements or by physiological measures.

2 System

2.1 Overview

The current implementation of our opthalmic surgical simulator was developed to test the system's response time and prototype the functionality of several surgical instruments. Since virtual reality applications require a real-time frame rate, a mass-spring network was initially chosen to perform the necessary physical behaviors of the models. The mass-spring algorithm is also parallelizable. Models were based on cross-sections derived from published statistical averages on anatomical curvature and thickness [10]. Alias Studio software was used to construct and export all surface models. Physically based models were composed of triangle sets for flexibility while static models consisted of triangle meshes for speed. Available surgical instruments are: a pick, blade, suction cutter, drainage needle, and laser. None of the instruments had any moving parts. The current VR interface consists of a 3D mouse and stereo glasses, but a more nonintrusive interface is under development which will consists of two tracked vitrectomy instruments, a microscope-like housing for the stereo glasses, and a wrist support structure. Although tactile feedback is not supported, most vitrectomy maneuvers do not generate strong contact forces. The intersection of an instrument and a model involved testing a general line/sphere intersection routine with each surface vertex. Simple disease simulation consists of a planar fibrovascular tissue with perpendicular traction and a force function to simulate rhegmatogenous detachment. The software is comprised of C++ classes with the OpenGL graphics library and the Electronic Visualization Laboratory's CAVE library [9] running on a duel Silicon Graphics MXE Octane workstation. Figure 3 shows the exterior and interior views of the model.

2.2 Physics System

Flexible structures such as the retina and fibrovascular tissue were modeled as above but the conversion program fitted a vector spring through each edge. Vector springs were developed as a more stable spring algorithm by Alan Millman at the Electronic Visualization Laboratory. Spring stiffness constants and models' mass distribution were based upon local surface area [17]. Vertices can be marked as instances to propagate forces between different models, or they can be marked as fixed to prevent them from being integrated. Global force functions include gravity, intraocular pressure and viscosity. Incorporating measured elasticity material properties for all physical structures is currently under investigation.

2.3 Disease Simulation

A circular fibrovascular tissue model was constructed and attached onto the posterior section of the retina model via common instance vertices. An inward perpendicular contraction force was generated by reducing the natural rest length of the tissue model's springs. This caused the model to shrink inwards pulling the retina with it. To approximate a rhegmatogenous detachment, a simple local force function was implemented which added a radial force towards the center of the vitreous chamber to selected retinal vertices.

2.4 Instrumentation

Pick A pick is primarily used to elevate tissue. When the simulated pick intersects a surface, all of the intersecting vertices are linked its current position. Nearby vertices react by the force propagation of their shared springs. Current work will couple the pick with the light probe so that tissue models can be elevated before being cut. In addition, a fracture algorithm has been planned to subdivide surface springs and triangles when a spring's length exceeds a set limit. Figure 4 shows a screen snapshot of the pick instrument as well as the other instruments available in the simulator.

Blade A new interactive cutting algorithm is currently being implemented to subdivide surface springs and triangles along the path of the blade instrument. The blade's path will be approximated with a set of parallelograms which can be quickly intersected with a model's spring list. Springs will be subdivided about their intersection points and induce adjacent triangles to subdivide. A partial intersection algorithm has also been outlined when a surface slopes away from the cutting path, or when cutting begins or ends within a triangle. Newly created springs' stiffness constants and vertices' mass values will be computed based upon the local surface area of the new triangle configuration. Figure 2 illustrates the steps in the subdivision process.

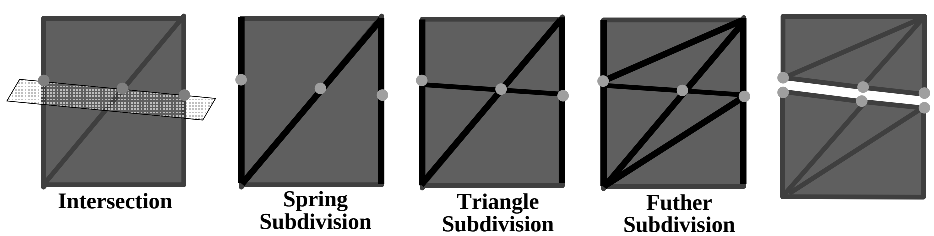

Fig. 2. Cutting subdivision

Suction Cutter The suction cutter attracts nearby vertices to its opening, and then subdivides and removes triangles similar to the blade's cutting algorithm when they are within a certain distance.

Drainage Needle A simple gas-fluid exchange is being implemented with a height ramp function to represent separate gas and fluid regions using different values for intraocular pressure and viscosity. The fluid-gas boundary is initialized at the top of the vitreous chamber and is decremented for each time step while the needle is activated until it reaches the needle's tip position. Individual vertices can quickly determine their region before computing their forces. Drainage of breaks is done by first testing if nearby vertices have the detachment force function and if they are all within the gas region for drainage to occur. If successful, then the deattachment force function's magnitude is decreased until it reaches zero.

Laser After breaks have been successfully drained, the laser instrument is used to adhere the surrounding retina so that fluids cannot reenter. This implementation first performs a ray-cylinder intersection from the laser's position to the retina's spring list to determine if springs are outside, inside or partially intersecting the laser's projection. If a spring is outside or not near its rest position, adhesion cannot occur and the spring is ignored. Internal springs near their rest position will have their vertices marked as fixed and have a small whitish circular map blended at their corresponding texture positions within retinal map to visually indicate adhesion. Partially intersecting springs are subdivided and then processed.

3 Evaluation

As a first step in evaluating the simulator in terms of a training environment for ophthalmology residents, a group of fellows and retinal surgeons will be asked to attend several evaluation sessions in which they will process three simulated surgical cases and rank the simulator's training potential through a modified Cooper-Harper survey. To allow for adjustment to the virtual reality interface, several short practice exercises with each instrument will precede the cases. Once the simulator's ranking is known, subjects will be asked to comment on the image quality, modeling detail, tracking accuracy, physical interface, and instrumentation.

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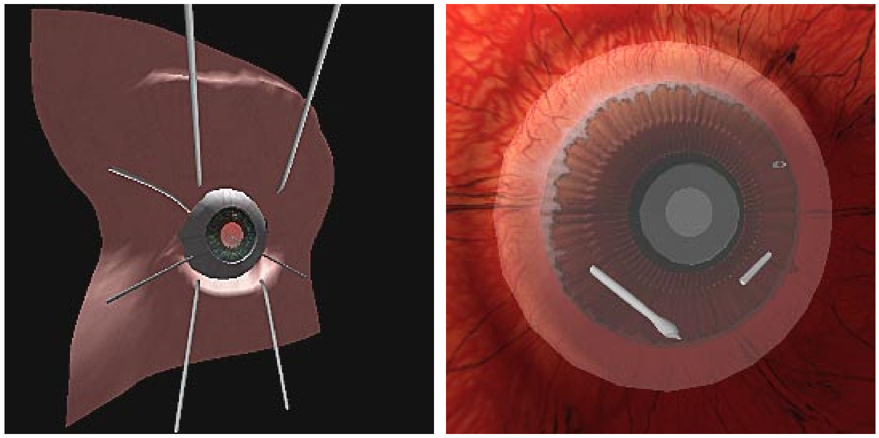

Fig. 3. Exterior and interior views of the VR model

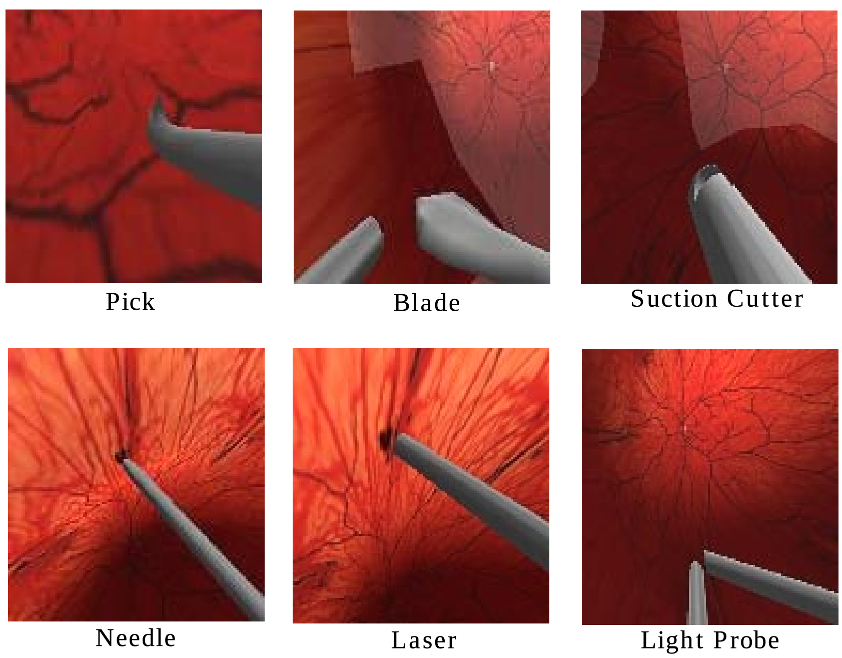

Fig. 4. Instrument screen snapshots