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CONTRACT NUMBER: DAMD17-94-C-4124

TITLE: Lock and Feel: Haptic Interaction for Biomedicine

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REPORT DATE: October 1996

TYPE OF REPORT: Annual

PREPARED FOR: Commander
U.S. Army Medical Research and Materiel Command
Fort Detrick, Frederick, Maryland 21702-5012

DISTRIBUTION STATEMENT: Approved for public release;
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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE October 1996	3. REPORT TYPE AND DATES COVERED Annual (30 Sep 95 - 29 Sep 96)	
4. TITLE AND SUBTITLE Look and Feel: Haptic Interaction for Biomedicine			5. FUNDING NUMBERS DAMD17-94-C-4124	
6. AUTHOR(S) Marc Raibert				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Boston Dynamics, Incorporated Cambridge, Massachusetts 02139			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Commander U.S. Army Medical Research and Materiel Command Fort Detrick, Frederick, Maryland 21702-5012			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200) Interaction through touch and manipulation is known as haptic interaction. We are working to develop advanced haptic technology that allows human users to touch, feel, grasp, and manipulate a set of special objects: objects located remotely, objects too small, too large, or too dangerous for normal human interaction, or objects that exist only in simulated worlds (virtual objects). The goal of this work is to develop the technological foundation of advanced haptic systems and to assemble that technology into a useful surgical simulator. In the first year of this effort we focused on developing the basic technology and methods needed to build interactive haptic applications. In this, the second year of effort, we have assembled these components into several prototype systems. We have built integrated systems for surgical anastomosis, heart palpation and aircraft maintenance. These systems were built upon a common software foundation that includes modules for virtual haptic interaction, physics-based simulation, and computer graphics. While these systems are not yet complete they demonstrate significant progress towards our goal of building virtual reality based training systems that are realistic, flexible, useful, and commercially viable.				
14. SUBJECT TERMS dynamic simulation, force feedback, haptic, virtual reality, contact detection			15. NUMBER OF PAGES 16	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited	

FOREWORD

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Mark Roubert ^{RRP} 12/4/96
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Look and Feel:
Haptic Interaction for Biomedicine
1996 Annual Report

1 Introduction

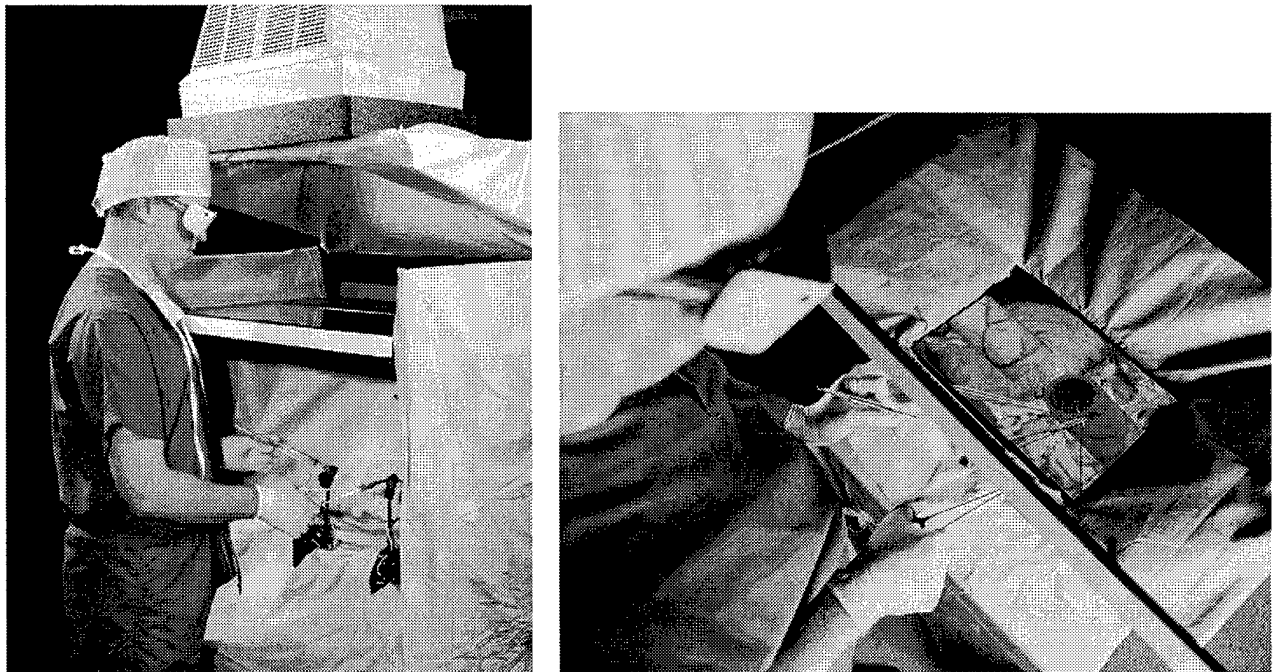


Figure 1: The Virtual Surgery Simulator allows the user to see, feel, hear and manipulate simulated human organs.

People use their hands to touch, manipulate, and learn about the world around them. Interaction through touch and manipulation is known as haptic interaction. We are working to develop advanced haptic technology that allows human users to touch, feel, grasp, and manipulate a set of special objects: objects located remotely, objects too small, too large, or too dangerous for normal human interaction, or virtual objects that exist only in simulated worlds (Figure 1.)

Advanced haptic interaction will have a wide range of applications in biomedical, military, and civilian areas. It will allow design engineers to “pick up” new designs, “try them out,” and see how they behave, before they ever leave the drawing board. Engineers will sculpt the

shapes of new parts in the computer, as though made of clay. Remote experts will aid the local novice in performing delicate procedures. Medical students will train by manipulating virtual organs, without risk to human patients or animals. Students will probe any part of the virtual patient with impunity and view a wide range of conditions from any vantage point. This work will enable applications ranging from familiarization and training in domains requiring hand/eye skills (surgery, mechanics, maintenance, for example) to the enhancement of operations in remote, scaled, unfamiliar, and hazardous environments.

Our goal is to develop the technological foundation of advanced haptic systems and to assemble that technology into a useful surgical simulator. The surgical simulator we envision will allow training of biomedical procedures in a virtual environment that features realistic interaction with simulated anatomy and surgical tools through haptic force feedback, 3D graphics, and sound. In addition to direct training, surgical simulators could be used to assess surgical performance and play a role in certification. This report describes our progress in building such a system.

In the first year of this effort we focused on developing the basic technology and methods needed to build interactive haptic applications. In this, the second year of effort, we have assembled these components into several prototype systems. We have built integrated systems for surgical anastomosis, heart palpation and aircraft maintenance. These systems were built upon a common software foundation that includes modules for virtual haptic interaction, physics-based simulation, and computer graphics. While these systems are not yet complete they demonstrate significant progress towards our goal of building virtual reality based training systems that are realistic, flexible, useful, and commercially viable.

2 Integrated Haptics Applications

We are building a series of advanced haptic systems that consist of a mechanical force-feedback device, a real-time computing system, a dynamic simulation system, and computer graphics and sound(Figure 2). Next we describe these systems: a simulator for surgical anastomosis, a demonstration of virtual heart palpation that uses volumetric 3D visual displays, and a simulator for aircraft maintenance. While the functionality of each of these systems is significantly different, they all build upon a common foundation and thus contribute to the overall goal of developing advanced haptic systems.

2.1 The Virtual Surgery Simulator

The primary focus of activity of the "Look and Feel" project remains the development of the Virtual Surgery Simulator (Figure 1.) This simulator is an integrated system that allows users to reach into a virtual human body to touch, feel, grasp and suture two deformable tubes. The

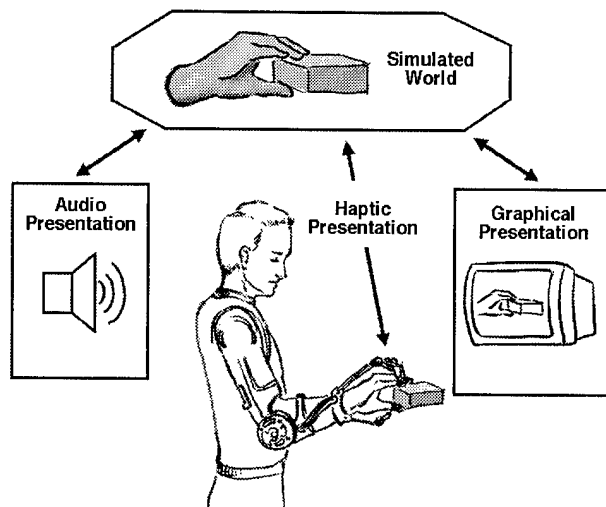


Figure 2: Haptic, Graphic, and Audio Presentation of a Virtual Object

user holds real surgical tools connected to Phantom force feedback devices. By holding a needle holder in one hand and forceps in the other, the user can manipulate two virtual tube organs and suture them together to practice an end-to-end anastomosis. The forces of interaction between the tools and the simulated tubes are reflected to the user with the Phantom while the virtual workspace is visually displayed using 3D computer graphic images. Coordinated visual and tactile displays allow the user to work in an intuitive way while exploring the basic techniques of the surgical anastomosis.

The simulated elements in the anastomosis demonstration are two deformable tubes, forceps, needle holder, needle and suture (Figure 3.) The look and feel of the tubes can be changed to represent different anatomical elements. Tube diameter, thickness, length, compliance, surface friction, and resistance to puncture are just a few parameters that can be used to accommodate different surgical applications. Texture mapped graphics derived from photographs of real biological tissue help make the simulated elements look realistic.

We have constructed a Virtual Surgery Station that allows the surgeon and surgical subject to be in the correct relative position (Figure 1.) The user stands with hands at table height holding the forceps and the needle holder. Looking down at his hands, the surgeon instead sees a mirror reflecting the computer graphic image of the subject and the virtual tools. This image is

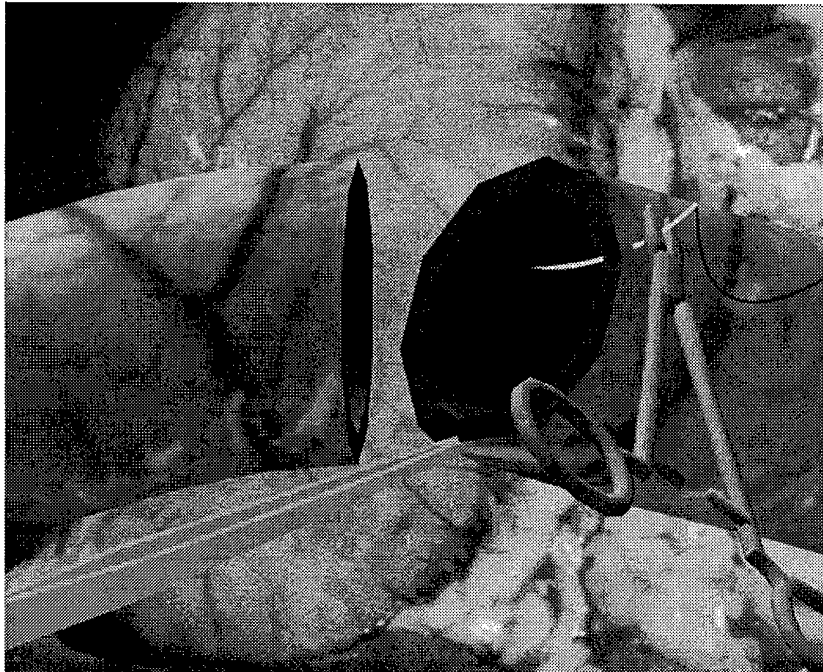


Figure 3: The Virtual Surgery Simulator features deformable tubes that can be sewn together using needle, suture, needle holder, and forceps.

produced in approximately the correct location by using an SGI monitor mounted overhead. A hand rest allows the surgeon to stabilize his hands for delicate manipulation. We have delivered a version of this Virtual Surgery Station to Dr. Tom Krummel at Pennsylvania State's Hershey Medical Center. Dr. Krummel intends to integrate this trainer into his virtual training lab at the Hershey Medical Center. We have also demonstrated this system at the meeting of the Association of Academic Health Centers.

2.2 Palpation of a Beating Heart

Boston Dynamics Inc. in conjunction with Digital Media Associates has created a system that allows the user to touch, poke and pluck a simulated, beating heart with medical instruments. The user can touch a 3D volumetric display of the heart with medical instruments mounted to Phantom force-feedback devices. The user actually feels the heart whenever the physical tool "touches" the floating 3D image because the visual and haptic images of the heart are coincident in space. An audible heart beat is synchronized with the visual and haptic heart displays.

The volumetric 3D display is created by projecting computer graphic images of a beating

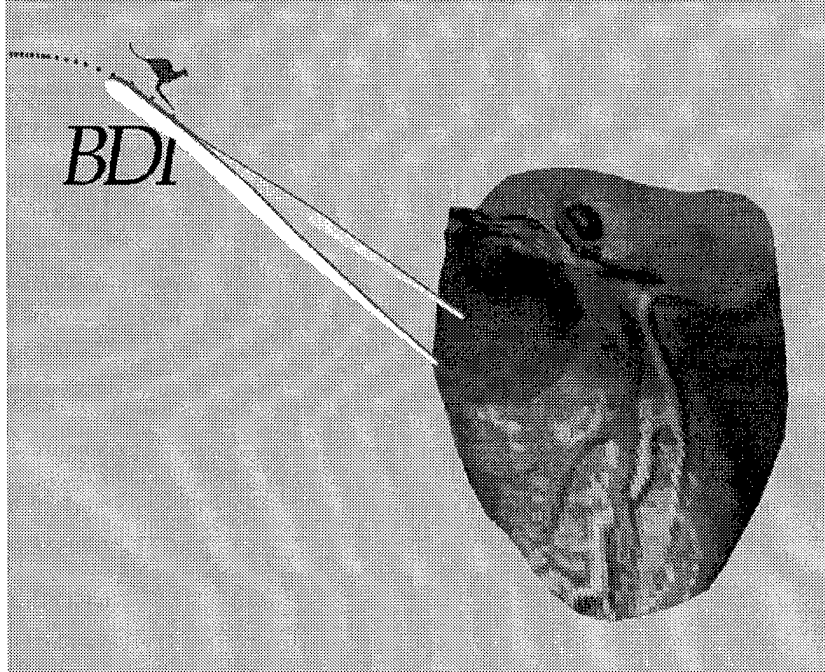


Figure 4: The Virtual Heart: the user can see, feel, and hear the heart beat as well as poke and pluck its deformable surface.

heart onto a screen contoured to the shape of a heart. The image of this screen is projected into the haptic workspace using mirrors. The projection system, the 3D-RT, was built by Digital Media Associates. It consists of a high quality projector, the heart contoured screen, and the mirroring system. BDI created the haptic algorithms, dynamic simulation, computer graphics, and sound of the beating, deformable heart. This unique combined display system makes it easier to touch virtual objects by putting haptic and visual images together.

2.3 Virtual Aircraft Maintenance Training

The technology that provides the foundation for advanced haptics systems is largely independent of the application area. In a separately funded project we developed the Virtual Aircraft Maintenance Trainer. This project has leveraged the funding for surgical simulator development because the basic issues regarding dynamic simulation, haptic force-feedback, and computer graphics are common to all haptics systems.

We developed the Virtual Aircraft Maintenance Trainer to explore the feasibility of replacing expensive mock-ups of aircraft used for maintenance training with less expensive computer



Figure 5: The Virtual Maintenance Trainer allows the user to push buttons, throw toggle switches, turn dials, observe lights, and listen to audible tones, and manipulate linkages during the evaluation and adjustment of aircraft systems.

hardware and software. The virtual maintenance trainer we built allows a user to perform the essential elements of two real-world maintenance training tasks performed by the US Marines on the AV8B aircraft, a vertical take-off and landing attack fighter. One task is diagnosis of a failed Radar Warning Receiver System Built-In-Test (RWR BIT). The second maintenance task is adjustment of the Vernier/Non-Linear Nosewheel Steering Linkage.

Using the Virtual Maintenance Trainer the trainee can push buttons, throw toggle switches, and turn dials in the cockpit, as well as observe indicator lights, listen for audible tones and measure voltages as part of running and diagnosing an avionics self-test. Simulations of the cockpit panels, buttons, dials, switches, and electrical pins allow the technician to see, feel, and hear the avionics system operations. The linkage adjustment procedure involves manipulating a simulated four-bar linkage through its range of motion, measuring the forces required to move the linkage between two hard stops, and adjusting those forces by tightening or loosening a friction nut on the linkage. The dynamic simulation of the linkage obeys the kinematic and dynamic constraints of the real physical device and allows interactive attachment or detachment from the rudder pedal actuator, and joint friction adjustment. The user can feel the shapes of

the links in the mechanism, as well as the forces needed to move it.

3 Progress on Components of an Advanced Haptic System

An integrated system for advanced haptic interaction needs to have three parts: a part that mechanically interfaces to the user's hand (and/or arm), a part that mediates the interaction between the hand and virtual or remotely located objects, and a part that simulates how the objects will behave when touched. These components are force feedback devices, haptic algorithms, and physics-based simulation, respectively. In Table 1 we summarize our progress on a list of development tasks for advanced haptic systems including the virtual surgical simulator. Next we detail our progress in these areas.

3.1 Advanced Haptic Interface Devices

The Phantom haptic device is a light weight, high bandwidth mechanical interface that allows the user to touch and manipulate a virtual or remotely located object. Haptic fidelity and high resolution are important for conveying a detailed sense of touch and are thus emphasized over kinematic complexity and high force capacity. High fidelity and resolution are obtained by maximizing bandwidth through the design of stiff, lightweight, and low friction structures and transmissions. The Phantom is interfaced to both a PC and an SGI graphics workstation. Haptic algorithms and object simulation code are run on the PC while the graphics workstation is used for 3D visual display.

The Phantom is both an input device and an output device. It can apply forces back to the user along the three translational axes. The position and orientation of the tool or probe mounted to its tip are measured using encoders. Instrumented surgical tools or mechanical tools mounted to the Phantom provide a familiar interface to the user. A powered, two finger device has been designed by the MIT group and tested at BDI. This device can apply a gripping torque to the user to simulate the sensation of grasping an object with two fingers.

Further development of the haptic device is underway and will include piezo-vibration stimulators for ultra-high bandwidth sensation, multi-fingertip interaction, and large workspace.

3.2 Haptic Algorithms

Haptic algorithms mediate the exchange of forces between simulated objects and the user. The two most important haptic algorithms are for contact detection and contact force modeling. Contact detection is used for determining when two simulated objects are touching. Contact force models are used to compute the forces of interaction between simulated objects. Contact

Table 1: Progress List for Advanced Haptic System Development

- *Advanced Haptic Interface Devices:* The haptic device is the mechanical interface that allows the user to touch and manipulate a virtual or remotely located object.
 - Phantom haptic device interfaced to SGI and PC
 - Instrumented medical tool attachments
 - * Debakey forceps
 - * needle holder
 - Virtual medical tools
 - * debakey forceps
 - * needle, needle holder, and suture
 - * scalpel with scalpel holder
 - * hemostatic forceps
 - * intestinal forceps
 - * dissecting forceps
 - * scissors
 - * retractor
 - Instrumented gimbal measures tool position and orientation
 - Powered, two finger attachment designed and tested (MIT Task)
- *Haptic Algorithms:* These algorithms mediate the forces the user feels with the Haptic Interface Device.
 - Two handed interaction demonstrated
 - Two finger manipulation demonstrated
 - Rigid body contact force models
 - Flexible body contact force models
 - Coulomb friction
 - Haptic textures for bumps, sand paper, ridges
 - Haptic textures mapped onto shapes
 - Contact detection between 3D polygonal shapes
 - Contact detection between point or line and flexible tubes
 - Contact detection between point and grid maps
- *Physics-Based Simulation:* Real-time physics-based simulation is used to calculate the behavior of objects, interactions among objects, and interactions between objects and the user
 - Automatic simulation generation for rigid body systems
 - Loadable object shapes from CAD files
 - Programmable bulk properties of simulated objects
 - Compliant flexible skin
 - Compliant flexible tubes
 - Calcified artery
 - Compliant beating heart
 - Coordinated 3D volumetric display and haptic display
 - Suture two tubes together with surgical needle and suture
 - Texture mapped graphics

forces can arise from interpenetration of objects, sliding between objects, or from haptic textures applied to surface geometry.

3.2.1 Contact Detection

The contact detection algorithm determines when simulated objects collide or when the user is touching a simulated object. The algorithms use the geometry of the simulated objects to compute the distance separating them. We use several contact detection algorithms that are optimized for real-time performance and that are tuned to the object model type. For example, we use a linear-time Lin and Canny type algorithm for contact between convex rigid polyhedra. This general contact algorithm is insensitive to the number of polygons on an object. We use a grid-depth type algorithm for point contact on polyhedra with mild concavities and a specialized algorithm for computing contact between points or lines and a flexible tube.

3.2.2 Contact Force Models

The interaction force between two touching simulated objects is computed with a contact force model. We use penalty method techniques in our contact force models. Characteristics such as surface compliance, friction, textures, puncturability, and surface feature resolution are controlled by the contact force model and can be modified to suit the application.

3.2.3 Haptic Texture Mapping

The goal of haptic texture mapping is to permit haptically perceivable textures to be overlaid on basic object geometry. A haptic texture is a force model whose parameters depend upon the spatial location of the haptic device relative to the underlying geometry. Our basic technique is to superpose forces due to haptic textures and forces due to contact with the underlying geometry. The spatial information for a haptic texture is derived from loadable images and can be used to change different parameters in the contact force models. Using haptic textures we have created the feeling of scratchy sand paper, smooth bumps, and discrete ridges on a flat surface. We are currently working on mapping haptic textures to rigid objects and deformable organ models.

3.3 Physics-Based Simulation

Our system uses real-time physics-based simulation to calculate the behavior of objects, interactions among objects, and interactions between objects and the user. Objects can be isolated bodies, mechanical linkages, or more complicated things like tool mechanisms, deformable tissues, or organs. A basic idea of the work is that physics-based simulation allows virtual objects

to move as real objects do; obeying the laws of physics, they feel like real objects when touched, and move realistically in response to touching.

The foundation of our object simulator is software that we developed in previous work that automatically creates highly-optimized dynamic simulations of things that move from simple descriptions of the objects. The physical simulations include material properties that can be changed by the user to tune the feel of the object. For example, we can change the mass of a rigid body, the compliance of its surface, or the coefficient of friction between a surface and the haptic device.

3.3.1 Rigid Object Loader

A general object loader is working that allows multiple 3D objects to be loaded, dynamically simulated, and touched or manipulated. The software includes automatic contact detection, equation generation, and 3D graphics. The shape of these objects can be defined with a CAD file that describes their surface geometry. The geometry is used for both visualization and contact detection. Bulk properties of the bodies like mass, coefficient of friction, or surface impedance can be specified by the user. The haptic tool used for manipulation in the virtual environment is a special kind of simulated object. Its position and orientation are driven by the Phantom. The forces of interaction between it and other simulated objects are computed from the haptic algorithms.

3.3.2 Flexible Tissue

To support the simulation of surgical procedures, we have expanded our simulation library to include prototype simulations of flexible tissue and flexible tubes. At BDI we are using flexible tissue simulation techniques that strive for computational simplicity and speed while providing convincing behavior. One prototype flexible tissue simulation included a planar surface that deformed when pushed or pulled. Rigid objects with varying surface compliance could be positioned beneath the flexible tissue to simulate a palpation task. We also have simulations of whole and severed hollow tubes. The tubes move when touched and the surfaces deform when the tubes are poked or plucked. By varying the radii of the tubes with time we can simulate the look and feel of a pulsing vessel. The flexibility or surface deformation of a flexible tube can be tuned to best approximate the feel of biological material.

4 Commercialization and Related Work

BDI is developing and selling products that are closely related to the ARPA funded work.

- BDI is marketing Tangible Reality(TM), a turn-key virtual environment system that includes visual images, sound, and touch. The system consists of a force-feedback device, a real-time simulation computer, a physics-based simulation environment, simulated objects, real-time 3D computer graphics, real-time 3D sound effects, and networking. Early versions of the product will support standard sets of physics-based simulated objects. Later versions will support user-defined objects and deformable objects. This product provides an initial channel for commercialization of results from the proposed research. For example "palpating in" and "haptic texture mapping" are obvious candidates for enhancing the product as we understand and develop them.
- We delivered a special version of Tangible Reality designed for training surgical procedures. This version of the system supports two-handed anastomosis. Thomas M. Krummel, M.D., Chair of the Department of Surgery at Penn State's Hershey Medical Center is building "The Virtual Hospital." The VR Anastomosis Simulator is a key feature in his concept for reducing the cost and improving the quality of medical teaching.
- We delivered to Digital Media Associates a system that allows the user to touch, poke and pluck a simulated, beating heart with medical instruments. The user can touch a 3D volumetric display of the heart with medical instruments mounted to Phantom force-feedback devices. The user actually feels the heart whenever the physical tool "touches" the floating 3D image because the visual and haptic images of the heart are coincident in space. An audible heart beat is synchronized with the visual and haptic heart displays. We have plans to continue this joint project to combine force feedback haptics, dynamic simulation, and 3D volumetric displays.
- We have developed a joint project with Musculographics Inc. to develop a trainer for wound debriedment for the U.S. Army at Fort Bragg. Initial phases of this project involve development of a leg and leg wound simulator with haptic tool interaction for training. BDI will provide the haptic components of this project. A version of this simulator is included in the FY97 P.O.M.
- Nissho Electronics Corp. is a Japanese distributor of the BDI Tangible Reality System.
- In an effort to demonstrate the applicability of VR technology to aircraft maintenance training we developed the VR Maintenance Trainer for the Joint Advanced Strike Technology Program. This project significantly leveraged our ARPA-funded project and offers other military applications.

5 Conclusions

Two years into the "Look and Feel" project we have assembled much of the basic technology required to build integrated haptics systems that allow the user to see, hear, and touch simulated objects. These worlds can include rigid body, multi-link, dynamic objects, deformable organs, and articulated tools that can be manipulated by the user. Haptic algorithms detect collisions between simulated objects and compute contact forces between them. Force-feedback devices convey the forces of interaction to the user. Physics-based simulation computes the response of simulated objects to external forces and 3D computer graphics display the visual scene to the user. Using these component technologies we have constructed prototypical advanced haptic systems that allow the user to perform procedures such as surgical anastomosis, heart palpation, and aircraft maintenance. While these prototype demonstrations do not replicate all the detail found in real surgeries or training environments, we believe they take a significant step towards the goal of building useful virtual training environments.

In the near term we will continue to work towards the goal of producing a surgical simulator for training or evaluating medical personnel. To this end we will focus on making the interaction with biomedical objects more realistic and natural. We will add performance measurement and display features to the simulator. These recording, display, and playback features will help the surgical trainee review and improve surgical technique by providing quantitative measures of needle placement accuracy, force level, and tissue damage. Once these features are working, the user will be able to practice important elements of surgical anastomosis, including proper handling of the medical tools, techniques for grasping tubes, and suturing techniques including proper needle orientation, needle placement, puncture forces, suture spacing, and suture tightening. We will incorporate new features into the simulator such as haptic textures, and a set of re-configurable organs that allow the user to tune the look and feel of the organ to suit the application.

Additional performance from virtual training applications will likely require more complex object simulations and contact detection software. We will continue to optimize and refine our contact detection algorithms, dynamic simulation techniques, and computer graphics software so that we can do more with the computers we currently use. In addition to making it possible to create more realistic virtual environments, more efficient software will allow us to create useful low-end haptic systems that run on inexpensive computers.