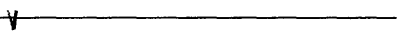# A Graphic/Photographic Arthroscopy Simulator

by

Pascal Roger Chesnais

Bachelor of Science
Hofstra University
1985

Submitted to the Department of Architecture
in Partial Fulfillment of the Requirements of the Degree of

Master of Science in Visual Studies

at the Massachusetts Institute of Technology

June 1988

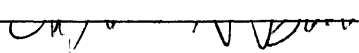©Massachusetts Institute of Technology 1988

Signature of the Author _____

Pascal Roger Chesnais
Department of Architecture
February 9, 1988

Certified by _____

Andrew Lippman
Lecturer, Associate Director Media Laboratory
Thesis Supervisor

Accepted by _____

Stephen A. Benton
Chairman
Departmental Committee on Graduate Students

1

A Graphic/Photographic Arthroscopy Simulator

by

Pascal Roger Chesnais

Abstract

This thesis describes the design and implementation of a computer based training system for arthroscopic surgery. The goal of this system is to enhance a doctor's spatial visualization of the procedure by primarily addressing the navigational component of the learning task.

Arthroscopy is used both for diagnostic and surgical procedures in the knee and other joints. In the arthroscopic procedure, a viewing probe is inserted into the knee (or other joint) from one location, and surgical tools are inserted from others. The surgeon performs procedures that vary in complexity depending on the operation being performed, while limited to the fish-eye view of the anatomy provided through the viewing scope. Surgeons generally practice this procedure on artificial knees that replicate the anatomical features of the knee.

This system uses an instrumented arthroscope providing positioning information to direct a computer graphic work station. The computer graphics generated are used to augment the photographic images that originate from the arthroscope.

The physical and functional characteristics of the graphic/photographic arthroscopy simulator are described. Principles relevant to the design, construction and application of the system are given, and present and future applications are discussed.

Contents

List of Figures

Chapter 1

Introduction

This thesis explores the design of a computer based training system for arthroscopic knee surgery. The goal of this system is to enhance a doctor's spatial visualization of the procedure. Arthroscopy is used both for diagnostic and surgical procedures in the knee and other joints. In the arthroscopic procedure [1], a viewing probe is inserted into the knee (or other joint) from one location (portal), and surgical tools are inserted from others[2] (Fig. 1.1). While limited to the fish-eye view of the anatomy provided through the viewing scope, the surgeon performs procedures that vary in complexity depending on the operation being performed. These
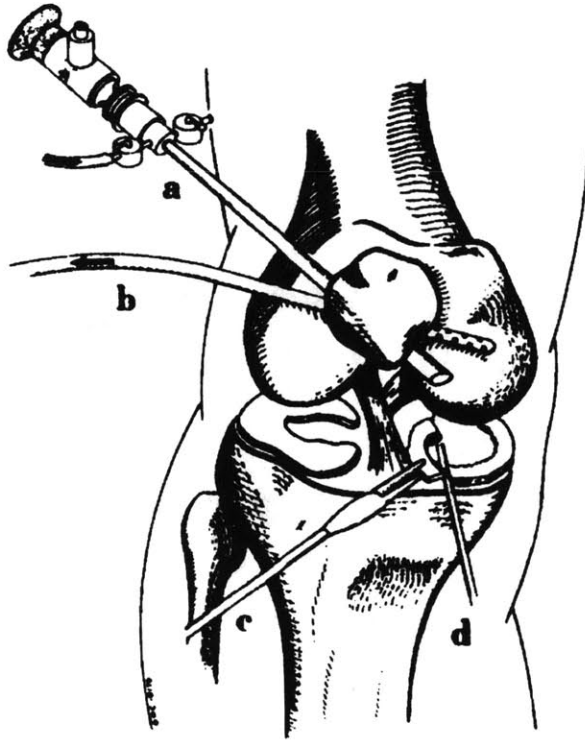
Figure 1.1: Arthroscopic surgery for removal of torn knee cartilage involves making up to four tiny incisions for the (a) arthroscope, (b) irrigation tube, (c) "grabber" and (d) knife. (source: MGH News, April 1980).

procedures are difficult to learn. The views presented to the user do not contain visual references which would allow the doctor to orient himself to the external world.

The benefit of such procedures is that only small incisions are needed, thereby reducing the recovery time for the patient. The alternative is conventional open surgery[3] in which incisions of up to 6 inches are made in the area of interest, necessitating long recovery and resulting in major discomfort. Because of this, arthroscopy is used with increasing frequency (Fig. 1.2 from "Peanuts" by Charles M. Shulz). It is seen as a means of
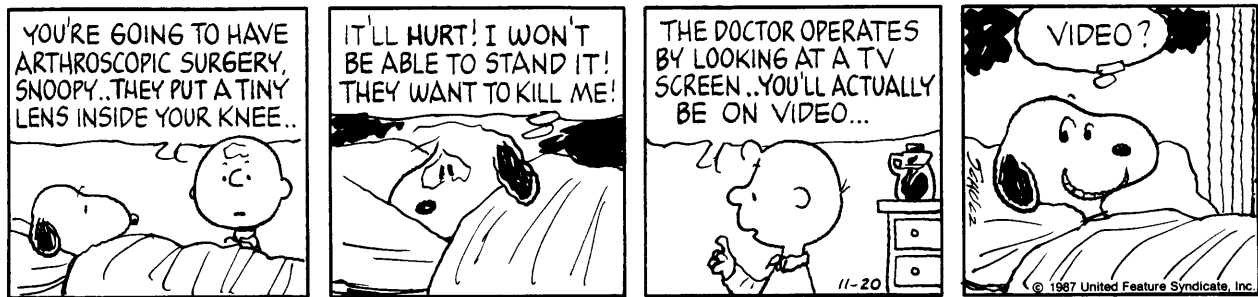
Figure 1.2: Simple description of arthroscopic surgery (©1987 United Features Syndicate/Reprinted with permission).

remedying sports related injuries quickly. In the case of professional sports, this is of the utmost importance[4]. However, this procedure is not without its critics[5]. For instance, debris from meniscus removal, a common arthroscopic procedure, can be left behind undetected. This may serve as a catalyst for yet further injury.

A serious problem for novice surgeons is that of constructing accurate mental models of the joint in question from the distorted arthroscopic image. For example, even the basic operation of locating an instrument inserted through another portal can be difficult. The arthroscope view is a two dimensional view of the scene distorted by the lens, and is not necessarily oriented correctly. Objects of interest can easily be lost behind parts of the joint or be out of view.

Students generally practice on artificial knees, cow's knees and ultimately, cadaver knees. Their main objectives are to learn surgical procedures given limited visual aids, and general navigation skills for manouvering within the knee.

This thesis addresses primarily the navigational component of the learning task. The goal is to combine visual information already provided by the arthroscope with a computer generated model of the joint in question. This computer graphic is intended to augment the video display and potentially provide alternative views which aid in probe manipulation.

We augment the artificial knee used in training with a computer graphic model. The graphics, which are generated by a high quality computer system, are coordinated with the arthroscopic image by means of an instrumented arthroscope that acts as a joystick for the display system.

We intend to use the computer generated graphics in the following ways:

- to provide secondary views of the joint which show the exact instrument position.

- to augment the image in the arthroscope with anatomical features not present in the mechanical knee simulators.

- to provide a computer generated locating device which can be manipulated by an input device, other than the instrumented arthroscope, adding to the interactivity of the system.

- to allow data from other medical imaging systems to be integrated with the video from the arthroscope (i.e. MRI, CT data).

The remainder of this document is split into four sections. The first describes the design considerations of the system. The following section is devoted to the experimental environment and implementation of the project. The last two sections focus on possible enhancements and concluding remarks.

Chapter 2

Design considerations

Our simulator aims at two subject areas, in which we hope will aid doctors in learning this procedure quickly:

- Arthroscope Manipulation and Navigational Aids - our system must be able to clearly communicate the scope's orientation, position and motion so that the student can see what motions results from his actions.

- Simulation - our system must be able to generate situations which do not exist in the mechanical knee.

2.1 Arthroscope manipulation

The first problem encountered by arthroscope users is determining the orientation of the viewing scope. Since the view from the probe is circular it is difficult to determine the scope's orientation from the scene without actually moving the scope (Fig. 2.1). We would like to provide visual cues to help orient the user. To do this, part of the information being provided by the instrumented arthroscope to the computer is the probe's rotation about the axis of insertion. Using this information it is possible to display the orientation of the probe with respect to some external reference (i.e. bottom of the camera) at all times by merging it with the video from the probe.

To allow the widest possible view with the least amount of motion, the arthroscope has an offset of 30 degrees (Fig. 2.2). This allows a user to look around an area of interest solely by rotating the probe. This minimizes tissue damage resulting from manipulating the arthroscope. However novice users have difficulties navigating since the center of view is not the direction of motion. Intuitively, one would expect the center of the screen to correspond with the direction which one is facing. In the case of the for-
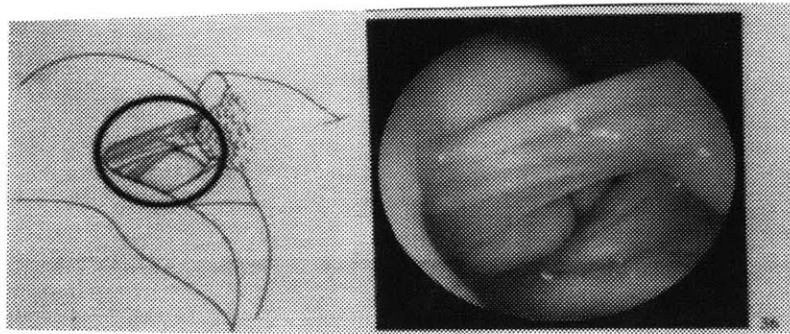
Figure 2.1: View from an arthroscope (source: Arthroscopy of the knee joint page 45).

ward viewing arthroscope typically used in this procedure, the direction of motion is at the bottom of the scene. To alleviate any possible confusion, it is desirable to overlay a cross-hair on the video, marking the direction of motion. This would not be of much use in the case of a rear-facing arthroscope.

The arthroscope can be thought to turn or move as if on a pivot. When properly oriented, to move up, one pushes down on the opposite extremity of the probe (Fig. 2.3). However since the probe can be rotated, the "rules" the user relies on for manipulating the probe change based on the
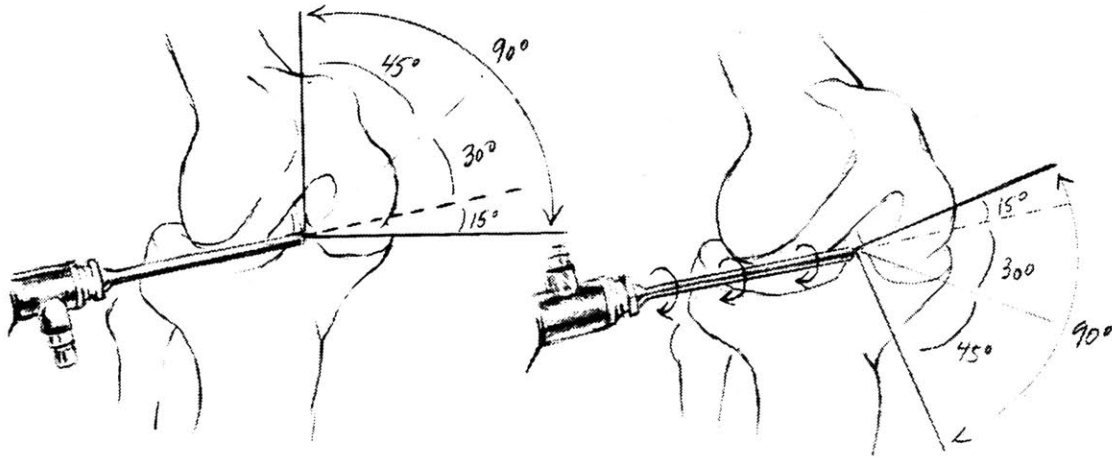
Figure 2.2: Rotating viewing probe gives wide view.

probe's orientation. For example if the probe is rotated 180 degrees, such that the view is "upside down" relative to the user, the motion needed to manipulate the probe is completely reversed. To move up the user must lift the arthroscope's extremity up. Confusion arises from the continuously changing rules needed to manipulate the probe. In the simulator, different views of the procedure are presented to the user. "Seeing" where the probe is, in a manner independent of the probe's rotation, gives the user a stable reference when performing manipulations. In our system three orthogonal cross sectional views of the knee are superimposed onto the view from the arthroscope, giving a bird's eye view of the procedure. The probe's posi-

13

tion is drawn with major "landmarks", such as major bone structure, for the doctors to orient themselves. It is believed that this feedback aids in quickly learning the manipulations required to properly move the arthroscope around in the knee.

2.2 Navigational aids

The same bird's eye views mentioned earlier can be used to show what objects lie in the path while in navigating through the knee. Since we are using a mechanical knee, it can be accurately modelled by the computer. Objects that are easily recognized through the arthroscope can be used as "landmarks" for maneuvering through the knee. For our system, we use a crude representation of the knee(Fig. 2.4), with major bone structures used as landmarks. However, static images, drawn from medical databases, or an artist's rendition of knee anatomy can be used as a richer source of positional information. This would indeed be desirable, as doctors do not generally have major bone structures in the field of view to aid them in navigation.
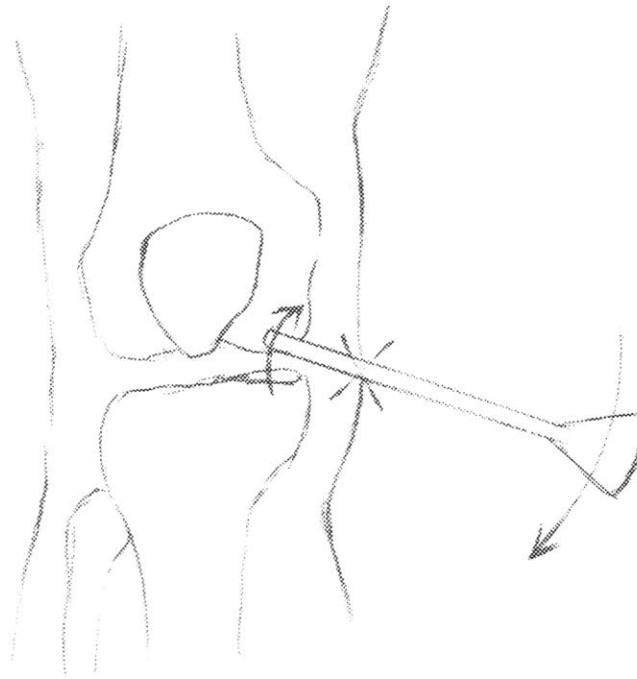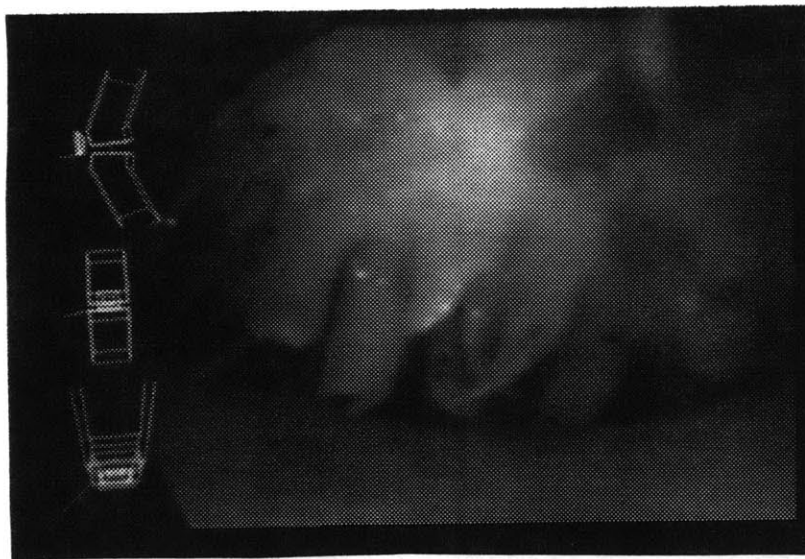
Figure 2.3: Pivoting action of arthroscope

Figure 2.4: Photograph of navigational information overlaid on probe's view

2.3 Simulation

In simulation, we are concerned with generating objects not present in the knee, such as floating debris that doctors encounter during surgical procedures. These are unavailable in the practice knee since it lacks the fluids that are used in the real surgery. This requires the creation of views that will be superimposed on the video from the arthroscope. When generating computer graphics using the instrumented arthroscope, it is possible to think of the arthroscope as a moving camera. The information we get from this instrument allows us to know its position within the mechanical knee at all times. The rendering software can use this information to render the image from the "current" vantage point within the knee.

In the simulation portion of our simulator, we are concerned with coordinating the views from the arthroscope video and the computer generated database. The views from both must be visually consistent to superimpose properly. Ideally we would like to pre-distort the computer generated image simulating a view through a fish-eye lens, or even undistort the video image, but the computer graphics techniques[6,7] necessary are too complex for the type of graphics engine we will consider using for our simulator.
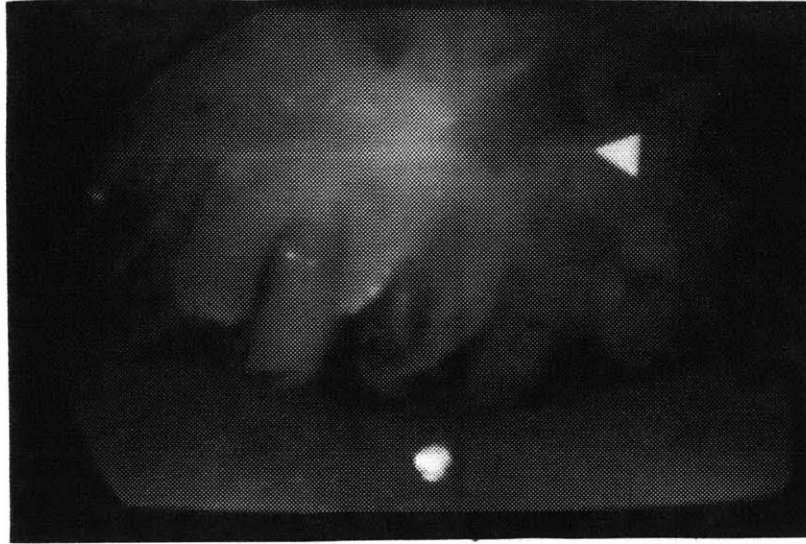
Figure 2.5: Computer generated objects mapped with probe view.

An adequate substitution for our simulator is to use simple perspective projections[8].

The computer generated objects that we use for our simulator need not be complicated. But their motion must correspond to the "camera" motion of the arthroscope. We generated a simple generic object representing floating debris, and placed it near the front of the probe (Fig. 2.5) in our simulator. This object's presentation with the video image consistently tracked with the motion of the arthroscope.

2.4 Object location and tracking

In addition to simple objects added in the scene, a locator (Fig. 2.5 wedge shaped object) was added to allow the student or teacher to point out an object of interest. The locator is controlled using an input device in addition to the instrumented arthroscope. Once the locator object is positioned at an area of interest, its movement will be directed by the instrumented arthroscope.

Chapter 3

Experimental Environment

The graphic/photographic arthroscopy simulator is composed of four major components: an instrumented arthroscope, a practice knee, a computer graphics engine, and a video/graphic synthesizer (Fig. 3.1). In a normal arthroscopy training system, the user would have only a practice knee and arthroscope to work with.

The instrumented arthroscope is the principle means of user control in our system. It is also the primary source of visual information for the user. The computer graphics engine provides supplementary visual information to the user, which aids the student in learning how to manipulate the arthroscope. It will also generate objects for the simulation of the interior of the

knee. The video/graphics synthesizer is the crucial element in the system. It optically overlays the computer graphics with the video, presenting the user with only one place to concentrate during the procedure.

3.1   Instrumented arthroscope

The arthroscope used for our simulator is a 4mm 30 degrees offset forward looking probe with a 83 degree field of view angle (Fig. 3.2). The arthroscope consists of both a fiber optic light tube, and a viewing tube with a miniature fish-eye lens. Rear-viewing arthroscopes are also common, and are difficult to use since one can not see in the direction of travel. Though we did not explore the use of rear-viewing arthroscope for our system, it owuld be desirable to do so.

The arthroscope is typically connected to a high powered light source (200 to 300 watts) via a flexible fiber-optic tube to illuminate the scene. The arthroscope can be attached to a video camera via an adapter which clamps to the eye-piece. The color video camera used in our simulator generates a NTSC signal which we can merge either electronically or optically with the images generated by the graphics engine. Typically, in the surgical
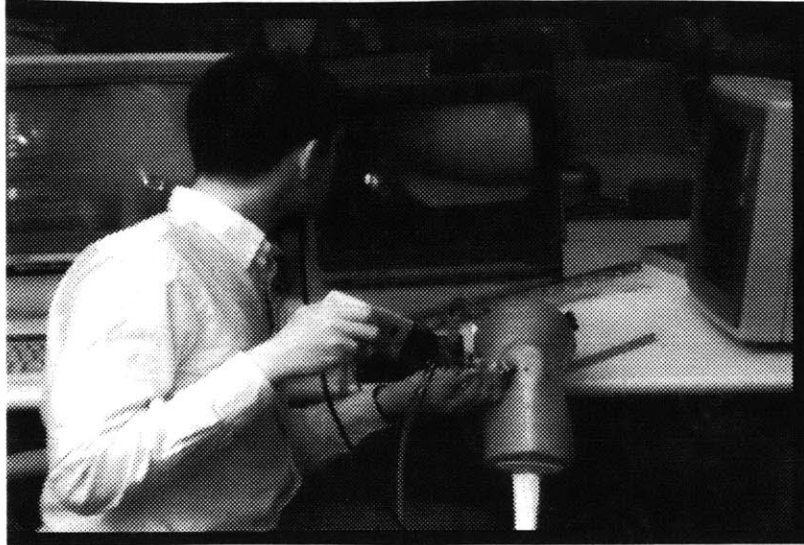
Figure 3.1: The graphic/photographic arthroscopy simulator.
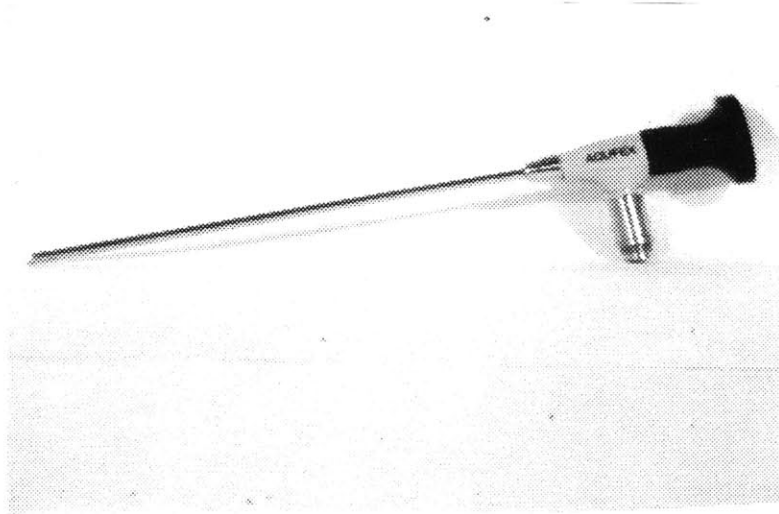
Figure 3.2: Acufex 4mm 30 degrees arthroscope.

Four Degrees of Freedom
Positioning Information Returned by Instrumented Arthscope

penetration

rotation about axis

tilt angles
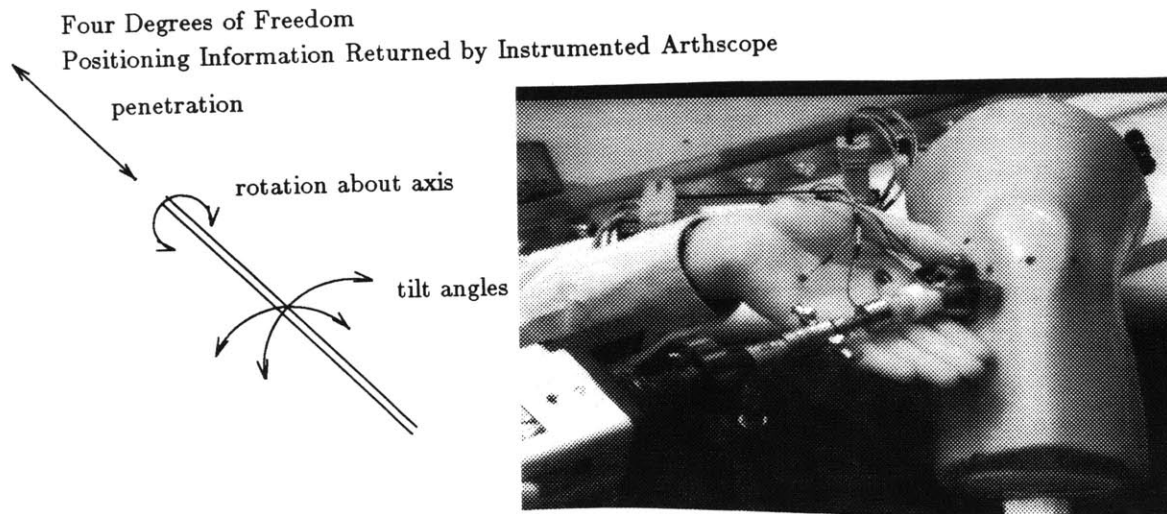
Figure 3.3: Four degrees of freedom instrumented arthroscope.

environment, the signal is viewed on a monitor and recorded for archival

purposes.

The arthroscope is fitted with a gimbal which allows one to know the

position of the viewing probe[9] with four degrees of freedom (Fig. 3.3).

Information returned by the probe includes depth of insertion, rotation

about axis of insertion, and pivot up and down about the point of entry.

Rotation about the axis of penetration is determined by a rotary vari-

able differential transformer. The other positions are determined by hall

effect sensors. The sensors produce voltage readings giving their position

with a high degree of accuracy. These analogue measurements are con-

verted to digital readings via an analogue to digital converter (ADC). Once the probe is calibrated, the ADC reading can be converted simply to give angle and position measurements.

3.2 Practice knee

As in most arthroscopy training systems, a mechanical practice knee is used. These knees come with portals for the arthroscope and other instruments (Fig. 3.4). Practice knees can be ordered with common abnormalities, allowing doctors to practice procedures that they can expect to find in real practice. Every effort is made to make these practice knees as anatomically correct as possible. Usually all that is missing is body fluids, and some tissue structures that are too difficult to model.

The benefits of using such a knee include having fixed portals for the probe and instruments, and the ability to generate a standard database of the knee used. This is important for knowing exactly where the point of entry for each instrument is, and allowing us to know the location of obstacles the student is likely to encounter.

In addition, the artificial knee will provide us with the realistic anatom-
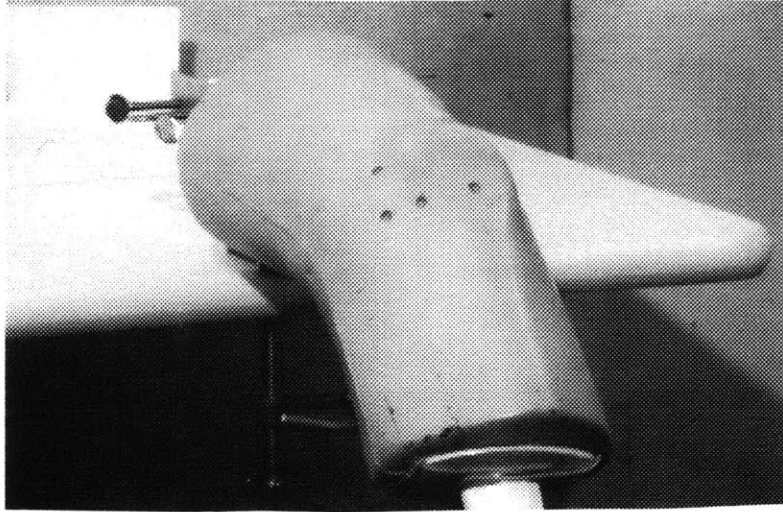
Figure 3.4: Practice knee.

ical views for our simulator. The views from within these model knees are more realistic than we can hope to generate with current computer graphic techniques (Fig. 3.5), due to the complexity and richness of the image.

3.3 Computer graphics engine

The graphics engine is used to provide supplemental visual information to the images originating from the viewing probe. The graphics engine for the simulator must be able to render images in as close to real time as possible. The time interval between frame updates must be small enough so that
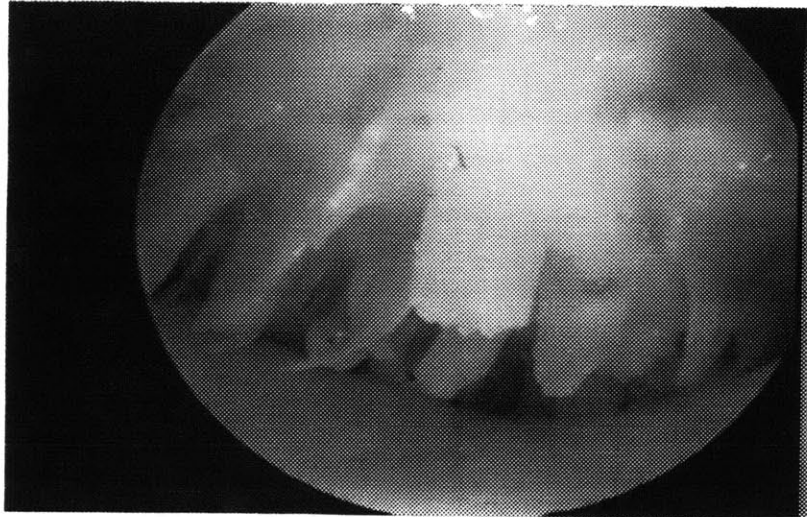
Figure 3.5: View from within practice knee.

the delay between frame update is barely perceptible. The graphics engine must be capable of being directed by the instrumented arthroscope, and able to render many different views at once from different types of image databases.

A great deal of effort has gone into implementing many three dimensional rendering algorithms in hardware. Today there exist many low cost, graphics engines that produce high quality output.

The HP-9000 computer work station is the link between the graphics engine and the instrumented arthroscope. It is a general purpose work station built around the Motorola 68020 processor. The work station is equipped

with a HP Renaissance graphics engine. The Renaissance generates high resolution (1280x1024) non-interlaced images. The Renaissance is capable of adequately generating both the two and three-dimensional graphics in real-time that are needed for our system.

3.4 Graphic/video synthesizer

Overlaying the video image with the computer generated graphics in real-time is critical to the success of this system. Since the graphics engine (HP Renaissance) generates video signals which are incompatible with the video signals generated by the viewing probe's camera, we can not simply mix the two images. There are two types of solutions for dealing with incompatible video signals - one optical, the other electronic.

In the case of electronic synthesis it is possible to purchase a standards conversion box which will reduce the 1280 by 1024 resolution non-interlaced video to NTSC resolution interlaced video. This unit essentially has a frame store and processor which converts the high resolution video to NTSC. Unfortunately much information is lost in the process of filtering down the high resolution images. Another possibility is to convert the NTSC resolution

image up to the same resolution as the graphic image, and electronically merging them. Such units need to be custom built and are currently very expensive. Alternatively it is possible to point a second NTSC camera at the high resolution monitor with the computer graphics, and mix the two signals with a traditional television switcher. The problem with such systems is twofold: the high resolution graphics are degraded, and there is a synchronization problem which, without correction, will result in "roll bars" in the image.

The optical solution to the problem is to use a half-silvered mirror to merge the two images. Such a solution has been applied previously [10,11,12]. Use of the mirror enables one to simply merge two images; both inexpensively, and with no loss of resolution. The images are merged together by placing a mirror, which is both partially reflective and transmissive, at a 45 degree angle, in between two monitors which are perpendicular to each other. The viewer sitting in front of one monitor sees the image from the other monitor superimposed onto the first monitor's image (Fig. 3.6). However, such a setup is bulky and difficult to calibrate properly. Calibration of this system entails aligning the two monitors, which are similar in size, such that the views are in registration with each other.
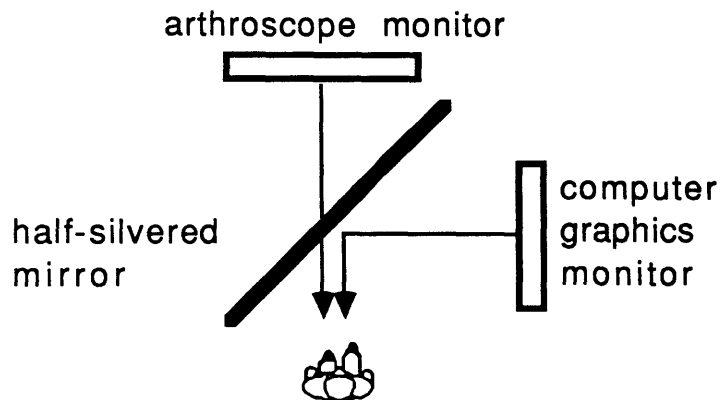
Figure 3.6: Using a half silvered mirror as a graphic/photographic synthesizer

Minor adjustments can be corrected with the computer when generating the graphics. The human eye can accommodate slight differences in view distances.

3.5 User Controls

In addition to the instrumented arthroscope the work-station offers additional user input interfaces, such as a graphics tablet, mouse, knob box, button box and keyboard. These input devices provide us with a means of "pointing" to objects of interest within the scene. Each of these devices

has its advantages. Of particular interest is the knob box with its rotary controls which can arbitrarily be configured to represent complex object transformation operations simply. Ease of use is essential in this system, as the user must focus his attention on the task being performed.

3.6 Software Environment

Our system was developed under the UNIX system V time sharing system. All programs were developed with the 'C' programming language. The computer graphics generated in this project used the Rendermatic [13] graphics software package developed by the Computer Animation Research Group at the Media Laboratory. This programming environment allowed for quick development of our system. Most of the essential features of the simulation portion of the project could be implemented by basic graphics operations. Probe positions were translated to simple camera positioning commands in the rendering pipeline. As an adequate substitution for real anamorphic processing needed to duplicate the distortions caused by a fish-eye lens we used perspective projections supported in the package. This package was adapted to take advantage of the Renaissance hardware

as much as possible. Other computer graphic programming for this project used the Hewlett Packard Starbase graphics package.

3.7   Implementation description

The instrumented arthroscope is connected to the HP 9000 computer work station via an analog to digital converter (ADC). The main loop of all our programs continually polls the position of the arthroscope and then performs various tasks.

Two programs were developed to implement the various design issues discussed in this thesis. The first addresses the arthroscope positioning component, the second deals with simulation and other manipulation issues. This reflects more the order of software development of this project rather than any particular implementation limitation issues. Both programs are in a continuous loop, receiving probe position information and updating the display accordingly.

The first program used HP Starbase uniquely; this was done to take advantage of a known stable programming environment. Starbase is a device independent programming library which is optimized for specific hardware.

A wire frame cross sectional database of the major bones in the knee (femur, tibia, and patella) was entered by hand. Our use of bones was mainly out of ignorance of what one really sees through the arthroscope. The wire frame was derived through the use of medical books, but is not to scale with the practice knee we use. The idea was to give the user a rough idea of how the probe is moving through the knee. To accomplish this a line representing the probe is drawn over the cross section. The probe orientation can be quickly determined by using a set of transformation matrices[14] (Fig. 3.7 the first view is a translation into the knee, then a rotation representing the pivot, and finally a translation to the point of entry). These transformations are in a device independent system allowing objects to be scaled to any database used. Though the cross section is being continually updated with the probe data, it is essentially static. It can be replaced easily with something more appropriate. Only the probe position would need to be updated. Three orthogonal views are presented to the user; this is accomplished by treating these views as graphic view ports[15], each with a different eye view point.

The second program was developed later using the Rendermatic graphics package[13] as well as HP's Starbase graphics package. This occurred
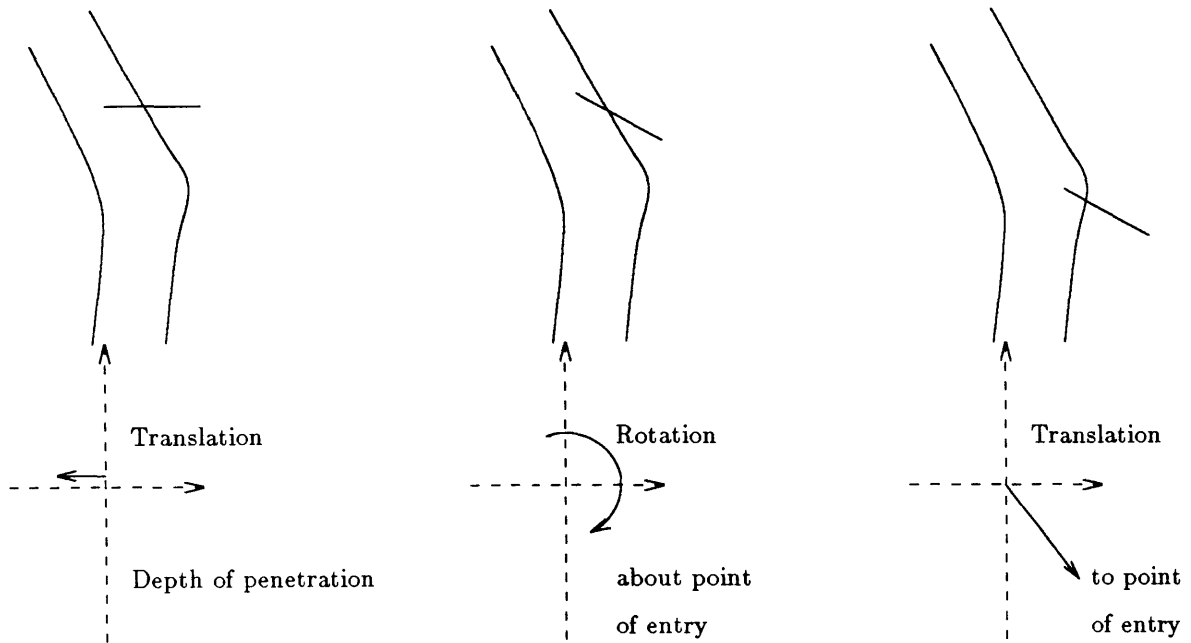
Figure 3.7: Probe position is determined by a series of transformations.

since we use both the HP Renaissance graphics engine, and the accompanying overlay planes (which can be thought of as a separate frame buffer).

The overlay plane was dedicated to navigational aids, such as the cross hair marking the direction of probe motion and references to the external world for orientation. The cross hair was a static marker, needing to be drawn only once. Its position was determined experimentally with the half-mirror in place. The external reference used was the floor, as this would be a quick and easy reference that the user would understand. However drawing functions in the overlay plane were found to be extremely slow, so updating occurred only when a significant change of probe rotation occurred (every

two or three degrees).

The simulation employing Rendermatic was used to create simple objects with the HP Renaissance. These objects were represented as a list of polygons[16] which is common in computer graphics. Simple objects of up to 200 polygons (this depending on size) can be rendered without major delays. However the use of real medical data (MRI,CT scans) would be prohibited by the inability to render large quantities of polygons, unless we first filter the data to simplify the structure.

The probe position is used to determine the eye view point for the rendering of the objects. Probe offset is taken into account, while the optical distortion is emulated by a wide field of view with perspective projection. The matching of the view from the probe with the view from the screen was accomplished by first physically moving the two monitors so that the centers matched, and then translating the rendered view for fine tuning.

Chapter 4

Future enhancements

4.1 Graphic Photographic Synthesis

In our system we have explored the merging of images from the arthroscope

and the computer graphics system optically or electronically, however this

synthesis does not occur in the data domain. In the long run it would desir-

able to do real-time digital image processing [17], to process the video from

the viewing probe with the images produced by the graphics engine. Such a

system will need to be able to acquire the video images and process them at

rates beyond the capability of currently available hardware. It is, however,

foreseeable that such a system will exist. Generally, we are interested in two

types of image manipulation for our simulator. The first consists of eliminating the distortion of the fish eye view from the arthroscope and mapping the digital image onto a 3D database. Real time processing of the computer graphics to simulate the view of the arthroscope is also performed.

4.2   Medical databases

In our simulator we used only a medical database of bones inside the knee. This skeletal database was entered by hand by Donald Stredney at Ohio State University. However there exist other sources of medical data which can be enhanced and then manipulated by the computer. Medical imaging has progressed dramatically, and high quality three dimensional data is now available , such as magnetic resonance imaging (MRI or NMR)[18], and computer aided tomography (CAT) scans. Already such data enjoys wide spread applications in surgical planning[19,20], radiation treatment[21], and prosthesis design[22,23]. Systems have been developed that manipulate these databases in meaningful ways, such as object segmentation, so that soft tissue and bone structure are displayed separately[24,25]. In our simulator we would use such data to aid in navigating through the knee. Surgical

textbooks [26] make extensive use of cross sections of the area of interest to describe the surgical procedures (Fig. 4.2). Similar cross sections can be generated from finely sampled MR data, in planes that are perpendicular to the motion of the arthroscope. From the cross sectional slices we can build three dimensional objects for our simulator, though it is not evident that this is the best presentation for doctors.

Since the different tissues are identifiable in the data by the computer, it is possible to colorize them in a manner which could aid in manipulating the arthroscope. For example, pliable tissue could be color coded in one color allowing doctors to know that the arthroscope could squeeze through that area. Sensitive areas could be colored differently as a warning to the surgeon. The cross section orientation could be positioned in a manner to convey the easiest passage for the arthroscope.

4.3   Additional positioning devices

Although our instrumented arthroscope provided adequate data for our system it is perhaps not the best positioning device for the task, as it fails to compensate for the flexibility of the skin. Other position sensing devices
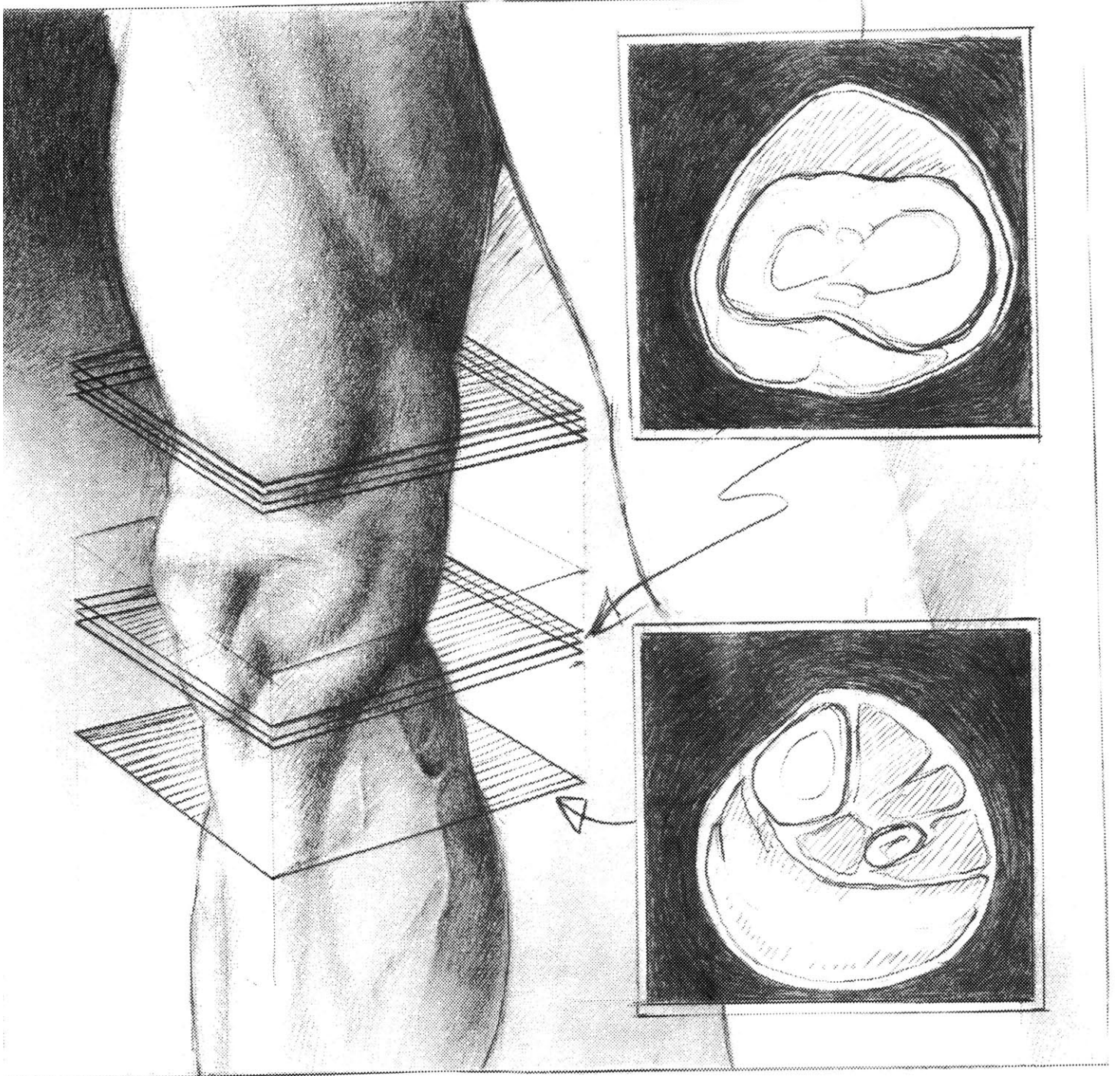
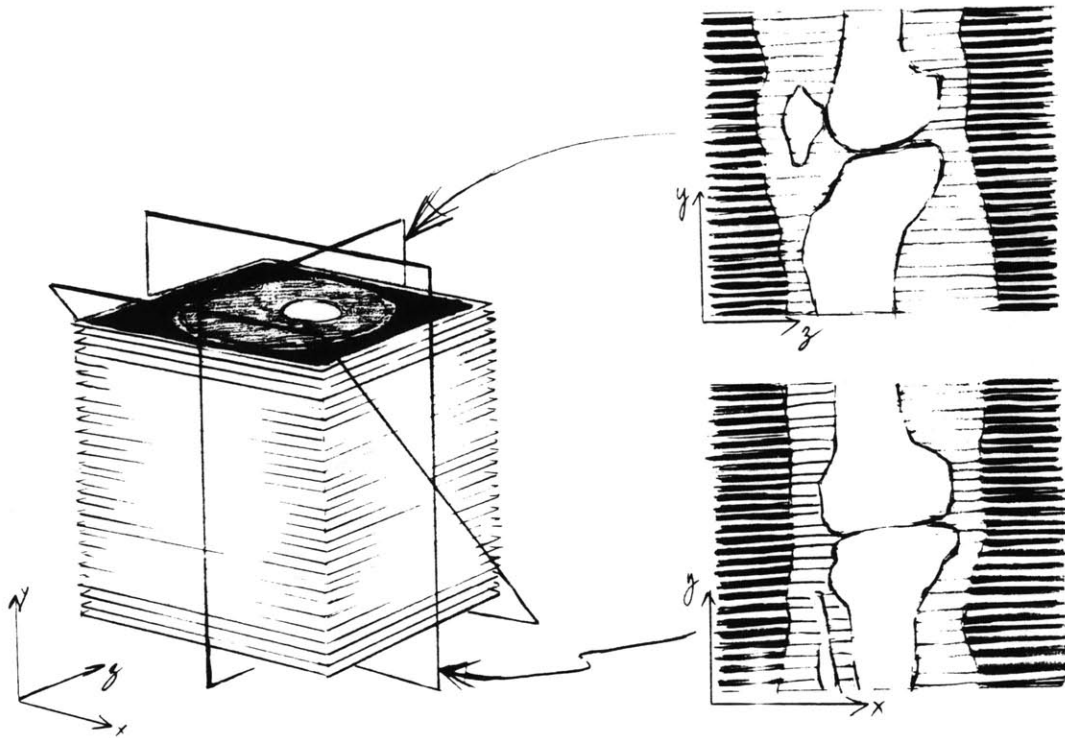Figure 4.1: Anatomy of the knee joint.

Figure 4.2: Possible cross section derivations.

exist, such as the Polhemus navigation [27] device which return the absolute position of the arthroscope from the sensor. The sensor can be mounted in our system on the back of the video camera. With this supplementary information it would possible to account for the stretching of the skin. This would make for a far more accurate system.

4.4 Instrumenting surgical tools

In this thesis we developed a training system around an instrumented arthroscope. Our primary objective was to teach the manipulation of the

probe. However once other tools are instrumented as well, this opens the system to a new set of teaching possibilities which are procedure specific. For example it would be easy to simulate surgery by allowing computer generated objects to be "cut away" with one tool, and clean up the area with another. In addition since the objects are computer generated, the computer can keep track of all the debris, a source of complications of arthroscopy, and inform the student as to whether or not the procedure was successfully completed.

Chapter 5

Conclusion

In this thesis we have designed and implemented the first stage of a training system for teaching arthroscopic surgery. This system aids doctors learning the procedure by using computer graphics to supplement views from the viewing probe. The key to our system is the instrumented arthroscope, which allows us to accurately determine the position of the viewing probe at all times. This also makes possible the merger of computer graphics with the video from the viewing probe. The computer graphic techniques required for this system, in general, are not complex. The artificial knee provides the realistic views needed for the doctors to learn procedural aspects of arthroscopy. The training system augments the views from the

40

probe in a manner that facilitates the manipulation of the arthroscope. The simulation aspect of our system is also explored. Given that we use a mechanical knee, it was not difficult to scale and distort the computer generated graphics to match the view from within the knee. The ability to create computer generated objects opens the simulator to a wide variety of training possibilities that are not available on a mechanical knee training system alone. However there are still limits to the types of training situations we can create. For instance, though it is possible to create a simulation of cutting away at a computer generated object, and floating objects, it is doubtful that one could generate the look of fluids, such as blood, which is not uncommon in this procedure. Our system differs from other computer aided medical system in that it is an interactive training system, providing immediate feedback to the user, rather than simulating a procedure and returning a result later. In general, medical imaging is making substantial progress. There are very few medical procedures which would not benefit from a training system like ours.
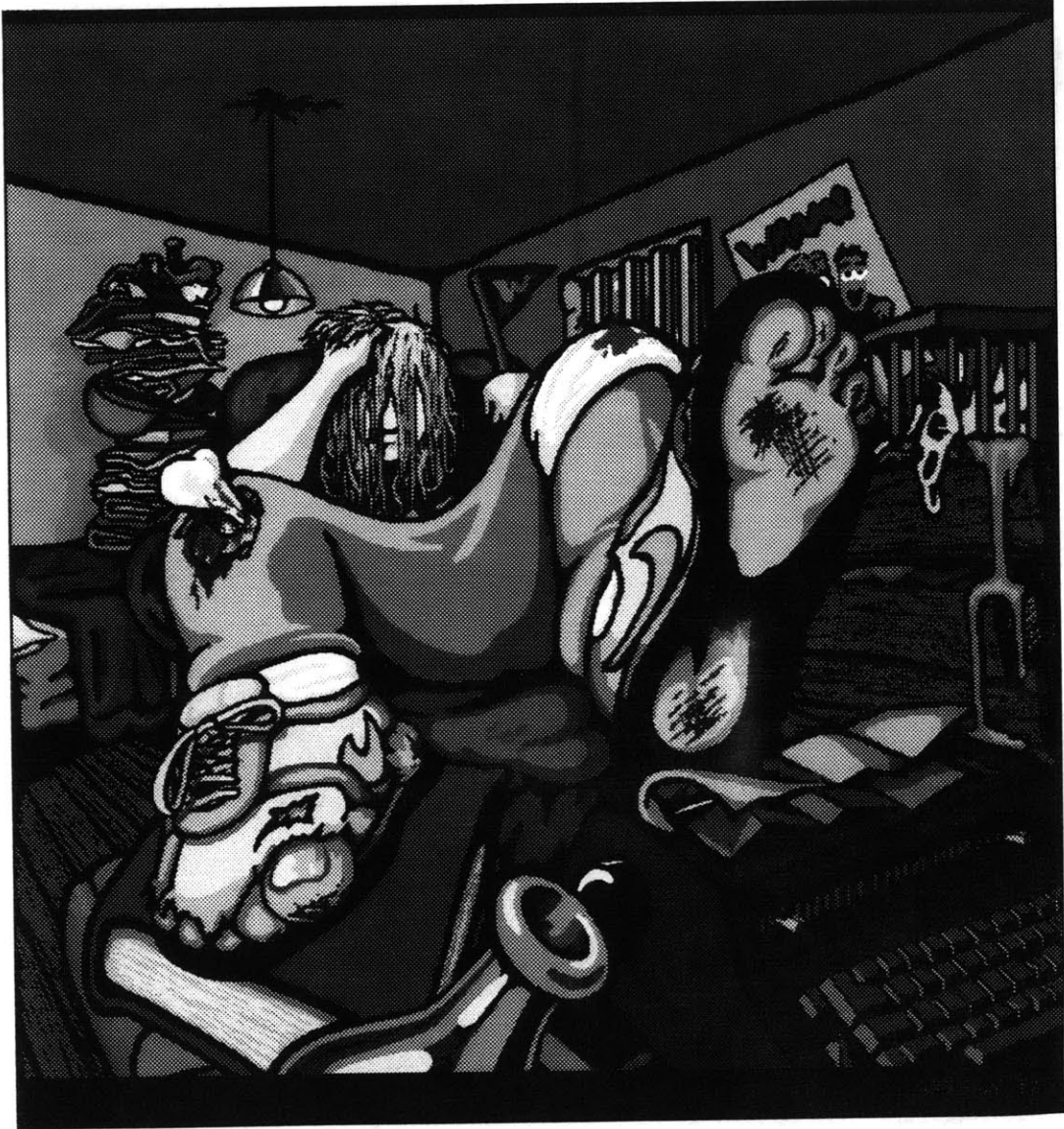
Acknowledgments

Figure 5.1: "The Runner" by Bob Sabiston

Bibliography

[1] Hans-Rudolph Henche. *Arthroscopy of the Knee Joint.* Springer–Verlag, 1978.

[2] Dinesh Patel and Paul Denocourt. Arthroscopic surgery: coordinating portals for operative arthroscopy. *Contemporary Orthopaedics,* 10(1), January 1985.

[3] I. S. Smillie. *Injuries of the Knee Joint.* E. & S. Livingstone, 1970.

[4] Don Lessem. Atheletes try 'microsurgery' on shoulders. *Boston Globe,* March 18 1985.

[5] Arthoscopy offers innovative method of knee repair. *Harvard Medical Area Focus,* September 1980.

[6] Mark Holzbach. *Three-Dimensional Image Processing for Synthetic Holographic Stereograms.* Master's thesis, Massachusetts Institute of Technology, September 1986.

[7] Michael Teitel. *Anamorphic Raytracing For Synthetic Alcove Holographic Stereograms.* Master's thesis, Massachusetts Institute of Technology, September 1986.

[8] J. D. Foley and A. Van Dam. *Fundamentals of Interactive Computer Graphics.* Addison Wesley, 1982.

[9] Phyllis Karen Kristal. *Video-Graphic Arthroscope.* Bachelor's thesis, Massachusetts Institute of Technology, September 1987.

[10] Andrew Lippman. And seeing through your hand. *Proceedings of the Society of Information Display,* 22(2), 1981.

[11] Christopher Schmandt. Input and display registration in a stereoscopic workstation. *Displays*, 89–92, April 1984.

[12] Christopher Schmandt. Interactive three-dimensional computer space. *SPIE Conference on Processing and Display of Three-Dimensional Data*, 1982.

[13] Brian M. Croll. *Rendermatic: An Implementation of the Rendering Pipeline*. Master's thesis, Massachusetts Institute of Technology, August 1986.

[14] Alvy Ray Smith. *The Viewing Transformation*. Technical Memo 84, Lucasfilm Ltd., June 1983.

[15] William H. Newman and Robert F. Sproull. *Principles of interactive computer graphics*. McGraw-Hill, 1979.

[16] David F. Rogers. *Procedural Elements for Computer Graphics*. McGraw-Hill, 1985.

[17] Steven Yelick. *Anamorphic Image Processing*. Bachelor's thesis, Massachusetts Institute of Technology, May 1980.

[18] Ian L. Pykett. Nmr imaging in medicine. *Scientific American*, 246(5):78–88, May 1982.

[19] Michael W. Vannier, Jeffery L. Marsh, and James O. Warren. Three dimensional computer graphics for craniofacial surgical planning and evaluation. *Computer Graphics*, 17(3):263–273, July 1983.

[20] Linda J. Brewster, Sushma S. Trivodi, Heang K. Tuy, and Jayaram K. Udupa. Interactive surgical planning. *IEEE Computer Graphics and Applications*, 31–40, March 1984.

[21] Charles E. Mosher Jr., George W. Sherouse, Peter H. Mills, Kevin L. Novins, Stephen M. Pizer, Julian G. Rosenman, and Edward L. Chaney. The virtual simulator. In *Proceedings of 1986 Workshop on Interactive 3D Graphics*, pages 77–87, ACM, Chapel Hill, N.C., October 1986.

[22] John W. Granholm, Douglas D. Robertson, Peter S. Walker, and Philip C. Nelson. Computer design of custom femoral stem protheses. *IEEE Computer Graphics and Applications*, 26–35, February 1987.

[23] Micheael L. Rhodes, Yu-Ming Kuo, Stephen L. G. Rothman, and Charles Woznick. An application of computer graphics and networks to anatomic model and prosthesis manufacturing. *IEEE Computer Graphics and Applications*, 12–25, February 1987.

[24] Samuel M. Goldwasser, R. Anthony Reynolds, Ted Bapty, David Baraff, John Summers, David A. Talton, and Ed Walsh. Physician's workstation with real-time performance. *IEEE Computer Graphics and Applications*, 44–57, December 1985.

[25] Abigail Christopher. At the frontiers of medical imaging. *Computer Pictures*, 62–66, January/February 1987.

[26] Willis Cohoon Campbell. *Campbell's Operative Orthopaedics*. Volume 1, C. V. Mosby Company, 6 edition, 1980.

[27] *Comm-Spasyn Operator's Manual*. Polhemus Navigation Sciences Division, 1983.