IMAGE ANALYSIS AND VISUALIZATION

Report of Working Group 4
Medical Imaging Technology Roadmap

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PREFACE

This report of the "Image Analysis and Visualization" Working Group is the second of five that, once completed, will comprise the Medical Imaging Technology Roadmap. This Roadmap is intended to provide a market-driven forecast of technologies needed to improve patient care and enhance the global competitiveness of the Canadian medical imaging sector. The Roadmap should strengthen technology development, diffusion and adaptation and help to guide public and private sector decision making with respect to product development, investment, human resources and other policy areas.

Overall direction and guidance for this project is provided by the 14-person Medical Imaging Technology Roadmap Steering Committee (see Appendix A for the membership list). Steering Committee members represent companies, researchers, clinicians and government organizations involved with the Canadian medical imaging sector. Industry Canada serves as a catalyst and facilitator of the roadmapping process. A total of 75 people representing more than 50 organizations are participating in the project, creating opportunities for potential alliances and information sharing.

The major accomplishments to date, in addition to publication of WG1's report on "Future Needs for Imaging in Health Care" and this one on "Image Analysis and Visualization", are as follows:

- Publication of "Medical Imaging: Discussion Paper";
- Articulation of the vision, purpose and goal of the project;
- Development of a "members only" web site to facilitate communications;
- Establishment and tasking of five working groups:
    - WG1 - Future Needs for Imaging in Health Care
    - WG2 - Image Generation and Capture
    - WG3 - Transmission and Connectivity
    - WG4 - Image Analysis and Visualization and
    - WG5 - Emerging Technologies; and
- Identification by the working groups of issues to be addressed and critical technologies to be examined in the Roadmap.

The projected date for completion of the Medical Imaging Technology Roadmap is Fall 2000. For up-to-date information, visit the public web site at http://strategis.ic.gc.ca/medimage.

EXECUTIVE SUMMARY

1. INTRODUCTION

This report of the “Image Analysis and Visualization” Working Group identifies and describes critical technologies in five key areas of image analysis and visualization: integration of images from different modalities; image analysis; image visualization; image analysis and visualization for image-guided therapy; and systems for simulation and training.

2. INTEGRATION OF IMAGES FROM DIFFERENT MODALITIES

The goal of image integration is to enable clinicians to view integrated images and visualize a patient in three dimensions, combining anatomical, functional and physiological information. This will enable better surgical planning and therapy delivery through the inclusion of a more complete information package. The ability to integrate images from diverse imaging modalities as well as from different equipment manufacturers and to build a comprehensive database of image information is the key to successful image integration. Technologies must be developed and software created that will allow for the integration of images in a format that will enable users to rapidly verify the integrated data set and display it in a useful manner.

3. IMAGE ANALYSIS

Spectral imaging can provide a powerful tool to aid medical professionals in the diagnosis and treatment of disease. This section covers current applications of spectral analysis in medicine, the visualization and rendering of spectral data, and a number of challenges for spectral analysis in medicine. Image analysis tools that include three spatial and two other dimensions (time and frequency or wavelength) as well as tools and real-time aids that are specific to particular clinical applications have potential for future growth.

4. IMAGE VISUALIZATION

The goal of 3-D image rendering and visualization is to provide the diagnostician or therapist with a more complete view of the anatomy, reducing the variability of conventional 2-D visualization techniques. This section covers three broad classes of 3-D display techniques: surface-based, multi-planar and volume-based rendering. Medical imaging visualization is central to improvements in disease diagnosis and monitoring as well as, among other things, surgical and therapeutic guidance and monitoring. For 3-D imaging to become widely accepted, real-time, intuitive tools that are able to automate the manipulation of multiple parameters are needed. These tools must integrate with the imaging modalities and PACS networks and be adapted to particular clinical applications at low cost.

5. IMAGE ANALYSIS AND VISUALIZATION FOR IMAGE-GUIDED THERAPY

Image-guided surgery and therapy offers a less invasive, less costly approach to patient care for a number of procedures. However, the requirements for a successful system are demanding. This section describes technologies used for image-guided surgery and therapy under the following headings: accurate systems for instruments tracking in the body; flat-panel stereoscopic display systems; heads-up display systems; automatic patient-image registration; force feedback technologies for visualization; surface matching; and bone-mounted markers. The subsection on user interface issues emphasizes the importance of obtaining a detailed understanding of the interaction of the human visual/sensory system with available tools such as VR displays, high-speed interaction, haptic feedback, robotics, etc. Aggressive future development is required on haptic interfaces and stereoscopic and head-mounted displays.

6. SYSTEMS FOR SIMULATION AND TRAINING

There is a great need to develop effective training based on high-fidelity VR simulation models for medical students at all levels up to and including practising clinicians. Among the benefits would be more systematic feedback about learning outcomes to students, reduced reliance on animals and cadavers, ease of training for rarely practised procedures and techniques, and the ability to evaluate completely new techniques. This section describes the technologies required to provide effective systems for simulation and training using portable and realistic medical images, that is, visual display systems; kinesthetic and tactile simulation; simulation of odours; modelling and image generation; human factors for system design; assessment of trainees; and continuing education, remediation and remote training. The need for the development of systems that will provide training on laparoscopic and open procedures is particularly noted.

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INTRODUCTION

1. SCOPE

The scope of the “Image Analysis and Visualization” Working Group was to identify and describe enabling technologies that need to be developed to fulfill future patient and market needs with respect to image analysis and visualization. This includes the creation of information technology to enable computers to be able to identify and define structures, to integrate images from different modalities and to render information into a form which allows for better presentation of the information and hence interpretation, therapeutic intervention and systems for simulation and training.

2. MEMBERSHIP

The “Image Analysis and Visualization” Working Group consists of representatives of the corporate sector, the research community and clinicians. A complete membership list is found in Appendix B

3. OUTLINE

This report identifies and describes critical technologies in five key areas of image analysis and visualization:

- Integration of images from different modalities;
- Image analysis;
- Image visualization;
- Image analysis and visualization for image-guided therapy; and
- Systems for simulation and training.

As the Working Group was divided into subgroups to focus on each of the above key areas, a “critical technology template” (see Appendix C) was used to bring consistency to the resulting work. It was agreed that a heading would be omitted from the template or a new one added at the end of the template where the need was compelling; however, the existing headings would be used to the extent possible.

INTEGRATION OF IMAGES FROM DIFFERENT MODALITIES

1. GOALS

Health care facilities and researchers use various imaging modalities to benefit from the different information that they provide. Key to the improvement of image analysis and visualization is the ability to integrate images from these diverse technologies as well as different equipment manufacturers and build a comprehensive database of image information. The goal of image integration is to enable clinicians to view integrated images and visualize a patient in three dimensions, combining anatomical, functional and physiological information. This will enable better surgical planning and therapy delivery through the inclusion of a more complete information package. Full integration in health care and research facilities will only be possible if standards for image display, recording, transmission and interpretation are developed and adopted by all imaging equipment and post-processing developers and vendors. The goal is to have images that can be processed and transmitted to post-processing equipment, regardless of the institution or equipment supplier(s).

2. DESCRIPTION

Computed tomography (CT) and magnetic resonance (MR) data is digital. Other traditional modalities such as radiography, angiography, nuclear medicine, positron emission tomography (PET), and ultrasound, acquired analogue information that could not be integrated with other imaging data without significant manipulation and digitization of the data. The advent of digital imaging technology in these modalities will allow improved visualization of comprehensive sets of information. To truly benefit from this digital data acquisition, technologies must be developed and software created that will allow the integration of functional, anatomical and physiological information in a format that will enable users to rapidly verify the integrated data set and display it in a useful manner.

3. IMPORTANCE

Following the revolutionary advances in medical imaging, the next quantum step will be in the post-processing and manipulation of those images to provide clinicians and researchers with a more complete view of structures and functions being imaged. Accurate image integration will be key to allow the users to extract the most relevant and comprehensive information to facilitate and improve clinical decision making.

4. CLINICAL REQUIREMENTS

For the integration of images to have clinical value, the user interface must be relatively easy to manipulate, while reproducible with rapid verification. The input devices must be open in architecture so that data from multiple existing imaging systems can be co-registered, avoiding large amounts of capital expenditure for new equipment within the hospital and research environment. The integration task will be driven by need for automation so that minimal time is required to achieve the desired results and verification must be simple and very reliable as critical decisions will be made based on the output. The graphics for displaying the output will require very sophisticated abilities to view in multiple formats as well as simultaneously with the integration reference data.

5. ALTERNATIVES

The present alternative is to view the different modalities simultaneously and then mentally integrate the images. This leads to many potential issues on subjective interpretation.

6. MATURITY AND RISK

Today, the ability to integrate images is evolving with the existing technology to co-register different modalities such as CT and MR, nuclear medicine and CT, or PET and MR. The key to successful execution of this technology will be the ability to integrate information from all modalities. Intuitive user interfaces with more widely used standards will better enable rapid and successful adoption of the technology. As computer technology continues to expand to meet increasing demands, the ability to acquire the speed necessary to permit clinically relevant usage will improve and further reduce the risk of failure. Presently, there is no coordination among the different developers or methods. This may result in no standard being reached, establishing barriers within some institutions across various pieces of equipment or may expedite the work to solve the overall complexities of the challenges that different modalities present.

7. AVAILABILITY

Many research facilities and commercial imaging suppliers presently offer software packages to integrate images from different imaging modalities such as CT and MR, nuclear medicine and CT, or PET and MR. Progress is being made daily on continuous development of new methods and software for integration.

8. BREADTH OF APPLICATION

Image integration will be widely used in many applications. Once the technology for image integration is available, it can be rapidly translated to other applications. For example, integrating MR and PET information into oncology planning will also translate to other surgical planning and functional therapy usage. This is true for all integration, where the applications are vast, but the challenge is restricted to the ability to accurately perform and rapidly validate the integration. The more complex issue will be to design the different display systems required for different applications.

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IMAGE ANALYSIS

1. GOALS

The use of imagery in medicine can greatly enhance the quality of diagnosis and treatment that doctors can provide. Most often, imagery is considered to show intensity as a function of two or three spatial dimensions. In addition to this, there is a large amount of information that can be obtained by collecting images as a function of time, frequency, or at different wavelengths within the electromagnetic spectrum. Plots of intensity versus time, frequency or wavelength, i.e., spectra, can be used to identify the substance that is being imaged. Thus the goal of this section is to examine the status and future of spectral imaging in medicine.

2. DESCRIPTION

2.1 Introduction

Spectroscopy is the study of the interaction of electromagnetic radiation with matter. The sensed electromagnetic radiation can be emitted either naturally or stimulated in some manner, e.g., using a laser beam, or magnetic field. This radiation may be collected over a range of wavelengths, and/or as a function of time. It is thus possible to obtain a spectrum for every voxel of space. These spectra may be analyzed and processed to determine the molecular make-up of (or different temporal responses in) the imaged region.

2.2 Current Applications of Spectral Analysis in Medicine

Current applications include the use of spectral imaging to:

- differentiate cancerous from non-cancerous tissue;
- identify chromosomal abnormalities;
- diagnose retinal disease;
- determine skin health and transplant viability; and
- enhance diagnostic endoscopy.

Spectral imaging is used both for in vivo applications, and in the laboratory. Spectral data may be displayed either as collected (raw data), or after significant processing to extract information and interpret the received data. Typically the raw data are hard to interpret, thus it is usually necessary to include several processing steps before displaying the data.

2.3 Visualization and Rendering of Spectral Data.

As mentioned above, once the spectral data is acquired, it can either be displayed directly, or processed first. For example, the rendered data may be a combination of selected wavelengths. Alternatively, classification and/or segmentation algorithms may be run on the data before it is rendered. Classification may be unsupervised, e.g., automatic clustering of similar spectra, or supervised, i.e., require user input, or require that the data be matched to a spectral library. However, the use of spectral libraries usually requires that the collected data be well calibrated. Many classification algorithms are capable of classifying to the sub-voxel level (i.e., if the imaged voxel consists of more than one substance, the resultant spectrum will be a combination of the constituent spectra), in which case the classifiers generally return class probabilities.

2.4 Challenges for Spectral Analysis in Medicine

There are a number of challenges that need to be faced in the collection and interpretation of spectral imagery. These include:

- the large amounts of data to be managed, displayed and used simultaneously;
- simultaneous display of spectral/spatial information, without overloading the viewer;
- separation of components of mixed voxels and display of mixed-voxel results;
- real-time interpretation algorithms; and
- coregistration with other image modalities.

3. IMPORTANCE

Spectral imaging can provide a powerful tool to aid medical professionals in diagnosis and treatment of disease. For example, it opens the doors to real-time identification of tissue composition, which aids decision making and localisation of treatment.

4. CLINICAL REQUIREMENTS

Clinical requirements include:

- real-time image manipulation and rendering;
- intuitive tools to control the multi-dimensional image and to allow extraction of needed information; and
- low-cost subsystems well integrated with the imaging modality or the PACS network.

5. ALTERNATIVES

Although currently not available, image analysis tools including three spatial and two other dimensions (i.e., time **and** frequency or wavelength) should gain increasing importance in the future.

6. MATURITY AND RISK

Useful spectral imaging systems are already available and used in medical imaging systems, however the number of such applications is limited at present. Systems for co-display of spatial and spectral information are continually improving. Spectral visualization and interpretation techniques are general tools that can be applied to any spectral image data. However, to be useful, they must be modified and adapted for a particular clinical application. Each application has particular needs that must be addressed, and tools that must be provided. Real-time aids for interpretation of the spectral information also need to be developed on an application basis. Tools for management of the large amounts of data collected are becoming available.

7. AVAILABILITY

Imaging spectrometers are widely available. There are many existing spectral analysis software packages already in use, for example, in MR imaging, MR spectroscopy and medical microscopy. However, as the science evolves, the hardware and software must evolve with it.

8. REFERENCES

An example of a commercially available imaging software that can be used to analyze both 3-D-time or 3-D-frequence/wavelength is EvIdent™. More information, including references for its application for both MR and IR images can be found at http://www.ibd.nrc.ca/informatics.

IMAGE VISUALIZATION

1. GOALS

Three-dimensional rendering and visualization addresses the subjectivity of the conventional 2-D exam. In conventional 2-D imaging, an experienced diagnostician views a sequence of 2-D images, mentally transforms them into an impression of the 3-D anatomy and pathology, then makes the diagnosis or performs an interventional procedure. This approach is sub-optimal primarily because 2-D imaging techniques are used to view 3-D anatomy/pathology. This is particularly important in interventional procedures such as brachytherapy, or biopsy, as the process of quantifying and monitoring small changes during the procedure is severely limited by the 2-D restrictions of conventional imaging. Specifically, 3-D rendering and visualization imaging addresses the following limitations:

- Conventional image viewing is 2-D. Therefore, the diagnostician must mentally transform multiple tomographic or projection images to form a 3-D impression of the anatomy/pathology during the diagnostic examination, or during an image guided interventional procedure. This process is not only time consuming and inefficient, but more important, variable and subjective, which may lead to incorrect decisions in diagnosis, planning and delivering the therapy.

- Diagnostic (e.g., obstetrics) and therapeutic decisions (staging and planning) often require accurate estimation of organ or tumour volume. Volume measurement techniques based on 2-D imaging use only simple measures of the width in two views and assume an idealized shape to calculate volume. This practice potentially leads to inaccuracy and operator variability.

- It is difficult to place the 2-D image plane at a particular location within an organ, and even more difficult to find the same location again later. Thus, 2-D image viewing is sub-optimal for planning or monitoring therapeutic procedures, or for performing quantitative prospective or follow-up studies.

- Due to the restrictions imposed by the patient's anatomy or position, it is sometimes impossible to orient the 2-D image to the optimal image plane. Visualization of the anatomy is hindered, preventing accurate diagnosis of the patient’s condition and monitoring of interventional procedures.

The goal of 3-D image rendering and visualization is to overcome these limitations. Three-dimensional image rendering and visualization will provide the diagnostician or therapist a more complete view of the anatomy in 3-D, thereby reducing the variability of conventional visualization techniques.

Medical ultrasound imaging is inherently tomographic, providing information that is necessary for reconstructing and visualizing 3-D images. However, unlike CT and MR imaging, in which the images are usually acquired at a slow rate as a stack of parallel slices, ultrasound provides tomographic images at a high rate (15-60 images per second), and the orientation of the images is arbitrary and under the user control. The high rate of image acquisition, arbitrary orientation of the images, ultrasound image speckle, shadowing, and distortions, provide unique problems to overcome, and opportunities to be exploited in extending ultrasound imaging from its 2-D presentation of images to 3-D and time-varying 3-D (or 4-D).

Over the past two decades, many investigators have focussed their efforts on the development of various types of 3-D image rendering and visualization techniques. However, because of the enormous demands on the computers needed to produce real-time, low-cost systems, most attempts did not succeed or did not enter the mainstream of diagnostic use. It is only in the last few years that computer technology and visualization techniques have progressed sufficiently to make 3-D image rendering and visualization viable as a routine tool.

2. DESCRIPTION

2.1 Introduction

The discovery of x-rays over 100 years ago heralded a new way of visualizing the human body. X-ray imaging produces a radiographic shadow as a 2-D image of the 3-D structures within the body. Although this imaging approach is extremely useful and is still in use today, all 3-D information is lost to the physician. Many attempts have been made to develop imaging techniques in which 3-D information within the body was preserved in a recorded image. In the early 1970's, the introduction of CT revolutionized diagnostic radiology. For the first time, 3-D information was presented to the physician as a series of tomographic, 2-D image slices of the body. In addition, for the first time in radiology, computers became central in the processing and display of the images. The availability of true 3-D anatomical information stimulated the field of 3-D visualization for a variety of applications in diagnostic radiology.

Once reconstructed, the 3-D image can be viewed interactively using any 3-D visualization software. The imaging modality and its acquisition characteristics are crucial in determining the quality of the final image. Nevertheless, the rendering technique chosen also plays an important, and at times, dominant role in determining the information transmitted to the operator by the 3-D image display. There are many techniques for displaying 3-D images that are still being actively investigated by numerous investigators and commercial companies. Three-dimensional display techniques can be divided into three broad classes: surface-based, multi-planar, and volume-based rendering. The optimal choice of the rendering technique is generally determined by the clinical application, and is often under the control of the user.

2.2 Surface-based Rendering (SR)

The most common 3-D display technique is based on visualization of surfaces of structures or organs. In this approach, a segmentation and classification step precedes rendering. In the first step, the operator or the algorithm analyzes each voxel in the 3-D image and determines the structure to which it belongs. Boundaries of anatomical structures can be identified by the operator using manual contouring, or by algorithms that can use simple thresholding or more complex statistical and geometric properties of parts of the 3-D image. Segmentation of boundaries in 3-D images is still a very active area of research and many opportunities exist for innovations and application-specific developments. Once the tissues or structures have been classified and their boundaries identified, the boundaries are represented by a wire-frame or mesh and the surface is texture mapped with an appropriate colour and texture to represent the anatomical structure.

The wire-frame rendering approach was used first in 3-D image rendering because it is the simplest and does not require advanced computer workstations. In this approach, the boundaries between structures are represented by a network of lines, which can be viewed in a 3-D perspective. The wire-frames or other more complex representations of the surfaces can be texture-mapped, shaded, illuminated, and depth cues added, so that both topography and 3-D geometry are more easily comprehended. Automatic rotation, or user-controlled motion, is generally useful to allow the operator to view the anatomy from different perspectives. This approach has been used successfully by many investigators in rendering of the skull, colon, skeletal structures, heart and in obstetrical applications.

2.3 Multi-Planar Viewing (MPR)

This technique requires that either a 3-D voxel-based image be reconstructed first, or an algorithm be developed that extracts any arbitrarily oriented plane from the originally acquired images. Two approaches have been developed to view the 3-D image information. In the first approach, computer user interface tools are provided to the operator to allow selection of single or multiple planes, including oblique from the 3-D. With appropriate interpolation, these planes may appear similar to the images that would be obtained by 2-D imaging techniques. Often, three perpendicular planes are displayed on the screen simultaneously, with cues providing relative orientation information. This method presents 2-D images that are familiar and allows the operator to orient the planes optimally for the examination.

A second approach is based on multi-planar visualization with texture mapping. In this technique, the 3-D image is presented as a polyhedron representing the boundaries of the reconstructed volume. Each face of the polyhedron is rendered, using a texture-mapping technique with the appropriate 2-D image for that plane. User interface tools are provided, allowing the polyhedron to be rotated to obtain the desired orientation of the image. The faces of the polyhedron can be moved in or out parallel to the original, or reoriented obliquely, while the appropriate ultrasound data is texture-mapped in real time on the new face. In this way, the operator always has 3-D image-based cues relating the plane being manipulated relative to the rest of the anatomy.

2.4 Volume-Rendering (VR)

Both the surface-based and multi-planar rendering techniques reduce the display of 3-D information to a display of 2-D information in the form of complex or planar surfaces. Since our visual senses are best suited for surface viewing and interpretation, these two approaches are easily understood by the operator. However, surface- or planar-based display techniques present only a small part of the complete 3-D image at one time.

An alternative approach is the volume rendering technique, which presents to the viewer a display of the entire 3-D image after it has been projected onto a 2-D plane. The most common approach used in 3-D ultrasound imaging is based on the ray-casting techniques, which project a 2-D array of rays through the 3-D image. Each ray intersects the 3-D image along a series of voxels. The voxel values along each ray are examined and weighted to achieve the desired rendering result. If the structures in the 3-D image have been segmented and classified, the voxels can be weighted and/or coloured appropriately to achieve a translucent representation. Another common approach is to display only the voxels with the maximum (minimum) intensity along each ray to form a "maximum (minimum) intensity projection" (MIP) image.

The most common approach used in 3-D image rendering and visualization is the translucency/opacity rendering approach. In this approach, the voxels along each ray are weighted according to:

$$C_{out} = C_{in}\,(1 - a(i)) + c(i)\,a(i)$$

where C_{out} is the value of the ray exiting from the ith voxel, and C_{in} is the value of the ray entering the ith voxel. The parameters c and a are chosen to control the specific desired rendering result, where a controls the opacity and c is a modified voxel shade value that can be based on the voxel value or local gradient, and chosen to control the luminance of the voxel. For example, if $a(i) = 0$, then the ray will be transmitted through ith voxel as if it were transparent; if $a(i) = 1$, then the voxel is considered to be opaque or luminescent depending on the value of c. Typically, the values of a are added along each ray and when the sum reaches 1, the value C_{out} is displayed.

Volume-based techniques, which display the anatomy in a translucent manner, preserve all the 3-D information, but project it (after nonlinear processing) onto a 2-D plane for viewing. Although depth cues can be added (e.g., stereo viewing), this approach results in images that are difficult to interpret. Thus, this approach is best suited for simple anatomical structures in which clutter has been removed or is not present. Investigators have demonstrated success, particularly in displaying fetal and vascular anatomy using 3-D ultrasound imaging techniques.

In general, ray-casting techniques are computationally intensive, requiring a very large number of rays to be used to generate satisfactory results. However, with current personal computers and efficient implementation of the algorithms, real-time manipulation of the 3-D image with continuous ray casting is possible.

3. IMPORTANCE

The past twenty-five years have witnessed revolutionary advances in medical imaging. In these years, the primary advances have been technological in nature, with development of new imaging instrumentation and continuing advances in their capabilities. The imaging techniques are now relatively mature, and we are poised for the next revolution in the capabilities and applications of medical imaging.

The general consensus is that this revolution will be based on medical imaging information management and processing. Central to this field is image visualization, with an objective of providing the physician with a set of powerful computational tools to help visualize and extract information from the huge amount of available multi-modality and multi-dimensional image data. With these tools, significant improvements will be realized in disease diagnosis, quantitative monitoring of disease progression or regression, surgical and therapeutic guidance and monitoring, and quantification of functional information and pharmacological response.

4. CLINICAL REQUIREMENTS

Clinical requirements include:

- real-time image manipulation and rendering;
- intuitive tools to control the multi-dimensional image to allow extraction of needed information; and
- low-cost subsystems that are well integrated with the imaging modality or the PACS network.

5. MATURITY AND RISK

Useful 3-D visualization tools are already available and used in 3-D imaging systems. However, they still require complicated user interfaces and an array of tools to manipulate the 3-D images. For 3-D imaging to become widely accepted, intuitive tools are required to manipulate the 3-D image allowing the user to view any section of the anatomy in relation to other sections. In addition, the user requires intuitive and real-time tools to produce volume-rendered images.

Currently, production of volume-rendered images requires manipulation of multiple parameters. Techniques are needed that provide immediate optimal rendering based on both image data and the organ being viewed, without significant user intervention.

6. AVAILABILITY

Scientific and technological advances in the past five years have enabled the development of clinically useful 3-D image rendering and visualization systems, e.g., virtual colonoscopy, 3-D ultrasound, facial reconstruction visualization software and neurosurgical navigation software tools. Some systems now allow real-time or fast 3-D acquisition, real-time reconstruction and real-time 3-D image rendering and visualization.

7. BREADTH OF APPLICATION

Three-dimensional rendering and visualization techniques are general tools that can be applied to any 3-D image data. However, to be useful, they must be modified and adapted for a particular clinical application. Each application has particular needs that must be addressed as well as tools that must be provided.

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IMAGE ANALYSIS AND VISUALIZATION FOR IMAGE-GUIDED THERAPY

1. GOALS

Image-guided therapy requires that images, often from multiple modalities, be registered with each other, with the patient and with a system for tracking instruments within the human body. Organs, tissues and lesions must be identified in the images, and they must be displayed to the surgeon in a manner that is intuitive, and non-intrusive to the operating-room environment. In order to adequately represent the human tissue that the images represent, the digital data must be rendered with high resolution, and the computer hardware must be capable of manipulating such data in real time. In order that the images possess the maximum degree of 3-D realism, they should be displayed to the surgeon using stereoscopic techniques, either via an unobtrusive flat-panel display, or via light-weight head-mounted display devices. As minimally-invasive surgery adopts the use of telerobotic techniques to minimize tremor in the surgeon's hand, and to facilitate micro-surgery through motion reduction, image-guidance will play an increasing role in cardio-thoracic, abdominal and joint surgery. The goal of this exercise is two-fold:

- To develop the technologies outlined below to improve their use for image-guided surgery and therapy; and
- To develop the methodology for integrating them together in a unified system.

2. DESCRIPTION

The technologies and user interface issues considered to be the most critical in the area of image analysis and visualization for image-guided therapy are described below.

2.1 Accurate Systems for Instrument Tracking in the Body

The defining aspect of image-guided surgery is a system that allows a probe to be tracked, within the body, and displayed in a 3-D image volume during surgery.

Many approaches exist to perform intra-operative surgical guidance. Some employ a probe that is physically linked by a multi-jointed arm to the apparatus restraining the patient's head, and the position of the probe is determined by sensing the angles at each joint [Zinreich 1993 and Golfinos 1998]. Others use ultrasonic [Reinhardt 1998], optical, or magnetic [Birkfellner 1998] methods to determine the probe's position. Each system has its advantages and drawbacks. The mechanical system is always in communication with the computer and does not rely on there being a line of sight between the probe and some signal transducer. On the other hand, it is bulky and intrusive in the operating room.

Ultrasonic, electromagnetic and optical methods allow the mechanical system to be dispensed with, but in the case of ultrasound and optical systems, there must always be an unobstructed "line of sight" between sensors on the probe and some transmitting device. Electromagnetic systems do not suffer from this disadvantage, but their performance is often limited by the presence of metallic devices in the vicinity of the position sensors. Some efforts have been made to combine optical and electromagnetic devices to build instruments that use an optically-tracked system to recalibrate a magnetically-based tracker in real time so that the magnetic tracker can "take over" from the optical system when sight-lines are broken. Currently both mechanical and optical tracking systems are employed routinely in image guided surgery procedures, and these devices generally achieve a tracking accuracy and precision of better than ~ 1mm.

At present, there are no satisfactory solutions to the problem of tracking an object (for example a catheter tip or a flexible endoscope) within the body unless one employs a real-time imaging system like magnetic resonance imaging (MRI), ultrasound or fluoroscopy. The size of the standard magnetic receptor precludes it from being incorporated within a probe-tip or catheter, forcing the tracking of an intra-cavity point to be achieved through tracking of a sensor connected to the probe-tip by a rigid rod. There has nevertheless been a report of a miniaturized magnetic probe that can be inserted within a catheter, but details of its performance are unavailable. One technology that shows promise for use in tracking situations in general, and in flexible endoscopes and catheters in particular, employs fibre optics. Specially treated optical fibres can be manufactured in such a way that the light transmission is a function of the radius of curvature of the fibre. This concept has been incorporated into a commercial shape-measuring device, "Shape-tape", from the Canadian company Measurand Inc., and it is believed that the technology has recently been licensed to Northern Digital Inc., another Canadian company that already has a world-leadership position in optical tracking systems.

Nevertheless, technology that can accurately track the position and orientation of multiple instruments within the human body without a "line-of-sight" requirement, remains elusive.

2.2 Flat-panel Stereoscopic Display Systems

Stereoscopic imaging is no longer in general use in diagnostic radiology, although there are some centres that still employ it routinely, while others use it on a sporadic basis. However, since the advent of 3-D imaging modalities, there is an increased need to navigate through large data spaces quickly. The use of 3-D visualization in surgical planning and guidance and the availability of inexpensive computational power that permits the interactive manipulation of 3-D volumes, has once again made stereoscopic visualization a compelling adjunct to surgical navigation. Stereoscopic visualization has been employed in the operating room by the surgical team at several sites, in particular, at the Montreal Neurological Institute (MNI). Initially, it was used for the integration of digital subtraction angiograms with MRI and CT for surgical planning purposes, and subsequently, it was used for the presentation of 3-D views to the surgeon during surgical guidance [Peters 1994 and Davey 1994]. One limitation of this technology is that it requires the use of bulky conventional monitors that are difficult to place near the surgical field. In addition, the stereoscopic images must be viewed using active or passive polarized eyewear that directs alternate image frames to the left or right eye respectively. While the ideal solution would involve the use of flat-panel displays, current LCD panel technology inherently polarizes the light, making such displays incompatible with standard shuttered or polarized eyewear.

By virtue of the fact that image-guided surgery relies on the use of a "virtual" representation of the body or specific organ in the form of medical images, all of the techniques discussed above contain elements of "virtual reality" or VR.

In image-guided surgery, VR techniques are beginning to play increasingly important roles as the emphasis grows towards the use of minimally-invasive procedures. Since direct visualization of the surgical field becomes more and more difficult as the surgical opening becomes smaller, the natural direction of research is towards the model-based realization of the structures being operated. Computer graphics technology can provide realistic looking 3-D images of structures derived from MRI or CT, and the emerging field of virtual endoscopy provides a prime example of this. Both surface- and volume-rendering approaches (see section on “Image Analysis”) are commonly employed in this field, and stereoscopic visualization is often employed to maximize the advantage of the 3-D image representation.

A useful adjunct to VR is "Augmented Reality" where real-time information from the "real world" is integrated with that from the 3-D model. This approach has seen extensive application in remote sensing and has been demonstrated in the context of image-guided surgery by superimposing video images with the 3-D (both monoscopic and stereoscopic) computed representation of the brain during neurosurgery as a means of combining real (patient) and virtual (3-D MRI) images. Others combine microscope images with digital representations of the operative field to give the surgeon a view of both the surface as well as underlying structures.

2.3 Heads-up Display Systems

The ultimate manifestation of this technology is a high resolution light-weight head-mounted stereoscopic display whose position relative to the patient is constantly tracked during the procedure. Such a device allows the surgeon a direct view of the operation, while at the same time projecting a registered virtual image (from 3-D MRI, for example) onto his visual field. As long as the head is accurately tracked during the procedure, the images will remain superimposed regardless of the surgeon’s head position. One of the greatest advantages of this approach is that it keeps the images, that would normally be displayed on an inconveniently placed computer monitor, within the surgeon's field-of-view at all times. With this system, images from the pre-operative studies are always in view. In addition, the real-time, video-based endoscopic images, being used for navigation within the ventricles for example, are always available to the surgeon without the need to turn away from the site of the operation.

It should be pointed out that Fakespace Systems Inc., a spin-off of Canadian Electrohome, is a world leader in the development of stereoscopic display for virtual environments, and has a vested interest in the advancement of this technology.

2.4 Automatic Patient-image Registration

If images are to be useful in planning or guiding surgical procedures, they must be registered to the patient, such that image-space (defined by the 3-D array of voxels) can be related directly to the real-world coordinate system of the patient. This process occurs in two steps. First the homologous points or surfaces must be identified in the image and on the patient, and then this information must be used to compute the transform matrix that relates the coordinate system of the image to that of the patient.

A great deal of effort has been expended on the development of techniques to register pre-operative images to the patient. The most common techniques involve the identification of structures and surface patches in both the images and the patient. One approach is to use a computer-tracked pointer to identify landmarks such as the outer canthi of the eyes, the tragus of the ears, and the nasion. These same structures are then identified using a cursor driven mouse within the 3-D images of the patient. This approach is not entirely satisfactory for two reasons. Firstly, there is bound to be some variation in the identified locations of the landmark points on the patient, as well as a problem of identifying exactly the same locations within the patient's 3-D image. Therefore, the best one can hope to do is to perform a least-squares approximation to the correct registration. Of course, the accuracy of the least-squares match will be improved as the number of homologous points is increased. Secondly, if all of the registration points are clustered together, a small inaccuracy in the registration in the region containing the homologous points can result in a magnified error at points remote from this region.

2.5 Force Feedback Technologies for Visualization

Recent efforts have been made to use the sense of touch as a modality for a user to exploit imaging data. This became possible with the advent of so-called haptic interfaces. These are human-computer bidirectional interfaces which can input data from a user's movement and can also return forces. There are many applications of these devices already, including commercial ones. For example, there is intense activity to use these devices in surgical training scenarios such as minimally-invasive procedures (see section on “Systems for Simulation and Training”). They tend, in that case, to be complex and expensive devices. At the other end of the scale, low-cost devices are already commercialized on a large scale by the gaming industry. Medium-complexity devices are believed to provide advantages in the visualization of medical data, especially in three dimensions, in almost all areas of medical diagnosis and treatment.

In the same way computer graphics technology is being driven by consumer applications (in effect, research tools are often the same as consumer products, including VR stereo displays), consumer haptic products are rapidly reaching a level of performance acceptable by the professional. This need results from the ability of modern medical imaging techniques to produce a 3-D volume of data representing the anatomy, vascularity or function of regions of the human body. The analysis of such large amounts of data present in each image presents a formidable problem to the radiologist or surgeon. Typically, these images are evaluated by displaying them using the tools provided by computer graphics. Except in the case of the stereoscopic visualization, all of the 3-D images are effectively represented as 2-D intensity maps on 2-D screens.

Another significant factor is that although these images are representations of solid collections of objects with different properties, they are represented exclusively visually. With 2-D displays, when cursor probes are provided to interrogate the volume, the cursor is allowed to freely roam through the volume and there is no feedback to the operator to inform her or him about the properties of the material and feedback about depth is limited. A clinician who examines an organ, either in-vivo or in-vitro, relies as much on tactile feedback as he does on the visualization of the organ. The multi-parametric nature of the typical 3-D medical image contains a rich description of tissue properties that is not necessarily possible, or even appropriate, to present visually.

Systems are needed to allow a better interrogation of 3-D medical image volumes by means of operator feedback in addition to the solely visual. It has been shown that, in general, well-designed, multi-modal presentation of data (graphic + haptic) could lead to significant reduction of errors in the interpretation and manipulation of data, especially in three dimensions. This applies in situations where the “operator” is a radiologist interpreting the data or a surgeon being guided by the images during a procedure. Due to a number of perceptual factors, the haptic feedback can be accomplished by incorporating simple, low-cost, two-degrees-of-freedom haptic interfaces.

2.6 Surface Matching

Some systems employ a surface-matching approach to complement the point-matching method. The use of surfaces extracted from 3-D patient images, acquired from multiple imaging modalities, to match these images in a common space, was described by Pelizzari and Chen [1989]. While their approach required two digital images, the same procedure can be followed to match the surface extracted from an image with physical samples of the same surface of the object. This technique involves using the probe to sample points on the surface of the patient, and then determining the best match of this point-cloud to an extracted surface from the 3-D patient image. This combined approach using both points and surfaces is described by Maurer [1998] and is incorporated in at least one commonly used commercial image-guided neurosurgical system. Under ideal conditions (i.e., in phantom tests where homologous structures are easily identified and there is no movement of the markers with respect to the object), accuracy approaching that of stereotactic frames can be achieved. However, under clinical conditions, where natural features on the patient's skin are identified, the accuracy obtainable from this type of approach decreases due to the subjective identification of homologous point-pairs on the patient and in the images. While this may be adequate for many neurosurgical purposes, it is not appropriate for procedures requiring great precision.

2.7 Bone-mounted Markers

The accuracy and precision of point matching procedures can be improved somewhat by using surface markers glued to the patient's skin. In this case, their location can be more precisely determined using the pointer and they can be automatically identified within the patient's 3-D images. While this improves the precision of the matching, there remains the problem that skin mounted markers can move with respect to the underlying bony anatomy and therefore add additional error. Maurer [1997] has convincingly demonstrated that the only way to achieve patient-to-image registration with the same accuracy as can be obtained with a stereotactic frame is through the use of bone-mounted fiducial markers. Even though the implantation of these reference markers constitutes a procedure that is approximately as invasive as the installation of a stereotactic frame, it can nevertheless be performed under local anesthetic and represents a level of invasiveness that is minor compared to the surgical procedure that is to follow.

The above discussion illustrates the level of difficulty experienced in accurately registering the patient to his or her images, even assuming there is no subsequent tissue shift after the surgical procedure begins. Image registration is often believed to be the most error-prone aspect of image-guided surgery. It is important that not only robust procedures be developed to achieve the appropriate patient-image registration, but that their implementation be automatic, or at least require a minimum of intervention by the surgeon.

A Canadian company, Sandström Trade and Technology Inc., holds the global license for the "Laitenen" stereotactic frameSa device that is fastened to the patient's head via pressure rather than screws (as is normal with a conventional stereotactic frame). While this system has some shortcomings with respect to reproducibility and patient comfort, it could well represent the basis of a simple patient-image registration technology.

2.8 User Interface Issues

Perhaps the greatest challenge to the successful adoption of image-guided surgery systems in the operating room of the future relates not to technology, but to the user interface. Over the last two years, affordable high-speed computing hardware has become available. Such hardware (e.g., a 500MHz Pentium III-based computer, equipped with a sophisticated but inexpensive video processor) now allows interactive surgical image-guidance to be performed in real time (images updated in fractions of a second), with the images presented to the surgeon stereoscopically. It is interesting to note that most of the improvements in computer and visualization hardware are currently being driven by the consumer video gaming industry! It is nevertheless unfortunate that to date little effort has been expended to ensure that the human factors issues relating to the use of such equipment in the operating room (OR) have been adequately addressed. The key will be to design these systems so they are unobtrusive and simple to operate in the OR without the need for a computer specialist on hand. The logistics of data management (acquisition of images, merging them with scans from other sources, segmenting relevant structures) must be handled either automatically or with a minimum of intervention. It must ultimately be possible to operate computer systems in the OR without the need to use the keyboard, or complicated switching devices. The image-guided surgery system must not add complexity to the OR environment.

In sum, the psychophysical issues of manipulating objects within a virtual 3-D environment have barely been addressed to date. Today's technology provides a wealth of tools (VR displays, high-speed interaction, haptic feedback, robotics, etc.), but without a detailed understanding of how the human visual/sensory system interacts with these tools, their advantages may be lost.

3. ALTERNATIVES

The alternative to the use of this technology is to continue performing surgical procedures in the conventional, more invasive, manner. The status quo carries with it the risk of not taking advantage of the decreased patient trauma and the cost savings to the health care system offered by image-guided surgery and therapy techniques.

4. MATURITY AND RISK

Many of the techniques described are quite mature and form the basis of image-guided technology available already. The existing technology provides a stable base upon which advances can be based.

5. AVAILABILITY

Much of the technology is already available, at least in its basic form. Those aspects which require aggressive development include haptic interfaces and stereoscopic and head-mounted displays. These areas are also under intense development in the fields of robotics and the entertainment industry.

6. BREADTH OF APPLICATION

Outside its long-term role in radiation therapy, image guidance has, for the last 20 years, played a major role in brain and spine surgery, as well as in the orthopaedic area, while ultrasound image-guided therapy has recently seen application in prostate and breast treatment. However, as the demand for minimally-invasive procedures increases, it is expected that such techniques will be used in other body systems as well.

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SYSTEMS FOR SIMULATION AND TRAINING

1. GOALS

There is a growing need to develop a method of technical skills instruction outside the operating room. Laboratory-based training courses have been shown to produce improvements in the performance of technical skills on bench models and cadavers [Marteniuk 1976 and Perkins 1989]. Current training and simulation systems involving medical image analysis and visualization are largely limited to bench models, although there have been recent advances, notably in the endoscopic and laparoscopic environment (e.g., HT Medical Systems, Virtual Presence Medical). There is a great need to develop high-fidelity VR models for simulation, and to evaluate the effectiveness of these models for training.

More specifically, the expected benefits include:

- providing more systematic feedback about learning outcomes to students;
- reducing reliance on animals and cadavers;
- training for rarely practised procedures and techniques;
- adjusting the level of difficulty of common procedures;
- evaluating completely new techniques;
- opening the path to information technology-based training (sharing: special skills, data bases, etc.); and
- possibly impacting on telemedicine.

2. DESCRIPTION

2.1 Introduction

This section describes the technologies required to provide effective systems for simulation and training using portable and realistic medical images.

Simulation is firmly established in the commercial airline business as the most cost-effective method of training pilots. Pilots must achieve a certain level of proficiency in the simulator before they are allowed to fly a particular aircraft and must pass regular proficiency testing in the simulator to keep their licenses. Military organizations behave in a similar manner for training basic skills but also find that simulation is useful in training combat skills in complex tactical situations. The medical community is beginning to use simulation in a number of areas for training certain classes of medical personnel such as surgeons and anaesthetists. The popularity of conferences such as “Medicine Meets Virtual Reality” indicates the interest in this subject.

This technology involves the design of training systems that are safe, efficient and effective for of orienting new trainees or for providing advanced training to established clinicians. This involves the training of specific skills, as well as the generation of scenarios for the simulation of critical or emergent situations. Other goals of such a system include the ability to provide simultaneous training to a large group, ideally through multi-user interaction, but also for display alone. Key issues in the development of this technology are the sensitivity of the system to individual differences among trainees and the responsiveness of the system to user actions. The latter issue involves classical ergonomic issues such as speed and resolution of system output in response to user input. This issue may be magnified in a multi-user system.

2.2 Visual Display Systems

The entertainment industry is by far the main user of visual displays and little can be gained by trying to develop new technologies for the medical industry. The best approach is to adapt reasonably mature technologies which are not in danger of being declared obsolete. Simulation of procedures such as laparoscopic surgery would use displays similar to those used in the actual operating room. Simulation of open surgery, on the other hand, requires systems which have yet to be developed. The level of interaction between the surgeon and the patient's body probably requires an immersive display system such as a head-mounted display. The basic technologies already exist to make such a device and several companies in the U.S. are spending large amounts of venture capital to produce systems which could be used in many applications including, of course, entertainment. Several large companies such as Sony are also making and selling head-mounted display (HMD's) which could be adapted for medical simulation. The best approach for a developer of a simulator for open surgery would be to choose a system with good optical qualities and concentrate on developing a clear stable image which does not induce nausea or eye strain during prolonged use of the display.

Alternative designs either exist or should be better developed. "See-through displays", where a synthetic image is superimposed on an actual model and/or on the trainee's hand, are one such example. This could involve the use a high-resolution monitor operated in a stereoscopic mode with the cathode ray tube (CRT) screen at the level of the operating table. Fakespace Systems Inc. makes a similar device for use in computer-aided design applications. The actual display technologies for these and probably other approaches already exist and are not expensive. The characteristics of the displayed image need to be defined in some detail.

2.3 Kinesthetic and Tactile Simulation

The use of force feedback to simulate forces and pressures on an operator's hands and fingers has been found to be extremely effective in telerobotic applications. This feedback actually addresses two human sensorial modalities referred to as the *haptic channel*. *Tactile sensations* are associated with discriminative touch as in the perception of surfaces. It comprises sensations of pressure, local features such as curvature, orientation, puncture, texture, thermal properties, softness, wetness, friction-induced adhesion or lack thereof and micro-failures or vibrations. *Proprioceptive,* or *kinesthetic perception* is the awareness of one's body state, including position, velocity and forces supplied by the muscles through a variety of receptors located in the skin, joints, muscles, and tendons. It is often associated with limbs, but of course applies to all articulated parts of the body subject to voluntary motor control.

Technologies which can address kinesthesia are becoming mature, as seen by the intense industrial activity in the U.S., Europe and Japan, as well as in many university-based centres, in surgical simulation that incorporates haptic devices.

The same technologies have been used in simulations of laparoscopic surgery; however, extending this technology to open surgery, where a surgeon can select various instruments at will, will require a good deal of innovation and may require a different approach. A training device which did not simulate surgical task forces may still be of some use and would obviously be less expensive but would probably meet with disapproval from many surgeons. Accurate simulation of forces would enhance the realism of the overall experience and make the training device far more effective. The situation is not as advanced as far as tactile simulation is concerned, due to the relative absence of adequate tactile displays.

2.4 Simulation of Odours

The actual chemical components which cause the odours associated with various medical conditions are probably well known. Introducing the relevant odour in the vicinity of the internal organ as it is cut open would not be a difficult task. Unless surgeons are unanimous in requiring odour simulation it would probably be offered as an option.

2.5 Modelling and Image Generation

Creating a realistic image of the internal organs of the body as a surgeon would see them during an operation is considerably different from creating an image of a solid environment such as an airport for a flight simulator. In the latter case only the external surfaces are modeled and objects normally retain their original shape. Internal organs however are made of soft tissues which change shape as pressure is applied to the organ and can be cut open to reveal their internal structure. Blood flowing from the cut surface will also change the appearance. It has been suggested that an image generator architecture based on voxels, i.e., very small cubic data base elements would be more appropriate than the conventional data base models which use two dimensional polygons. It may, however, be both economically and technologically advantageous to use the conventional architecture in a manner which allows real time construction of polygons as body tissues or organs are cut open and moved apart. Real time probably has to be no faster than 15Hz. Textures based on photographic images of typical tissues and organs, both healthy and diseased, would be applied to the polygons in a similar manner as in flight simulation. The obvious advantages of this approach is that higher speed computers will enable a closer approximation to real time and PC-based image generators, which are relatively inexpensive and are becoming even more so, can be used to create the final image.

The actual implements used by the surgeon and nurses will almost certainly have to be virtual in order to allow them to be occluded correctly as they are inserted into the virtual body. This will also apply to any fingers or hands which are inserted into the body. This implies that highly accurate tracking devices will need to be developed. The whole issue of how to blend the virtual world in the real world is quite interesting and needs to be tackled. One obvious approach would be to use a hollow mannequin on a real operating table covered with sheets in such a way that a virtual image of the area to be operated on would appear in the correct place. Another approach would be to create an entire virtual body using a head-mounted display. It is difficult to envisage any approach which would provide the realism of an actual operating room but developers would have to try various approaches to see which worked best. Obtaining data regarding the visual appearance of tissues and organs as they are manipulated and cut open during the course of an operation is probably available from the libraries of many teaching hospitals. Data regarding the elasticity of tissues and organs and how their shapes change due to the pressure of fingers and instruments will be more difficult to obtain and may require some experimentation.

Once a system has been developed to simulate the above functions, simulating moving body parts and blood flow would be done in the same manner. This will of course require more computational power and the achievement of close to real time simulation will require extremely efficient software. Collision detection will be another task requiring considerable computational power. Various algorithms are used in flight simulation. In air-to-air refuelling for example, nine vectors are computed from the tip of the refuelling probe to determine when and where the probe touches the aircraft being refuelled. This would work quite well for a scalpel being manipulated by the surgeon but other techniques may have to be used to determine when a hand touches a body part or when one body part touches another. The resulting forces and the effect on the body parts will also have to be computed.

The modelling of other participants such as nurses and anesthetists would probably not be attempted at first. It would probably be sufficient to have an instructor/operator perform the functions of other personnel who would normally take part in the operation. As medical simulation progresses, however, this function will increase in importance and technologies such as voice recognition, robotics and expert systems (or artificial intelligence) will be used.

2.6 Human Factors for System Design

There are several design considerations that need to be addressed in the development of a functional computer-based surgical simulator. One type of simulator may be used for the training of skills, as would be required in early training, while another may be useful for repeated practice of a particular skill across scenarios. This may include the introduction of critical and emergent situations. Another consideration is the use of simulators for the training of more than one participant, and especially, accurately modelling the input of several users simultaneously. Finally, the system should allow for variation in the trainee's level of ability, and make appropriate adjustments, e.g., whether at a fine or gross level of tissue handling.

2.7 Assessment of Trainees

To design an effective training system, one must first establish objectives that are attainable and relevant to the field for which training is being offered. The second issue that must be addressed is whether the training corresponds to the objectives. Finally, and perhaps most importantly, the assessment of performance must provide a summary of the extent to which the objectives were met. Thus, the success of the training program depends on the attainment of relevant objectives. The great challenge, then, for all simulation designers, is to adapt the technology to the objectives of the training program. It is far too common to see significant compromises made in the objectives due to technological limitations. For example, a laparoscopic surgery simulator should provide trainees with the opportunity to experience all clinically-significant responses to their actions. This would include tissue deformation, bleeding, and lesion formation. Without this transferable knowledge, it is difficult to determine whether satisfactory performance on the trainer relates to performance in a clinical environment. For surgery, one obvious solution to this issue is the objective and reliable assessment of intra-operative performance. However, given the complexity of the OR environment and the lack of control over important variables in this setting, a highly-desirable alternative is to improve the look and feel of simulators for training clinically-relevant performance.

2.8 Continuing Education, Remediation and Remote Training

An increasingly important issue in the training of surgical procedures is that of continuing education. Established surgeons and family practitioners alike would benefit from the availability of training simulators for both advanced and minor procedures. In a recent study of graduating family physicians in Canada, Kelly [1998] found that many are uncomfortable with their skill level for routine technical procedures, specifically minor surgical procedures performed in the office. This issue will become increasingly important as it has been shown that performing minor surgical procedures in the generalist's office is more cost-effective than sending patients to specialists [Brown 1979]. Similarly, it may soon be mandated that surgeons retain certification by the completion of advanced refresher courses in technical skills. Finally, along with the established programs for the training of surgical residents, simulation and training centres will be called upon more frequently to assist trainees requiring remediation in technical skills.

3. IMPORTANCE

There are several forces that are placing increasing limitations on the operating room as the major venue for the acquisition of essential surgical skills. First, there is tremendous pressure on surgeons to be more efficient in the operating room due to increasing financial constraints within teaching institutions. Second, teaching hospitals are increasingly populated with patients with very serious and complex surgical problems that mandate the skill of expert technicians working at maximum efficiency. Third, there are appropriate ethical concerns with the teaching of basic surgical skills and procedures on living human patients.

4. ALTERNATIVES

Current alternatives to simulation and training systems involving medical image visualization include training on patients, live animals or low-fidelity bench models.

5. MATURITY AND RISK

Currently, there exist systems for the simulation of endoscopic procedures. There is a great need for the development of systems that will provide training on laparoscopic and open procedures.

6. AVAILABILITY

Current suppliers of computer-based simulators for surgical training include HT Medical Systems' endoscopic simulator and IV cath simulator and Virtual Presence Medical's computer-based laparoscopic trainer (MIST-VR).

7. BREADTH OF APPLICATION

The development of high-fidelity virtual trainers for surgery and medicine would be an important advance for all medical training facilities in Canada. The large number of undergraduate medical students would benefit from training in simple procedures, while more advanced procedures would be useful for residents and fellows, as well as practising clinicians wishing to upgrade their skills.

Recently, there has been increased discussion concerning certification of the maintenance of competence in surgical procedures. This will undoubtedly lead to an increased demand for continuing medical education in these areas.

Finally, the growing patient-driven demand for minimally-invasive procedures seems to be providing increased pressure for the re-training of established surgeons.

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Sources of Information

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    http://www.mdreport.com
Real Time Graphics
    http://www.cgsd.com/

9. CONTACTS

Industrial Contacts

Bertec Corporation, Columbus, Ohio
    http://www.bertec.com/
Biomedical Interactive Technology Centre, Atlanta, Georgia
    http://www.bitc.gatech.edu/bitcprojects/surgsim.html
Boston Dynamics Inc., Cambridge, Massachussets
    http://www.bdi.com/
CAE Inc., Montreal, Quebec
    http://www.cae.com/
Ciné-Med Customer Service, Woodbury, Connecticut
    http://www.cine-med.com/cinemed/service.html
EPIDAURE Medical Imaging and Robotics, Rocquencourt, France
    http://www.inria.fr/Equipes/EPIDAURE-eng.html
Fakespace Systems Inc., Kitchener, Ontario
    http://www.fakespacesystems.com
Haukom Associates, San Francisco, California
    http://www.haukom.com/

HT Medical Systems, Rockville, Maryland
    http://www.ht.com
Immersion Corporation, San Jose, California
    http://www.immersion.com
KISMET Medical Applications, Karlsruhe, Denmark
    http://iregt1.iai.fzk.de/KISMET/kis_apps_med.html
Medical Robotics Related Sites, University of California at Berkeley, Richmond, California
    http://www-path.eecs.berkeley.edu/~mcenk/medical/links.html
MPB Technologies Inc., Pointe-Claire, Quebec
    http://www.mpb-technologies.ca/mpb/products/space/freedom.html
Mitsubishi Electric Research Laboratory, Boston, Massachussets
    http://www.merl.com/
Millersville and Penn State Universities, Pennsylvania
    http://cs.millersv.edu/~webster/haptics
Muse Technologies (Virtual Presence Medical), Albuquerque, New Mexico
    http://www.musetech.com
n-Vision Inc, Mclean, Virginia
    http://www.nvis.com/opthalmi.htm
Simulab Corporation, Seattle, Washington
    http://simulab.com/
Sony of Canada, Ltd., Toronto, Ontario
    http://www.sony.ca
Surgical Dynamics Inc., Norwalk, Connecticut
    http://www.surgicaldynamics.com/
Uniformed Services University of the Health Sciences, Bethesda, Maryland
    http://surgery.usuhs.mil/Bionic.html
University of Colorado Health Sciences Center, Denver, Colorado
    http://www.uchsc.edu/sm/chs/products/products.htm
University of Washington School of Medicine, Department of Surgery, Seattle, Washington
    http://depts.washington.edu/surgery/
Virtual Motion, Pittsburgh, Pennsylvania
    http://www.vm3.com/
Virtual Presence Medical (Muse Technologies), London, United Kingdom
    http://www.VRWeb.com/

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APPENDIX A

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APPENDIX C

Critical Technology Template

1. **TECHNOLOGY WORKING GROUP**:
WG name.

2. **CRITICAL TECHNOLOGY**:
Technology name.

3. **RANKING**:
Rank of this technology among the technologies investigated by the WG (i.e. 3/5).

4. **GOALS**:
The performance goals of the technology:
- *are driven by customer requirements;*
- *should be defined in quantitative and qualitative terms (without disclosing proprietary information);*
- *include economic (cost, etc.), time (cycle time improvements, etc.), and physical property considerations.*

5. **DESCRIPTION**:
Brief technical description of the technology.

6. **IMPORTANCE**:
Why is the technology critical (e.g., regulatory requirements, customer demands, financial and other competitiveness issues); when is the technology required; to whom is the technology critical; what happens if the technology is not available or implemented.

7. **CLINICAL REQUIREMENTS**:
What clinical requirements must the technology satisfy?

8. **ALTERNATIVES**:
Other technologies, non-technological solutions, product substitution, etc.
- *Each WG should be familiar with the technologies under investigation by the other WGs, so that linkages can be made among alternative or competing technologies.*

9. **MATURITY AND RISK**:
- *What can the technology do today;*
- *What incremental capabilities are required to produce the products required for the 2001 through 2005 time period; and*
- *What risks are associated in obtaining these incremental capabilities.*

10. **AVAILABILITY**:
Where is the technology currently available, from whom, how, cost considerations, etc.

11. **BREADTH OF APPLICATION**:
How broadly can the technology be applied: which areas of the medical imaging industry, what other industry sectors, etc.

12. **COLLABORATORS**:
Potential sources of help in developing or acquiring, and implementing the technology:
Examples: NRC, primes working with suppliers, etc.

13. **COST-BENEFIT ANALYSIS**:
Costs could include technology development or acquisition, and implementation. Benefits are based on an estimate of market usage of the enabling technology.

14. **REFERENCES**:
List of pertinent documents.

15. **CONTACTS**:
Resource persons for further information.