Principles and Applications of Medical Virtual Environments

F. P. Vidal[1], F. Bello[2], K. Brodlie[3], N. W. John[1], D. Gould[4], R. Phillips[5], and N. J. Avis[6]

[1] University of Wales, Bangor, UK
[2] Imperial College London, UK
[3] University of Leeds, UK
[4] University of Liverpool, UK
[5] University of Hull, UK
[6] Cardiff University, UK

Abstract

The medical domain offers many excellent opportunities for the application of computer graphics, visualization, and virtual environments, offering the potential to help improve healthcare and bring benefits to patients. This report provides a comprehensive overview of the state-of-the-art in this exciting field. It has been written from the perspective of both computer scientists and practicing clinicians and documents past and current successes together with the challenges that lie ahead. The report begins with a description of the commonly used imaging modalities and then details the software algorithms and hardware that allows visualization of and interaction with this data. Example applications from research projects and commercially available products are listed, including educational tools; diagnostic aids; virtual endoscopy; planning aids; guidance aids; skills training; computer augmented reality; and robotics. The final section of the report summarises the current issues and looks ahead to future developments.

Keywords: Augmented and virtual realities, Computer Graphics, Health, Physically based modelling, Medical Sciences, Simulation, Virtual device interfaces.

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1. Introduction

Over the past three decades computer graphics and visualization have played a growing role in adding value to a wide variety of medical applications. The earliest examples were reported in the mid 1970's when three-dimensional visualizations of Computerized Tomography (CT) data were first reported [RGR*74, HL77]. Today, a variety of imaging modalities are in common use by the medical profession for diagnostic purposes, and these modalities provide a rich source of data for further processing using computer graphics techniques. Applications include medical diagnosis, procedures training, pre-operative planning, telemedicine, and many more [MS01]. In 2003 the Eurographics Association launched the first of a bi-annual Medical Prize competition to acknowledge the contribution that computer graphics is playing in this exciting field and to encourage further research and development. The overall winner in 2003 was "Augmented Reality based Liver Surgery Planning" [BBR*], which uses computer augmented reality to support radiologists and surgeons in finding the optimal treatment strategy for each patient. The researchers' use of new media technology demonstrates well how far the state-of-the-art has progressed since the early work in medical visualization.

Below, we trace the history and development of the use of medical visualization and virtual environments (VE), and highlight the major innovations that have occurred to date. Dawson [DK98] summarises well the three most important criteria for surgical simulators: they must be validated, they must be realistic, and they must be affordable. It is only by satisfying all of these criteria that a surgical simulator can become an accepted tool in the training curriculum, and provide an objective measure of procedural skill. These factors are equally applicable to all medical applications where computer graphics is applied. The latest generation of computer hardware has reached a point where for some applications realistic simulations can indeed be provided on a cost effective platform. Together with the major changes that are taking place in the way in which medical professionals are trained, we believe that there will be a growing demand for the applications and techniques that are discussed in this report. Validation of these tools must of course be carried out before they can be used in everyday clinical practice, and this area is sometimes overlooked. The most successful projects are therefore multi-disciplinary collaborations involving clinicians, computer scientists, medical physicists and psychologists.

This state-of-the-art report includes a comprehensive reference list and summarises the important work and latest achievements in the field of medical virtual environments. In Section 2 below, we begin with an overview of medical imaging modalities. The current constraints on clinical training are then discussed, which highlight the need for extending the use of medical visualization and virtual environments. Section 3 focuses on the enabling technologies from advanced graphics algorithms, to specialist and commercial off the shelf hardware. Section 4 shows how these technologies have been used to provide innovative applications. Applications are categorized into the following areas: educational tools; diagnostic aids; virtual endoscopy; planning aids; guidance aids; skills training; computer augmented reality; robotics; and telemedicine. This section ends with an overview of the currently available commercial products that implement a medical virtual environment. Section 5 discusses the current and future challenges in this domain, and we end with conclusions.

2. Background

2.1. Retrospective of Medical Imaging

The interest for physicians to look into the human body has existed since antiquity. Indeed the first reference of endoscopy corresponds to the description of the examination of the rectum with a speculum by Hippocrates (460-375 BC) [BF00]. Since this first reference to a medical imaging technique, much progress has been made: examination of the internal organs and structures of the body using visible light has become commonplace and many other physical properties have now been adopted for imaging purposes.

The history of the first imaging technique, endoscopy, is recalled in Sub-section 2.1.1. Then, the evolution of X-ray imaging, from the first radiograph to micro-tomography, is highlighted in Sub-section 2.1.2. Having highlighted two of the main modalities of medical imaging, ultrasound is then reviewed in Sub-section 2.1.3. The modality which has became more and more popular, nuclear magnetic resonance imaging, is presented in Sub-section 2.1.4. Finally, nuclear medicine imaging is briefly introduced in Sub-section 2.1.5.

2.1.1. Fibre Endoscopy

The first endoscope was built in the early 1800's by Philip Bozzini. This instrument, called the "Lichtleiter", could be introduced into the human body to view internal organs using a candle as the source of light directed into the cavity of the body and redirected to the eye of the observer [Lit96]. However, he never tested it in humans because his colleagues were hostile to the procedure [BF00]. Nevertheless five decades later, in 1853, Antoine Jean Desormeaux, considered as the "Father of Endoscopy", first introduced the Lichtleiter into a patient with a lamp flame as the light source [BF00, Lit96]. It was mainly used for urological cases.

In 1881 Johann Mikulicz performed the first clinical use of esophagoscopy, an endoscopy with a rigid tube [Lit99]. Then, to observe the effect of pneumoperitoneum on the abdominal organs, Georg Kelling introduced, in 1901, a cystoscope into the abdominal cavity of a dog; this was the first laparoscopy [BF00, Lit99]. In 1910, Hans Christian Jacobaeus performed the first clinical laparoscopy and thoracoscopy on a human [BF00, Lit99].

After the second World War, the two most important improvements of endoscopic techniques came from the invention of the rod-lens system and the fiber-optic by Harold H. Hopkins. In 1957, Basil Hirschowitz tested the first fiber optic endoscope on a patient. It is a device using fiber optics and lens systems to provide lighting and visualization of the interior of the body.

In 1982, video-laparoscopy appeared with the introduction of the first solid state camera. Five years later, and thirty years after testing the first fiber optic endoscope, Phillipe Mouret performed the first video-laparoscopic cholecystectomy but never published it [BF00]. Since then, numerous contributions have carried surgery to a new approach: micro-invasive techniques.

Exhaustive retrospectives of endoscopy can be found in [BF00, Lit99].

2.1.2. X-ray and X-ray Tomography

As stated previously, the first attempts to obtain images from inside the human body used visible photons. X photons, which are non-visible to the human eye, were discovered in 1885 by Wilhelm Conrad Röntgen [Jen95]. After demonstrating images of bones, he was awarded the Nobel prize in 1901 for the discovery of X-rays. Since then, the conventional X-ray radiograph has been extensively used as a diagnostic aid in medicine [Zon95]. When X-rays are projected through the human body onto a photographic film or more recently, a digital detector, anatomical structures are depicted as a negative grey scale image according to the varying attenuation of the X-ray beam by different tissues. Conventional X-ray radiographs are still commonly used, for example in the diagnosis of trauma and chest disease. Landmarks in the evolution of Radiology include the first iodized contrast agent in 1943 which led to angiography, and the development of computed tomography (CT) from simple axial tomography enabling acquisition of volumetric data of anatomical structures.

X-rays are an electromagnetic radiation (like visible radiation), generally emitted when matter is bombarded with fast electrons (X-ray tubes). Their wavelengths are very small (typically from 10 to 0.001 nanometres). There are plenty of techniques for generating X-rays (X-ray tube, linear accelerator, synchrotron, *etc.*). Nowadays, X-ray tubes are still the main device used by radiographers to produce X-rays. The first accelerators (cyclotrons) were built in the 1930's. A few years after, in 1947 in the USA, at General Electric, synchrotron radiation was observed for the first time [Ble93, Wil96]. Initially, it was considered as a nuisance because particles lose energy. Nevertheless, the flow of photons is much higher than in the case of X-ray tubes. Nowadays, synchrotron radiation sources are compared to "super-microscopes" and are used in medical imaging [ST03], *e.g.* transvenous coronary angiography [EFE*00].

Many decades after the discovery of X-rays, in 1921, the first classical tomographic device was introduced. Later on, Hounsfield successfully tested the first clinical Computerized Axial Tomography (CAT, generally reduced as Computerized Tomography, or CT) in 1972 [Hou73] (Nobel Prize in Physiology or Medicine in 1979). Tomography is a non-destructive technique (NDT) [KS88, Mic01]. It is a multi-angular analysis followed by a mathematical reconstruction which produces images of transaxial planes through the body from a large number of projections. Generally, these projections are acquired using a coupled detector/X-ray source which rotates around the patient. Then, the reconstruction process produces a 2D slice or tomograph of X-ray attenuation coefficients. 3D datasets can be formed by stacking 2D tomographs. More recently, tomography with a spatial resolution better than 20 µm, called micro-tomography, has emerged. This can be achieved using micro-focus X-ray tubes, however the best images are produced by parallel and monochromatic X-ray beams of synchrotrons. This generates 3D images of micro-structure without an *a priori* model; for instance the 3D microscopy of a sample, about 1 mm in diameter, of bone from the calcaneum region obtained by biopsy [CLB*02].

2.1.3. Ultrasound

Independently, two decades after the discovery of X-rays, the first application of ultrasound in the field of medicine appeared, applied in therapy rather than in diagnosis. Diagnostic imaging techniques by 2D ultrasonography appeared in the early 1950's [Wil50, HB52, Gol00]. The first systems acquired only single lines of data. Nowadays it is possible to produce greyscale cross-sectional images using pulse-echo ultrasound in real-time. Pulses are generated by a transducer and sent into the patient's body where they produce echoes at organ boundaries and within tissues. Then, these echoes are returned to the transducer, where they are detected and displayed on a screen. The biggest advantage of this technique is the fast acquisition time, which enables rapid diagnostics producing greyscale images of nearly all soft tissue structure in the body. Two-dimensional ultrasound (2D US) has been used routinely in obstetrics and gynaecology since the 1960's [Gol00].

Nevertheless, ultrasound is not restricted to the field of one or two dimensional (1D/2D) signals. Indeed 3D imaging by ultrasound has been available since 1974 [DPD74] and clinically available since the 1990's. This method is well suited for examining the heart [DPD74, SR95, FK03] as well as embryos and foetus [Gol00]. The first techniques of 3D ultrasound were off-line and based on the combination of 2D images and their spatial position obtained with a mechanical articulated arm, into a 3D volume. A second method, called the freehand technique [BAJ*97], is also used to acquire volumes of ultrasound data. A position sensor is mounted on a conventional 2D US transducer. The transducer is swept through the region of interest and the position sensor allows the capture of multiple 2D US images. Several other data acquisition techniques are available [KVR03]. By gating 3D ultrasound acquisition with the ECG signal of the heart, 4D images of the beating heart can now be obtained.

2.1.4. Nuclear Magnetic Resonance Imaging

Another fundamental discovery in the field of 3D medical imaging is incontestably the technique of nuclear magnetic resonance imaging (NMRI) [Kee01], also called magnetic resonance imaging (MRI) due to the negative connotations associated with the term nuclear. It is also a tomographic technique which produces the image of the NMR signal in a slice through the human body. According to current knowledge, MRI is harmless, contrary to X-ray tomography which uses harmful ionizing radiation. Thus MRI has a great advantage over 3D X-ray imaging. However MRI is proscribed in patients with metal implants or pacemakers due to its use of a strong magnetic field.

The fundamental principle of the magnetic resonance phenomenon was discovered independently by Felix Bloch and Edward Purcell in 1946 (Nobel Prize in 1952). In a strong magnetic field, atomic nuclei rotate with a frequency which depends on the strength of the magnetic field. Their energy can be increased if they absorb radio waves with the same frequency (resonance). When the atomic nuclei return to their previous energy level, radio waves are emitted. Between 1950 and 1970, NMR was developed and used for chemical and physical molecular analysis. In 1971, Raymond Damadian showed that the nuclear magnetic relaxation times of tissues and tumours differed, consequently scientists were considering magnetic resonance for the detection of disease. In parallel to the development of X-ray tomography, Paul Lauterbur tested MRI tomography using a back projection algorithm similar to that used in X-ray tomography. In 1975, Richard Ernst proposed MRI using phase and frequency encoding, and the Fourier Transform (Nobel Prize in Chemistry in 1991), which is still the base of current MRI. A couple of years later, Raymond Damadian demonstrated MRI of the whole body and Peter Mansfield developed the echo-planar imaging (EPI) techniques. Since then, MRI has represented a breakthrough in medical diagnostics and research, indeed it allows human internal organs to be imaged with exact and non-invasive methods without deposing an energy dose. Later on, in 1993, functional MRI (fMRI) was developed. This allows the mapping of the function of regions of the brain. Lauterbur and Mansfield won the Nobel Prize in Physiology or Medicine 2003 for their discoveries concerning magnetic resonance imaging.

2.1.5. Nuclear Medicine Imaging

Nuclear medicine [Bad01] appeared in the 1950's. Its principle is to diagnose or treat a disease by administering to patients a radioactive substance (also called tracer) which is absorbed by tissue in proportion to some physiological process. This is the radiolabelling process. The substance can be given by inhalation of a radioactive aerosol, ingested or, by injection of radioactive pharmaceuticals into the blood stream. In the case of diagnostic studies, the distribution of the substance in the body is then imaged: unlike in X-ray imaging or therapy, no radiation is applied from an external source. Moreover diagnostic nuclear medicine studies are generally a functional form of imaging because the purpose is to obtain information about physiological processes rather than (as with X-ray imaging) anatomical forms and structures. The photons in nuclear medicine generally have a higher energy than X-ray. Therefore dedicated detectors, called gamma camera (or Anger camera), are used instead of films.

In the case of planar imaging, gamma cameras are used as ‘films’: nevertheless it is possible to reconstruct slices through the human body using similar methods to those used in CT (par. 2.1.2). In nuclear medicine, this method is called single-photon emission computed tomography (SPECT) and it allows 3D reconstruction of the distribution of the tracer through the body.

For positron emission tomography (PET), a positron emitter is used as radionuclide for labeling rather than a gamma emitter. Positrons are emitted with high energy (1 MeV). After interactions, a positron combines with an electron to form a positronium, then the electron and positron pair is converted into radiations: this is the annihilation reaction which generally produces two photons of 511 keV emitted in opposite directions. Annihilation radiations are then imaged using a system dedicated to PET containing an Anger camera specialized in high-energy. This system operates on the principle of coincidence, *i.e.* the diffference in arrival times of the photons of each pair of detected photons and by knowing that each annihilation produces two photons emitted in exactly opposite positions: 3D images are then reconstructed in the same way as SPECT.

2.2. Clinical Skills Training Constraints

The increasing availability of high resolution, volumetric imaging data (including multi-detector CT, high field strength MR, and 3D ultrasound) within healthcare institutions has particularly impacted on the speciality of Radiology, where such data are in widespread use for diagnosis and treatment planning and delivery. The generation of patient specific virtual environments from such information will prove pivotal in future developments in therapeutics, teaching, procedure rehearsal and augmented reality. This is exemplified in interventional radiology (IR), where various combinations of imaging data are used to guide minimally invasive interventions [Mer91]. This includes fluoroscopy for angioplasty and embolisation, CT and ultrasound for biopsy and nephrostomy and, at the development stage, open MR scanning for real time catheter guidance.

There is currently a shortage of radiology consultants, and specifically those specialised in IR, both within and outside the UK. Limitations in the current processes of apprenticeship training [Edu99] (par. 4.6), together with regulatory restrictions on working hours during training years, are driving a need for a fresh approach to teaching clinical skills. Further factors are patient issues during the learning curve, such as discomfort and complications, and the known deskilling which occurs in low throughput scenarios.

Amongst new paradigms for learning clinical skills, there is a precedent in surgery for training and objective assessment in validated models [MRR*97, TSJ*98, Eur94, FRMR96, LCG98, BT02]. Virtual environments have been introduced to train skills in laparoscopy, perhaps the most successful of these being the MIST VR (Mentice Corporation, Gothenberg) (par. 4.10.4) [TMJ*98]. Application of virtual environments (VE) to train in interventional radiological procedures, with specific objective measures of technical skill, would allow radiologists to train remotely from patients, for example within the proposed Royal College of Radiologists' training Academies. This would improve access to clinical skills training while increasing efficiency in the NHS due to removal of the time consuming early period of training from patients. Prevention of deskilling and a wider availability of IR skills could address unmet needs for these procedures, for example in cancer patients.

3. Enabling Technologies

3.1. Software Algorithms

In recent years there have been major advances in software algorithms for the display of medical data. The starting point is a 3D dataset acquired from some scanning device, and a typical first step is to apply a segmentation algorithm to identify different parts of the anatomy of particular interest. This is often done as a pre-processing step, to label voxels with an identifier indicating the type of material. The process remains semi-automatic, with user guidance needed in order to help correct identification. For example, region growing algorithms need to be initiated with a user defined seed point. Current state of art is reviewed in papers such as [BMF*03] who segment out the elaborate tree-like structure of the bronchi.

The main approaches to the visualization of volumetric data in medicine are described below. Brodlie [BW00] provides a more detailed survey. We then provide an overview of the main techniques used for combining two or more image modalities of the same patient - often called image fusion or 3D image registration. Finally we summarise the algorithms being used for soft tissue modelling - an important component of a medical virtual environment.

3.1.1. Surface Rendering

The principle of surface extraction algorithms is to extract explicitly an intermediate representation which approximates the surface of relevant objects from the volume data set. For example, we might want to extract the surface of bones from a CT dataset. The surface extracted corresponds to a specified threshold value. The surface is extracted as a polygonal mesh, typically a triangular mesh, which can be rendered efficiently by graphics hardware (Figure 1).

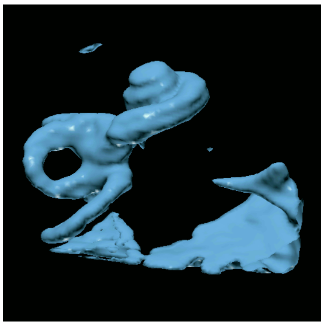
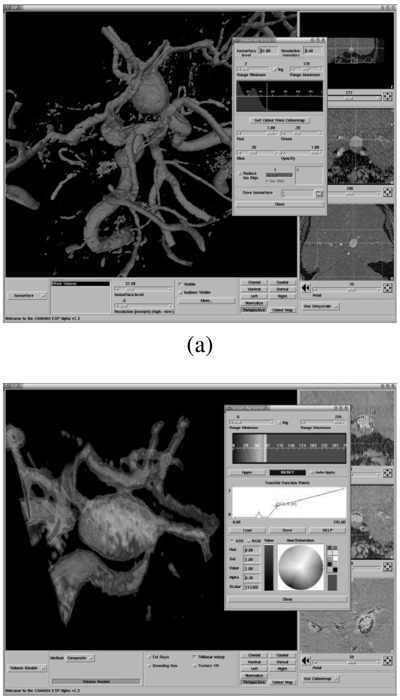


Figure 1: *Isosurface of a human cochlea generated from MRI data (image courtesy of Paul Hanns).*

The most popular algorithm in use is Marching Cubes [LC87], or one of its derivatives [DK91, GH95, LB03b]. The idea is to process the data cell-by-cell, identifying whether a piece of the surface lies within the cell, and if so, constructing an approximation to that surface. For large datasets, it is important to be able to identify quickly cells which contribute to the surface: current research on fast identification of isosurface location can be found in [CSA03] (contour trees) and [BS03] (searching 'interval' space defined by maxima and minima of cells).

Medical applications have been the first to exploit this facility. According to Schreyer and Warfield, most clinical applications involving 3D visualization can take advantage of this technique [SW02]. As an example, Figure 2(a) shows such a surface generated by *endovascular surgical planning software* implemented at the Manchester Visualization Centre (MVC) [PLL*01]. Here the high contrast in the source magnetic resonance angiography data make surface rendering a good technique for representing the network of blood vessels in the brain. In general, however, care must be taken to avoid the effects of false positives and false negatives as the surface extracted at a particular threshold value may not represent a true surface.



(a)

(b)

Figure 2: *Visualization from MRA data of a patient suffering from a brain haemorrhage (from [JM03]). (a) Surface extraction algorithm, (b) Ray-casting algorithm.*

3.1.2. Volume Slicing

Of course a simple approach to visualizing a volume is to visualize a series of slices, either parallel to one of the faces of the volume, or in an oblique direction. A difficulty with this approach is that vessels of interest such as vascular structures are non-planar and therefore cannot be easily followed in such an approach. A recent idea is to use Curved Planar Reformation, where a 'curved' slice following the trajectory of a vessel is presented [KWFG03].

3.1.3. Volume Rendering

In (direct) volume rendering, as opposed to explicit surface extraction, voxel-based data are directly visualized without extracting an intermediate surface representation. Figure 3 shows an example of a volume rendering obtained from CT data.

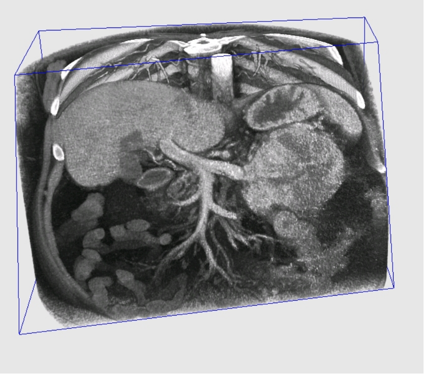


Figure 3: *Volume Rendering generated from CT Data Scan showing the relationship between the confluence of the superior mesenteric, splenic and portal veins with a large tumour.*

Each voxel of a 3D dataset is assigned a colour value and an opacity value, creating an entity which can be thought of as a multi-coloured gel. Voxels are assigned colour and opacity using the idea of a transfer function. A simple transfer function will assign colour and opacity from the value of the data, but in practice multi-dimensional transfer functions are used. For example, in the early work on volume rendering, the transfer function depended on both value and gradient, in order to highlight boundary surfaces [Lev90]. More recently, curvature-based transfer functions have been proposed [KWTM03].

There are four basic approaches to direct volume rendering. High quality, at the cost of compute time, is provided by ray casting and splatting; lower quality, but faster, is provided by shear-warp rendering and texture-based methods. The increasing power of graphics hardware is encouraging hybrid methods - for example, combined ray casting and textures [KW03].

A difficulty with datasets which are acquired from scanners (indeed any measuring apparatus) is the fact that the data is contaminated by noise. The edge detection concept of image processing can be carried over to 3D datasets, to provide a means of removing noise from the surface. This is described in [PSP*03] in the context of virtual colonoscopy.

Figure 2(b) shows another example from MVC's *endovascular surgical planning software*, illustrating the view of an aneurysm and surrounding blood vessels rendered by ray-casting [Lev90]. Whereas Figure 3 is a volume rendering of a high resolution CT data set of a patient with a large tumour below the stomach.

An important technique in medical volume rendering is maximum intensity projection, or MIP. This is particularly useful for the visualization of blood vessels from MR imaging. It is based on the fact that the data values of vascular structures are higher than surrounding tissue. Often a contrast agent is introduced into the blood stream before the patient is scanned so that the intensity value of the vascular structures is increased further. By modifying the ray casting technique to pick out the voxel of maximum intensity (rather than compositing contributions from all voxels as would normally be done), we obtain a fast, effective and robust technique [MHG00].

Currently, specialist companies are developing medical 3D visualization software. For instance, *Voxar 3D* [Vox] by Voxar, or *Vitrea 2* [Vit], by Vital Images, are fast software products, optimized for PC, which are DICOM compliant for integration into a hospital's network. *MedicView 3D* [Medb] is another generic software dedicated to visualization of 3D medical image files (*e.g.* DICOM format). It combines the three kinds of visualization, *i.e.* displaying all the 2D slices on the screen, rendering up to two isosurfaces with different iso values for rendering both skin and bone surfaces and, volume rendering including stereo visualization with *CrystalEyes*. *Voxel-Man 3D-Navigator* is another PC software designed for teaching and studying anatomy and radiology using interactive 3D atlas [Uni]. There are also hardware solutions for volume rendering as described in Sub-section 3.3.1.

3.1.4. Image Fusion

With the abundance of medical imaging technologies and the complementary nature of the information they provide, it is often the case that images of a patient from different modalities are acquired during a clinical scenario. In order to successfully integrate the information depicted by these modalities, it is necessary to bring the images involved into alignment, establishing a spatial correspondence between the different features seen on different imaging modalities. This procedure is known as *Image Registration*. Other terms used are Image Co-registration, Image Alignment or Image Matching. Once this correspondence has been established, a distinct but equally important task of *Image Fusion* is required to display the registered images in a form most useful to the clinician. In the abscence of computerised, automated image registration, it is the clinician's task to mentally combine the information from multiple images of a patient, compensating for the changes in subject position and the peculiarities of the modalities involved.

Image registration techniques have been applied to both monomodality and multimodality applications. Registration of images from multiple modalities is generally considered a more difficult task. Nevertheless, there are significant benefits to the fusion of different imaging modalities. For example, in the diagnosis of epilepsy and other neurological disorders, it is common for a patient to undergo both anatomical (MRI, CT, etc.) and functional (PET, fMRI, EEG) examinations. Image guided surgery also makes extensive use of pre-operatively acquired imaging data and intra-operatively generated surface imaging and/or ultrasound for procedure guidance. Automated registration of the information from all possible combinations of these various modalities benefits the clinician, surgeon and, ultimately, the patient.

Various classifications of image registration methods have been proposed [MF93, MV98, HHH01]. Classification criteria include Dimensionality (2D-to-2D, 3D-to-3D, 2D-to-3D), Domain of the Transformation (global or local), Type of the Transformation or Degrees of Freedom (rigid, affine, projective, non-linear), Registration Basis (extrinsic, intrinsic, non-image based), Subject of Registration (intra-subject or inter-subject) and Level of Automation (automatic, semi-automatic).

A large body of the literature addresses 3D-to-3D image registration, and it is certainly in this area where techniques are most well developed. 3D/3D registration normally applies to tomographic datasets, such as MRI or CT volumes. Examples include the registration of time-series MR images in the early detection of breast cancer [RHS*98, DSR*99]. Registration of separate 2D tomographic slices or intrinsically two-dimensional images, such as X-ray, are possible candidates for 2D-to-2D registration. Whilst the complexity of registration is considerably reduced compared to higher dimensionality transformations, examples of 2D-to-2D registration in the clinical domain are rare [HRC*91]. This has been attributed to the general difficulty in controlling the geometry of image acquisition [HHH01]. There are generally two cases for 2D-to-3D registration. The first is for the alignment of a 2D projection image with a 3D volume, for example when aligning an intraoperative X-ray or fluoroscopy image with a pre-operative MR volume. Secondly, establishing the position of one or more 2D tomographic slices in relation to an entire 3D volume is also considered 2D-to-3D registration [HRH*95].

Rigid registration generally describes applications where the spatial correspondence between images can be described by a rigid-body transformation, amounting to six degrees of freedom (three rotational, three translational). Rigid techniques apply to cases where anatomically identical structures, such as bone, exist in both images to be registered. Affine registration additionally allows for scaling and skewing between images, yielding twelve degrees of freedom. Unlike rigid-body transformations, which preserve the distance between points in the object transformed, an affine transformation only preserves parallelism. Affine techniques have proven useful in correcting for tomographic scanner errors (*i.e.* changes in scale or skew), although few approaches use an affine scheme as a substitute for the standard rigid-body transformation, as it does not greatly increase the number of problems which can be solved. Non-rigid registration approaches attempt to model tissue deformation and entail transformations with considerably larger numbers of degrees of freedom, allowing non-linear deformations between images to be modelled. In general, non-rigid registration is a more complex problem, with fewer proven techniques.

Landmark-based registration techniques use a set of corresponding points in the two images to compute the spatial transformation between them. We divide landmark registration approaches into *extrinsic* methods, based on foreign objects introduced to the imaged space, and *intrinsic* methods, *i.e.* based on the information provided by the natural image alone. Extrinsic approaches are common in image-guided surgery [MFM*92, MFG*95, MFW*97]. The artificial landmarks used, often referred to as *fiducial markers*, are designed to be highly salient and accurately detectable, preferably without human intervention. To achieve workable accuracy, care must be taken to ensure the coordinate computed for each marker within each modality corresponds to the same point in physical space. Intrinsic methods [EMCP89, FRR96, PDM*96] instead rely solely on anatomical landmarks which can be elicited from the image data. These are usually identified interactively by a skilled user. Intrinsic landmark-based registration is, in theory, a very versatile method of registration, as it can be applied to images of any type. However, automated and reliable identification of intrinsic landmarks remains a difficult problem.

Rather than develop correspondence between sets of points within two images, surface- or segmentation- based methods compute the registration transformation by minimising some distance function between two curves or surfaces extracted from both images. Segmentation-based registration methods have been used for both rigid and non-rigid applications [BHK01].

Voxel similarity-based algorithms operate solely on the intensities of the images involved, without prior data reduction by segmentation or delineation of corresponding anatomical structures [VW97, MCV96]. Voxel property-based methods tend to use the full image content throughout the registration process. Although the number of points to be aligned is far greater than feature-based registration methods, no feature extraction step is required. An immediate advantage of this approach is that any errors caused by signal noise or erroneous feature detection are likely to have less effect on the final accuracy of registration.

As noted in [MV98, HHH01], whilst there exists a large body of literature covering registration methods, the technology is presently used very little in clinical practice, with one or two major exceptions. This can be attributed to several likely factors. Firstly, image registration is a relatively new research area and awareness of the technology and its capabilities, along with support from clinical, scientific and commercial communities will take both time and financial investment. Secondly, image registration is only one component of an entire medical image analysis framework, whose other components (such as segmentation and labelling) in many cases may be insufficiently reliable, accurate or automated for everyday clinical use [HHH01]. Also, there are numerous logistical problems involving the integration of analogue and digital data obtained from different imaging modalities.

3.1.5. Soft Tissue Modelling

In general, soft-tissue modelling algorithms can be classified as either *geometrically-based* or *physically-based*. With geometrically-based modelling, the shape of an object is adjusted by changing the position of some control points, or by adjusting the parameters of an implicit function defining the shape. A typical example of this type of technique is Free Form Deformations (FFD) [SP86], where the object is embedded into a lattice of a simple shape. Deformation of the lattice causes a consequent deformation of the object. These methods are often fast, but the object deformation is carried out indirectly and may bear little or no resemblance to the physically plausible deformation. Recent research has focussed on improving the user interaction with the objects to allow direct manipulation - see [HZTS01] for example.

In contrast, physically-based modelling methods embed the material properties into the object model. Physics laws govern the movement of object elements. These methods can explicitly represent the real-life, dynamic behaviour of objects. Object deformation is applied in an intuitive manner, typically by interacting directly with the object. One of the most widely used approaches in physically based modelling is the mass-spring technique [KAM00, NT98]. The objects are constructed as a set of mass points, or particles, connected by damped springs. The particles move based on the forces applied. This is a relatively fast modelling technique and easy to implement. Reported difficulties with the mass-spring technique [LTK03] include unrealistic behaviour for large deformations, and problems with harder objects such as bone.

A different approach is a fast deformable modeling technique, called 3D ChainMail [Fri99, Gib97a, Gib97b, SGBM98]. A volumetric object is defined as a set of point elements, defined in a rectilinear mesh. When an element of the mesh is moved, the others follow in a chain reaction governed by the stiffness of the links in the mesh. Recent work has extended the 3D ChainMail algorithm to work with tetrahedral meshes [LB03a]. The resulting algorithm is fast enough to be used for interactive deformation of soft tissue, and is suitable for a Web-based environment.

Compared to the mass-spring technique, the Finite Element Method (FEM) approach [BC96] produces results of greater accuracy. An FEM model subdivides the object into a mesh of simple elements, such as tetrahedra, and physical properties such as elastic modulus, stresses and strains are associated with the elements. The equilibrium equations for each element, which govern their movement, are solved numerically. Because of its highly computational nature, this method is typically used in applications such as surgical planning [ZGHD00], where real time interaction is not required; it is not presently practical for most interactive applications.

While the ability to interactively simulate the accurate deformation of soft tissue is important, a system that does not include the capability to modify the simulated tissue has limited utility. Considerable efforts have been made by the research community to improve on the modelling and interactivity of soft tissue. Most of these efforts have concentrated on pre-computing deformations or simplifying the calculations. There have been several attempts at locally adapting a model in and around the regions of interest [CGS99, Wu01]. However, these models rely on a preprocessing phase strongly dependent on the geometry of the object, with the major drawback that performing dynamic structural modification becomes a challenging issue, if not impossible. More recently, a model which adapts the resolution of the mesh by re-tesselating it on-the-fly in and around the region of interaction was presented in [PBKD02]. This adaptive model does not rely on any pre-processing thus allowing structural modifications (Figure 4). Because of its highly computational nature, this method is typically used in applications such as surgical planning [ZGHD00], where real time interaction is not required; it is not presently practical for most interactive applications, but solutions are starting to appear, for example, in suturing [BTB*04].

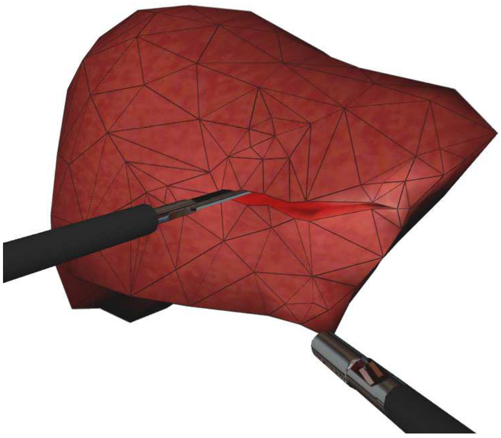


Figure 4: *Adaptive soft tissue modelling with cutting and grasping.*

3.2. Physical Properties of Organs / Tissues / Instruments (*e.g.* needles, catheters, wires)

In simulator models based on a VE, a sense of realism is important [DK98] and can be influenced through the visual and haptic [GPO02] (par. 3.4) elements. The skills of laparoscopic surgery are visuo-spatial and haptics are of lesser importance than in Interventional Radiology (IR) which relies heavily on a sense of touch. Haptics is therefore likely to be of greater importance in attaining 'reality' in simulation of IR procedures, though this is as yet, unproven. The force feedback ('feel') delivered in VR simulator models is generally an approximation to a real procedure, as assessed by experts. In virtual reality training systems, haptics based on real procedural forces should allow a more authentic simulation of the subtle sensations of a procedure in a patient. The nature of tissue deformation is however, nonlinear and this introduces a need to acquire information from direct study [CDL04, DS02] of static and dynamic forces in tissues. In evaluating needle puncture procedures, for example, in vitro studies are more essential for detailed study of the physical components and effects of overall summated forces. Thus the biomechanical properties, and consequently much of the 'feel', of a needle puncture derive from steering effects, tissue deformation, and from resultant forces at the proximal end of the needle representing integration of forces from the needle tip (cutting, fracture) and the needle shaft (sliding, friction, clamping, stick-slip) [KTK*02, DS02]. In evaluating the components of the integrated, needle driving forces, in vitro studies are essential in distinguishing the tip and shaft forces [DS02, SO02, KTK*02]. Owing to the different physical properties of living tissues, in vitro data requires verification by in vivo measurements [BUB*01]. While in vivo study offers a unique method of clarifying the integrated, needle driving forces in living tissues, there is a dearth of literature on measurement of instrument-tissue interactions in vivo: important studies have however been performed during arthroscopy [PWS*03] and in needle puncture in animals [BUB*01]. Until recently there were few devices available for measurement of instrument forces in vivo unobtrusively: use of cumbersome measurement systems for in vitro studies [APT*03, DS02, KTK*02] allows a high degree of accuracy with a facility to record needle orientation in relation to tissue specimens but these methods are not applicable to the in vivo scenario owing to their obtrusive nature. Flexible capacitance pads (Figure 5) present a novel opportunity to collect these data in vivo and calibration in vitro (Figure 6) has shown that output is stable and reproducible [HEM*04].

Figure 5: *Capacitance sensor with conditioning unit.*

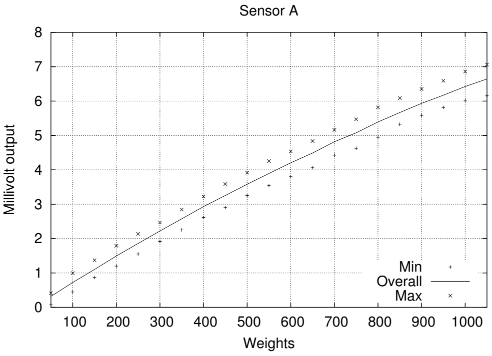


Figure 6: *Raw data loading curve (10 measurement series) sensor A: output (volts) / applied force (grams). Acknowledgement: AE Healey, J Evans, M Murphy, T How, University of Liverpool.*

These devices therefore provide a method of clarifying the resultant force generated by an instrument: they are unobtrusive, can be worn under surgical gloves and connected to recording apparatus during medical procedures. Needle guidance by ultrasound imaging during procedures in patients affords a method of correlating the integrated force values obtained from the sensors with the anatomical structures traversed by the needle [SO02]. Figure 7 shows sensor output over a 55 second period during ultrasound guided needle puncture of an artery in a male arteriopath. The elevated baseline is due to the compressive force of the finger stall used to secure the capacitance pads to the operator's finger tip. There is a low amplitude periodic waveform recorded during needle / vessel wall contact (commencing at left arrow in Figure 7) with periodicity correlating to the patient's pulse rate (72 beats / min). Just prior to vessel lumen entry there are two peaks of sensor output, the second being the maximum at 3.9 V which is equivalent to 5.1 Newtons. The final reduction in sensor output corresponds to the observation of vessel wall penetration by ultrasound imaging with an arterial blood jet from the needle (right arrow in Figure 7).

Using these methods, the integrated forces generated by needles can be evaluated during procedures in patients and will supplement, and provide a verification of, published in vitro studies and also of simulator model output forces, enabling re-evaluation of underlying mathematical mod-

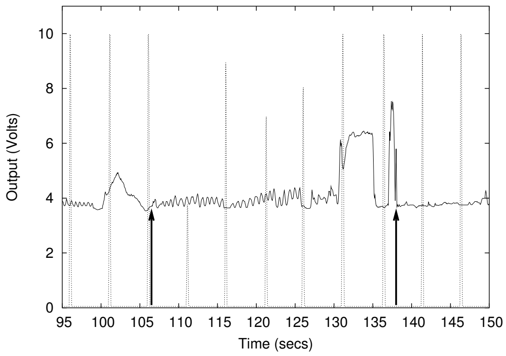


Figure 7: *Sensor output shown in Volts (black trace). Baseline as time (secs) with 5 second time points (dashed trace). Vessel wall contact at left arrow. Right arrow indicates vessel entry.*
Acknowledgement: AE Healey, J Evans, M Murphy, T How, University of Liverpool.

els [CDL04]. The technique and methodology described here requires further development in order to embrace the extensive armamentarium of instruments used in modern medicine. For example, the measurement of subtle torque forces used in narrow diameter devices such as guide wires and catheters requires development of new measurement methods. Ultimately, combination of visuo-spatial realism in VEs based on patient specific data, with haptics derived from in vivo studies, will deliver an authentic learning experience to the trainee.

3.3. Components of a Virtual Environment

Figure 8 shows a schematic of a simple VE system. In this case the visual display system employed is based on a helmet mounted display which is capable of delivering real time computer based images to the user's left and right eye. Such HMD systems may support stereographic vision and have other advantages in that they may provide an effective wide field of view display to the user. However, early HMD designs suffered from a number of problems and some of these still impact their utility in some areas such as surgical training, the most fundamental being that the real world is occluded by the HMD and the VE is a single person experience. Nevertheless, HMD based systems are to the popular press synonymous with Virtual Reality and it is for this reason that the term Virtual Environments has been adopted to reflect the fact that there are many other display options available today other that HMDs.

The following sub-sections explain the various components in more detail, particularly from the perspective of a medical VE.

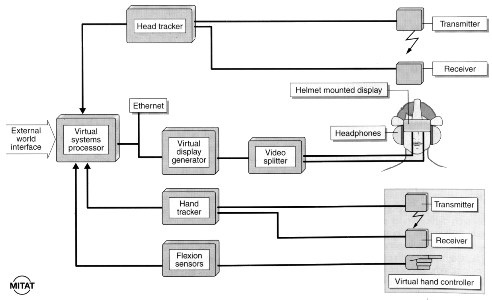


Figure 8: *Components of a Virtual Environment. Reproduced with permission of Taylor and Francis Publishers.*

3.3.1. Display Generator

Soferman [SBJ98] identified three generations in the evolution of graphics hardware, each of which had made significant strides in enabling the real time implementation of medical virtual environments. Since this time, a fourth generation of powerful consumer PC graphics cards has reached the market place with flexible programmable graphics pipelines. The impressive polygon rendering rates of these cards make surface extraction techniques extremely fast to implement. Further, the main drawback of volume rendering of being a computationally intensive task that can take many minutes to generate a 3D rendering is now being addressed by graphics hardware. Special purpose hardware has been built [PK96] and is today available commercially. This *VolumePro* card for PCs can deliver up to 30 frames per second for 512 cubed voxel data [Ter, PHK*99]. Another well known hardware acceleration technique is to use texture mapping hardware [CCF94]. This is often called *Volume Slicing* and has been used successfully in several clinical applications. The best performance is obtained on high performance SGI workstations where 3D texture hardware is available, and data sets of up to 512 Mbytes in size can be loaded into the dedicated texture memory - more than enough to cope with the size of data sets from today's modern scanners. Hardware look-up tables are used to apply colour and opacity to the visualization. SGI provide an application programming interface called OpenGL Volumizer [SGIb] that enables an application developer to take advantage of texture hardware support.

The texture mapping technique can also be adapted for more commonly available 2D texture hardware. In this case, three copies of the voxel data are required - sampled across the three orthographic projections. Only one data set is used for the rendering stage at any one time. As the volume rendered data is rotated it is necessary to swap between the three data sets which are used in the rendering calculation. More recently, standard PC graphics boards are now capable of implementing the volume slicing technique [MHS99, REB*00, RGW*03]. However, the size of the volume that can be manipulated is limited by the amount of dedicated graphics memory available and this can easily become a bottleneck when dealing with medium/large data sets. Texture data must be fetched via the Accelerated Graphics Port (AGP) from the main memory of the PC and this prevents interactive performance from being achieved. Future developments in graphics hardware will soon solve this, however.

3.4. Haptics

Haptics relates to the sense of touch. It can be divided into two major categories of sensory information: tactile and kinesthetic. Tactile information includes temperature, skin curvature and stretch, velocity, vibration, slip, pressure and local force. It refers to the initial contact with objects, geometry and surface textures. Kinesthetic information is related to the physical forces applied to and by the body including proprioception (sensing and awareness of body position). Kinesthetic rendering is often called force-feedback or force-reflection. A haptic interface is a force reflecting device which allows a user to touch, feel, manipulate, create and/or alter simulated 3D objects in a VR environment. Haptics is a technology that can be deployed in many areas, such as Medicine, to improve the intuitive interpretation of volumetric data, for visualization, diagnosis or surgical simulation, scientific visualization and data analysis. Haptics is a technology that can be deployed in many areas, such as Medicine, to improve the intuitive interpretation of volumetric data, for visualization, diagnosis or surgical simulation, scientific visualization and data analysis. Minimally invasive surgical training is an excellent example of where systems have been taking advantage of haptics technology [BDK*04].

User interface design and applications in haptics are in its early stages since haptic hardware has only recently become affordable. To a large extent this is due to haptic technology being difficult to achieve convincingly because the human sense of touch is far more sensitive than the senses of sight or sound. In visual systems a picture needs to be refreshed at only 30 frames per second to trick the eye into thinking it is seeing continuous motion. However, the sense of touch requires that a sensation be updated 1000 times per second or more to relay a convincing tactile experience.

Two main areas of application and research are currently being developed by researchers in the haptics field - *Virtual Environments/Telerobotic* systems and *Force Feedback/Tactile Display* systems. Although both types of systems seek to simulate force information there are differences in the types of forces being simulated. VE researchers seek to develop technologies that will allow the simulation or mirroring of virtual or remote forces by conveying large-scale shape and force information. Researchers in the field of Force Feedback and Tactile displays seek to develop a method of conveying more subtle sensory information between humans and machines, using the sense of touch.

Based on the magnitude of force generation, haptic devices can be categorised as follows:

- Virtual Environments/Telerobotics:
  1. Exoskeletons and Stationary Devices [BAB*92, LC97]
  2. Gloves and Wearable devices [BPBB02, Imma]
  3. Point-sources and Specific Task Devices [Sen, HCLR94]
  4. Locomotive Interfaces [Sar]
- Feedback devices:
  1. Feedback input devices/ Force feedback devices [Log, Mica]
  2. Tactile displays [WPH97].

The field of haptics is inherently multidisciplinary, borrowing from many areas, including robotics, experimental psychology, biology, computer science, systems and control, and others. It is a rapidly evolving field that is constantly expanding, providing the next important step towards realistically simulated environments. The sense of touch is so important to the way in which humans interact with the world that its absence in simulation technologies of the past has been a major shortcoming. Adding the sense of touch to the sense of hearing and sight currently addressed by simulation technologies is a very exciting development.

3.5. Spatial Tracking

The spatial tracking feedback loop is depicted in Figure 8. Spatial position of objects in real-time is required for a variety of reasons. It provides for tracking of interface objects (wands, hands, virtual tools and instruments, *etc.*) within virtual environments. Another use is to track the position of a user's eyes so that the rendered display adjusts to the user's viewpoint so as to provide correct motion parallax cues. Furthermore, in areas such as image guided surgery it allows the tracking of surgical instruments and the tracking of movement of patient anatomy, so that they all maintain their registration with computer-based surgical plans.

Spatial tracking can broadly be classified it terms of tracking technology, volume of operation and tracking performance in terms of accuracy and measurement rate. The most common forms of tracking are magnetic, optical, acoustic, inertial and encoded mechanical arms. For magnetic tracking (Ascension, Polhemus), a transmitter emits a magnetic field that is detected by sensor coils. Using multiple sensors, position can be reconstructed to provide a position in 3, 5 or 6 degrees of freedom (DOF). A recent development has been the miniaturisation of these sensors (NDI Aurora [NDI]) with sensors being as small as 8 × 0.8 mm Such sensors can be attached to catheters and other surgical instruments to provide spatial tracking within the human body.

Optical spatial trackers rely on tracking a number of markers on an object. For each marker a 3 DOF position is determined by a camera system. For rigid body objects the 6 DOF position is calculated from its constituent markers. There are two main types of camera system namely active and passive. For active systems each marker emits infra-red light that is detected by the camera. For passive systems, the markers are usually silver coloured balls which reflect infra-red light transmitted by a source close to the camera. There are numerous configurations for the camera system. For tracking small volumes, the normal configuration is two cameras each with a 2D array of optical CCD sensors (NDI Polaris [NDI]), or three cameras each with a linear array of optical sensors (NDI Optotrak [NDI]). Typically the accuracy of such systems is 0.1 to 0.5 mm. A disadvantage of optical tracking is that the line of sight must be maintained between the object and the camera system. This problem can be reduced to some extent by objects having a large number of markers.

For optical tracking of larger volumes such as in a CAVE (Cave Automatic Virtual Environment [CSD*92]) or in front of a large immersive wall, a more flexible and extensible camera system is becoming the system of choice. Here cameras, typically between 6 and 12, are placed to provide good coverage of the tracked objects. A calibration procedure, which takes just a few minutes, provides accurate calibration of the cameras with the capture volume. Passive markers are typically used with such systems. Such systems are provided by Vicon, Qualisys and Motion Analysis.

Another interesting development in spatial tracking concerns optical technology. Light is passed down a fibre and bends in the fibre reflect the beam, which can then be detected and thus allow the position of the fibre to be determined. Previously this technology had been used for tracking the position of fingers in VR-gloves.

Examples of other spatial tracking systems are Intersense [Intb], which combines acoustic sensing with inertial sensing. This system is suitable for working volumes of up to $2.5 \times 2.5 \times 3$ m^2. Systems such as the Faro arm provide a passive manipulator with position encoders on each limb of the arm which enables the position of the end-effector to be calculated relative to the base of the arm.

Another trend is the integration of spatial tracking technology into medical equipment. In virtual fluoroscopy, the C-arm of the fluoroscope is tracked by markers permanently attached to the C-arm [PPF*02]. When a fluoroscopic image is taken, the image is automatically calibrated to remove distortions and its position determined. The image and its position can then be used directly for quantitative surgical planning, registration with preoperative plans or act as a guidance aid for surgery (see Sub-section 4.5).

In addition to spatially tracking 3D points, surface tracking technologies have also been used for medical applications. For example, surface tracking by recognition of structured light patterns has been used to obtain surface detail of vertebrae during spinal surgery for registration purposes in image guided surgery. Laser scanning of patients receiving radiotherapy treatment can help ensure that patient position is correct for treatment.

3.5.1. Visual Displays

Visual displays are the devices that present the 3D computer generated world to the user's eyes. There are several general categories of visual displays, each providing a different degree of immersion, namely: desktop displays, head-mounted displays, arm-mounted displays, single-screen displays, and surround-screen displays. Most are capable of producing wide-angle stereoscopic views of the scene, although monoscopic projection may also be used. Desktop displays are the least exacting and a more restricted form of VE system, but have found favour in many areas. Such systems have nowadays been extended to include interaction with models and synthetic environments available over the internet [JR99]. Alternatives include a binocular interface such as that being used to simulate a surgical microscope in Figure 9. This is from a bone drilling simulator for rehearsing a mastoidechtomy procedure [AGG*02].

Figure 9: *Mastoidechtomy Simulator from the IERAPSI project (image courtesy of CRS4, and University of Pisa).*

Other display devices are based on projection technologies and include immersive workbenches, Reality Rooms and CAVEs [ML97]. Such projector based systems provide a greater sense of immersion than desktop systems using a standard computer monitor by affording a wider field of view. Since most VEs contain visual displays a subset of the components can be harnessed to create a visualization system. The quality of the projected image is also very important and to achieve both high resolution and a wide field of view, it may be necessary to employ a number of projectors, each one making up part of the composite picture. A good example of this is a Reality Room configuration which typically uses a large curved screen front projected by three projectors to achieve a horizontal and vertical field of view of 160 by 40 degrees respectively from the design view point. Unlike HMD systems, Reality Rooms allow a number of people to share and be involved in the display of the synthetic world at the same time and such systems have proved to be a very powerful presentation/visualization tools.

The latest developments in autostereoscopic displays are of particular interest for medical applications. They have the advantage that no special glasses need to be used by the clinician to see the 3D image. Clinicians often complain if they are required to wear special equipment. The holy grail of visual display systems would appear the computer generated holographic display which would allow a naturally viewed display which contains a ultra-high resolution rendering with appropriate depth cues. Such systems are still in research and development but early commercial offering are expected to be available within the next two years [BS00].

3.5.2. General Input Devices

The other feedback loop revealed in Figure 8 is that associated with interaction and manipulation of the VE. For fully immersive VEs the aim is to banish the keyboard and mouse and allow the user to interact with the VE in a more intuitive way. Ideally users should be able to walk around a VE and interact with virtual objects by grabbing and directly manipulating them using a “dataglove” or virtual hand controller [Vin95]. Input devices allow the user to interact with the virtual world, and there are a large variety of options available. Common examples include the data glove, three dimensional joy sticks and wands, and even voice recognition systems. Many custom devices are also in use, and some medical systems use the same instrument that would be used in the real procedure *e.g.* a needle and catheter for a vascular access simulator (*e.g.* [UTN*99]).

3.5.3. Other Senses

The immersive properties of VEs can be greatly enhanced by the appropriate use of 3D spatialised sounds. This allows the user as in real life to identify the location of sound sources providing in many applications valuable additional cues to support and augment visual displays. However, the processing requirements to be able to deal with multiple sound sources in this way are considerable and research into 3D spatialised sounds also highlights the requirement to properly model the users head and pinea to allow the construction of accurate head related transfer functions. Even employing some of these advanced techniques some users experience these virtual sounds as originating “inside” their heads and other have difficulty in distinguishing sounds from directly in front and behind the head [Ple74].

Other research projects involve the use of olfactory displays [KKK95] and the use of speech recognition systems [JM00] to provide a means of hands free interaction with the VE.

3.6. Grid and High Performance Computing (HPC)

Despite the increases in computational power available at very modest cost in the form of desktop PCs the real time constraints or user interaction and navigation place severe computational demands on such systems, which when coupled with large scale (often volumetric) data sets quickly overwhelm local resources. Few hospitals can afford to run their own HPC facilities, however, or have the expertise to do so. The concept of the computational and data grid, designed to allow end users transparent access to a wide variety of high performance computing facilities and data acquisition devices, therefore appears compelling. Consider the requirement for real time volume rendering in medical applications. Parallel processing techniques have been successful applied to volume rendering, such as in the Star-Ray system from Utah [DPH*03]. What if these capabilities were available to any hospital on demand?

Using the grid a user would be able to recruit and use distributed computational resources in a transparent manner. The Grid-enabled Medical Simulation Services (GEMSS) project [BBF*03] is a good example of several investigations currently in progress. GEMSS aims to develop Grid middleware to facilitate access to advanced simulation and image processing services for improved pre-operative planning and near real-time surgical support. To date most applications appear to be “batch” based. Extensions to allow large computational models and datasets to be processed in real-time are presently being investigated [GAW04]. Grid middleware would orchestrate and co-ordinate resource discovery, allocation and usage and the user would be unaware of the underlying complexities of these functions. Whilst an easy picture to paint in words the realization of the above in a robust and transparent manner is presently beyond the capabilities of present software solutions. Nevertheless, progress on overcoming several of the fundamental barriers to realizing the above has been swift and future developments promise to allow this vision to be turned into reality.

3.6.1. Remote Visualization

Recent developments in high performance visualization have made it possible to run an application on a visualization server and deliver the results in real time across the computer network to a client workstation. This is achieved by streaming the contents of the frame buffer on the server (where the graphics primitives are rendered) in a similar fashion to how MPEG movie files are streamed across the Internet. OpenGL Vizserver [SGIa] from SGI was the first product to support remote visualization. Figure 10 shows a volume visualization application being used to aid with hepato-pancreatic surgery. Vizserver is being used to deliver the volume renderings of the patient data to a laptop client in the Operating Theatre. Other products are now starting to appear that provide similar functionality such as AquariusNET from TeraRecon that uses a visualization server with a VolumePro card. Good bandwidth is needed on the network to ensure interactive updates on the client - typically 100 Mbits per second is a minimum requirement.

Remote radiation treatment planning (see also par. 4.4.1) has also been implemented by using high speed communications and a supercomputer resource [YGM*96].

Figure 10: *Remote volume visualization of patient data delivered to the operating theatre (from the Op3D project) [MJ03].*

4. Applications and Innovative Projects

4.1. Educational Tools

Traditional teaching of human anatomy involves dissection. The benefits include a spatial understanding which is difficult to glean from textbook demonstrations. Traditional methods are now less commonly used in the UK, having been largely replaced by problem based learning scenarios and pre-dissected specimens. Yet there are developing deficiencies in the anatomical knowledge of today's medical graduates, and such information is vital to their future practice in specialties such as surgery and radiology. A substitute for the traditional, interactive methods exists in the application of virtual environments where anatomy can be explored in 3D, with haptics. The facility to develop these methods has been drawn from data sets such as the visual human and more recently, the Chinese visual human project. While the former was around 15 GB, there are a number of Chinese variants with up to 1.1 TB of data, yielding vastly improved image resolution (0.1 mm) but some challenges for data manipulation and segmentation processes. Organ relationships, gunshot tracks, related physiology and histology can be learnt in a highly interactive manner. Anatomical structures can be explored and labelled, and can be made available in cross sectional format [SSL*04], segmented, isolated organ structure, or can introduce functionality, as in the contractility of muscle. Structures can be removed sequentially, returning to the learning advantages of traditional dissection. In addition, feedback to the trainee can be provided as to developing knowledge levels.

4.2. Diagnostic Aid

CT and MR scanners can provide 3D datasets of 512 image slices or more (par. 2.1), but only sixty images can be displayed on a typical light box. Consequently, the clinician never accesses the majority of the data that has been acquired, and has to reconstruct mentally his own 3D interpretation from those relatively few 2D images that fit onto the light box. One of the most significant advantages of the 3D visualization of such datasets is to use all of the available images and to present the data to the clinician at the same time and in an intuitive format. Moreover this 3D representation could be more significant to a non-specialist in radiology, such as a surgeon. The techniques used are described in Section 3.1. They allow the clinician to see the internal structure and the topology of the patient's data. Figure 3 is a good example of a volume rendering generated from a CT data scan showing the relationship between the confluence of the superior mesenteric, splenic and portal veins with a large tumour. Figure 11 is another interesting example, which was obtained using a Siemens Sensation 16, Multidetector Array CT scanner with intravenous contrast enhancement for maximum arterial opacification. The study was post-processed using a Leonardo workstation with Vessel View proprietary software. The anatomy depicted is unusual and shows separate origins of the internal and external carotid arteries from the aortic arch.

Figure 11: *Volume rendering of unusual anatomy with separate origins of the internal and external carotid arteries from the aortic arch.*

Note that all of the major scanner manufacturers (Philips, GE, Siemens, Picker, *etc.*) do already provide 3D visualization support and the value of 3D as a diagnostic aid is being demonstrated wth excellent results [Meg02]. Companies such as Voxar (Edinburgh, UK) and Vital Images (Plymouth, MA) have been successfully marketing 3D volume rendering software technologies for several years. Nevertheless, use of 3D visualization techniques today are still largely confined to the workstations in radiology departments.

4.3. Virtual Endoscopy

Virtual endoscopy (VE) is a new technique for visualization of internal structures that has some advantages over classical endoscopy (CE) [Rob96]. In CE, the endoscope is inserted in the patient body through a natural or minimally invasive opening on the body. A disadvantage of CE is its invasiveness and the fact that only a limited number of structures can be visualized. VE is not invasive (except radiation produced by CT and nuclear medicine) and enables visualization of any structure, providing for interactive exploration of the inner surface of the 3D model while being able to track the position of the virtual endoscope relative to the 3D model. Furthermore, the surgeon can record a trajectory through the organ for later sessions and save a movie to show other experts.

A disadvantage of VE is the lack of texture and color of the tissue which is a very important diagnostic information. However, if VE is combined with other tools that color-code the 3D models to highlight suspicious areas [HATK00, See01], the surgeon can have access to additional information during the diagnostic phase. Other limitations of VE include the cost to acquire CT and MRI data which is higher than that of conventional endoscopy and the low resolution of images which limits the resolution of the 3D model. The creation of a 3D model is time consuming and the use of 3D software can be non-intuitive and frustrating for novices. Despite all these limitations, clinical studies have shown that virtual endoscopy is useful for surgical planning by generating views that are not observable in actual endoscopic examination and can therefore be used as a complementary screening procedure and as a control examination in the aftercare of patients [RWRH*98, VA99, KKH*00, SCP*01].

The steps involved in building a VE system include: image data acquisition, typically high resolution CT scans, pre-processing and detailed segmentation to delineate all structures of interest, calculation and smoothing of the path for fly-through animation, and volume/surface rendering for visualization. Different approaches to each of these steps address different VE applications like colonoscopy, bronchoscopy, or angiography.

Virtual endoscopy is a new imaging technique with the potential to alter current clinical practice. Besides applications in the nose and paranasal sinuses, the larynx and the tracheobronchial tree, the small bowel and the colon, applications in the vasculature such as the aorta, the carotids, and even in the coronary arteries are currently being evaluated. Along with improvements in the spatial and temporal resolution of the imaging modalities, further improvements for automated path definitions [MWB*97], improved tools for user orientation during the virtual endoscopy, and improved reconstruction speeds allowing real-time fly throughs at high resolution, virtual endoscopy will undoubtedly play an increasing role in the future of whole body imaging.

4.4. Treatment Planning Aids

The use of medical imaging and visualization is now pervasive within treatment planning systems in medicine. Typically such systems will include a range of visualization facilities, fusion of images, measurement and analysis planning tools and often facilities for the rehearsal of operations. For all image-guided surgery systems (see par. 4.5.1 for neurosurgery planning), except for some trauma surgery where surgical planning is based on intra-operative imaging, surgery is planned preoperatively. Treatment planning systems are essential to such areas as spinal surgery, maxillofacial surgery, radiotherapy treatment planning (see par. 4.4.1), neurosurgery, *etc.* Shahidi [STG98] presents a good survey in this area. To date, the focus has been on providing greater precision when targeting treatment. The next challenges will be to provide real time systems, and to include functional data.

4.4.1. Radiotherapy Treatment Planning

The benefits of using 3D visualization techniques for radiotherapy treatment planning have been reported for many years [RSF*89, SDS*93]. A well used technique is called 3D conformal radiation therapy (3DCRT), in which the high-dose region is conformed to be close to the target volume, thus reducing the volume of normal tissues receiving a high dose [Pur99]. More recently, 3DCRT has evolved into *intensity modulated radiotherapy treatment* (IMRT) of cancer tumours [Int01] which relies on a sophisticated visualization planning environment. In IMRT the tumour is irradiated externally with a number of radiation beams (typically 5 to 9). Each beam is shaped so that it matches the shape of the tumour. The intensity of radiation is varied across the beam using a multi-leaf collimator (MLC). The shape and intensity of the beam is computed by an inverse planning optimisation algorithm. The goal of this algorithm is to provide a high radiation dose to the tumour whilst sparing normal tissue surrounding it. Particular attention is paid to reducing radiation to critical organs (*e.g.* spinal cord, heart, pituary glands, *etc.*). Planning involves visual identification of tumour(s) and critical organs, selecting the beam directions and defining the objective function and penalties for the planning optimisation algorithm. The radiation plan is then checked by viewing overlays of radiation dose on patient anatomy and various radiation dose statistics. Revised plans are produced by adjusting the parameters to the planning optimisation algorithm until a satisfactory solution is obtained. Comparisons of conventional techniques, 3DCRT and IMRT for different clinical treatments have been made [MGB*04] and verify that the techniques that use 3D visualization do indeed reduce dose. Researchers at the University of Hull have used a virtual environment to further enhance radiotherapy planning (Figure 12) by producing a full scale simulation of a real radiotherapy room used for IMRT with visualization of patient specific treatment plans displayable in stereo-vision on a large immersive work wall. Work is now underway to further develop the simulation as a tool for training radiotherapists with a study being planned to determine the benefits of immersive visualization for creating and reviewing radiation treatment plans.

Figure 12: *Virtual environment simulation of 3D radiation therapy treatment at the University of Hull.*

4.5. Guiding Aid

In the last twenty years, surgical techniques have undergone radical change. A growing number of procedures are now conducted using a *minimally invasive* approach, in which surgeons operate with instruments passed through small holes in the patient, not much larger than a centimetre in diameter. There are significant benefits to minimal invasion, such as reduced patient trauma, reduced blood loss and pain, faster recovery times and, as a result, reduced cost. However, by keeping the surgeon's hands out of the patient, we incur the cost of occluding the view of the surgical field. A high resolution miniature video camera inserted through an access port is depended upon to act as the eyes of the surgical team, who view the operation on monitors in the operating theatre. A number of surgical systems now provide colour and dual-camera configurations for stereo-vision capability. There are limits to this approach, however. Traditional optical imaging technology cannot be used to see within organs, or around corners, and so the range of treatments that can be accommodated in this way is restricted. If minimally invasive techniques are to prevail over their ancestors across more surgical interventions, new and more capable means of guidance are necessary [Mez01].

Image-guided surgery is the term used to describe surgical procedures whose planning, enactment and evaluation are assisted and guided by image analysis and visualization tools. Haller *et al.* describe the ultimate goal of image-guided surgery as "the seamless creation, visualization, manipulation and application of images in the surgical environment with fast availability, reliability, accuracy and minimal additional cost" [HRGV01]. A typical supporting infrastructure for image guidance capability is shown in Figure 13. Surgical systems incorporating image guidance for neurological or orthopaedic interventions are available from a number of manufacturers [Tyc, Com, Medc]. Within orthopaedics there has been considerable adoption of image-guided surgery techniques for spinal surgery [VBS99], moreover commercial image-guided approaches for unicompartmental knee surgery are now becoming available [Str] where surgery is considerably less invasive than the existing traditional open surgery approach.

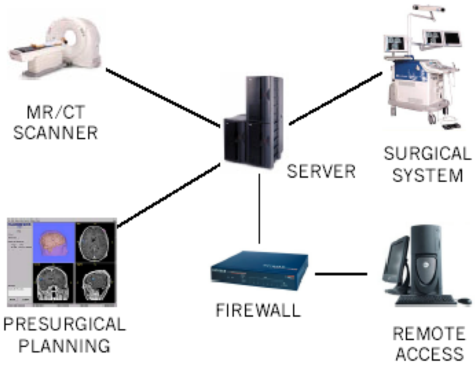


Figure 13: *Infrastructure for Image-Guided Surgery.*

4.5.1. Neurosurgery

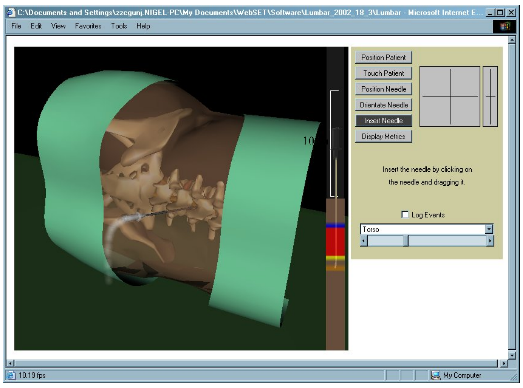
All neurosurgical interventions require considerable planning and preparation. At the very first stage, anatomical MR or CT images are taken of the patient's head and brain, and transferred to a supporting IT infrastructure (as illustrated in Figure 13). Specialised hardware is used to reconstruct the scanned images both as two-dimensional and three-dimensional views of the data. Pre-surgical planning tools allow a thorough review of all images obtained. Furthermore, the surgeon is able to interact with a three-dimensional visualization of the data by changing the viewing angle, adjusting the transparency and colouring of different brain structures, removing skin and bone from the image and so on. In addition, virtual instruments can be manipulated within the simulation, and their position and trajectory through the skull and brain displayed in real-time. These features provide considerable assistance in the general decision-making process of surgical planning. For example, in the case of tumour resection, the surgeon must take into account factors such as the accessibility of and optimal route through the brain to the site of the lesion, delineation of tumour tissue from the surrounding healthy tissue, location and avoidance of blood vessels, and crucially, the functional significance of the brain tissue surrounding the site of the lesion. For this latter requirement, the surgeon may call upon information obtained from a functional modality such as fMRI, or an electroencephalogram (EEG) investigation. By combining the functional and anatomical information, it is possible to determine the functional importance of the brain tissue likely to be encountered, and possibly damaged, during the procedure.

In the operating theatre, a different type of multi-modal registration is employed. Intra-operative guidance systems work by establishing a spatial correspondence between the patient on the operating table and preoperative anatomical data, enabling the localisation of surgical instruments and the patient's anatomy within the three-dimensional space of the operating theatre. With registration between tool, patient and theatre established, when an instrument is placed on the patient, the exact location of the instrument tip is projected onto anatomical images displayed on a computer monitor. Herein lies the essence of image guidance, enabling the surgeon at any time to 'see' the exact location of his instruments in relation to both the anatomy (whose natural view may well be obscured by blood and other obstructive tissue) and the surgical plan. Just as in the planning stage, critical functional information obtained preoperatively can be added to these images. In addition, intra-operative ultrasound images registered with the original MRI data can be used to update the position of the tumour and surrounding anatomy [HMM*98]. Whilst a coarser representation than that provided by intra-operative MRI [SKL02], ultrasound data obtained during the intervention can be used to detect and account for tissue shift that might otherwise render the registration dangerously inaccurate, and at relatively little extra cost [HRGV01, SKL02].

4.6. Skills Training Aid

The teaching of medical knowledge has for eons been a tradition and a major part of this process has been the teaching of clinical skills. The interventions practised in patients today have evolved through development and invention, with new technologies such as imaging, bringing vastly more complex therapeutic solutions. Yet the mechanism of this training process has remained largely unchanged until relatively recently. Training of the visual and motor skills required is an apprenticeship. Training in patients not only has discomfort associated with it, but provides with limited access to training scenarios [RAA*00] and makes it difficult to train in a time efficient manner [BD99]. In surgery, and in particular, laparoscopic surgery, the requirement for completely new, specialist clinical skills, has driven the development of novel solutions to training. Skills boxes and other bench models [BT02] have been shown to accelerate the acquisition of skills. The development of a laparoscopic simulator model using virtual environments (VE) to train skills using, initially, simple geometric shapes, with subsequent development of more realistic visual displays and haptics, showed for the first time that VE could be a highly effective training tool [TMJ*98].

Underpinning the acceptance of VE in teaching clinical skills is the process of validation, where objective studies are used to demonstrate resemblance to a real world task (face validity) and measurement of an identified and specific situation (content validity). Simple tests, such as construct validation, may show that an expert performs better than a novice in the model under test, while more complex, randomised controlled studies (concurrent validation) correlate the new method with a gold standard, such as apprenticeship [SGR*02]. Ultimately, predictive validity will evaluate the impact on performance in a real procedure. Clearly the reliability of the validation process, across evaluators (inter-rater reliability), and between repeated tests (test-retest reliability), must also be confirmed. There is a great deal of activity in this area. One example is the lumbar puncture simulator developed in the WebSET project (Figure 14) [DRJ02]. Validation studies have shown that this simulator does improve the training of students in performing this procedure [MMB*04].



Insert the needle by clicking on the needle and dragging it.

Figure 14: *Simulator for Lumbar Puncture Training (from the WebSET Project).*

As had happened within surgery, there is a developing renaissance in the teaching of the clinical and technical skills of interventional radiology (IR). Interventional radiologists are doctors, trained in radiology, including interpretation of X-rays, ultrasound, computed tomography (CT). This expertise enables them to use imaging to guide needles, catheters (tubes) and guide-wires through blood vessels or other organ pathways to treat various diseases. The catheters used may be a couple of millimeters in diameter and these minimally invasive procedures involve low risk and postoperative pain, short recovery times and avoidance of general anesthesia. IR techniques are developing rapidly and often replace open surgical procedures: in 2002, nearly 6000 IR procedures were performed in Mersey region alone, of which 45% were visceral procedures, mainly for treatment or palliation of cancer [Roc91]. Techniques available include angioplasty, stenting, stentgrafting, biopsy, tumour ablation, drainage of abscess, obstructed bile ducts and renal collecting systems.

Certification in certain core IR procedures is a part of general radiology training and depends in part on a logbook indicating the number of procedures performed: some trainees go on to higher, specialist training in IR. Straightforward invasive diagnostic procedures have long served to train core clinical skills in an apprenticeship in patients, yet such pure diagnostic studies are being rapidly supplanted by CT and MR imaging methods and consequently the trainee's first involvement may be in complex therapeutic interventions. While this does offer valuable training experience, exposure to these cases is limited, particularly in peripheral training centers. There are other issues with the patient centred nature of the apprenticeship, which may be associated with discomfort or pain, occasionally with complications due to inexpert manipulations of the trainee. Though the risks are minimized by the expert supervision which is a part of the training process, this need for supervision, and the prolonged procedure time, reduce case throughput. Pressures to improve throughput in the NHS, together with the Calman system in the UK, and implementation of the European Working time directive are further increasing the difficulty for trainees to acquire adequate and timely experience. At the same time, 134 of 400 consultant radiology posts advertised during 2002/3 remain unfilled (vacancy rate 7.6% against the National average of 4.7%).

There is therefore a need for a new training paradigm within interventional radiology. As in surgery, fixed models have been shown of value in training, for example using vascular models produced by rapid prototyping to train in catheterisation skills [CHB*98]. There are however, few models simulating the broader scope of IR procedures. The cost of rapid prototyping is a limiting factor and such models lack realistic physiology: once constructed, their anatomical content cannot be easily altered. For needle puncture procedures, fixed models lack robustness and are destroyed by repeated needle punctures. While animal models are used to train IR skills [LIW*95], and also incorporate physiology, they are expensive, with anatomical differences [DGB*98], a lack of pathology and, in the UK, of political acceptability.

At October 2003 there were 647 radiologists in training schemes in the UK. The Royal College of Radiologists (RCR) plans to pilot an e-learning scheme within 3 training academies, with up to 100 radiology trainees travelling to these sites. This environment will be ideally suited to training in practical procedures using models and it is envisaged by the RCR that VE will be a cornerstone in the acquisition of skills within the Academy environment and indeed, all training centres. There is the potential, using VE training, to reduce discomfort and risk to patients during the early part of the learning curve while developing greater proficiency in less time, increasing the overall number of trained personnel and maintaining skills in low throughput situations. This overall potential to increase effective manpower would improve case throughput while broadening the scope for skills to be acquired by other healthcare professionals such as cardiologists, vascular surgeons, nurses and paramedics [CCA*02].

At present the state of the art in virtual environments [DRJ02, DAS01, CDAS01, MAS*02] and haptics has led to considerable work in surgical simulation and some work in interventional radiology. Some academic and commercial models simulate catheterisation [HLN*02, ZGP99] and needle puncture procedures [Immb, JRP*01, MJS*03]. In only a few models, has development work been based on a Task Analysis [LCG98] and this will be essential in the development of clinically valuable, VE based, training models of interventional radiological procedures. Suitable virtual environments will be based on patient specific data with semiautomatic, or perhaps automatic, segmentation of vascular anatomy, organs, and ducts. While many skills can be acquired in simple geometrical shapes, the clinical 'reality' needed to simulate the patient environment will entail incorporation of realistic physiology, physiological motion and tissue deformation characteristics. Realistic haptics [GPO02] will require extensive and detailed study of the physical and physiological properties of organs and tissues, for example in needle puncture [APT*03, DS02], with verification of underlying mathematical models. This will require new developments in physiological measurement (par. 3.2), with close working between clinical, computer science and clinical engineering teams [HEM*04]. The use of patient specific data will enable challenging virtual training scenarios to be reproduced in an ad hoc manner, based on real cases, simulating complications and critical events and introducing a facility for pre-treatment procedure rehearsal. Scenarios will be viewed by a trainee as simulated fluoroscopy, CT and ultrasound and, using haptic interfaces, procedures of graded complexity will be practiced. For the first time it will be possible to learn the consequences of technical mistakes, and to experience complications, in complete safety. Virtual environments will confer an opportunity to train more rapidly, in a variety of case scenarios, maintaining higher skill levels, even where throughput is low. A further application of this technology is in augmented reality solutions to some of the technical, procedural challenges in image guided interventions, for example in difficult anatomy, or in the presence of physiological motion, where there is great potential for image registration methods to solve some of the inherent problems. On a cautionary note, uptake of the training aspects must be focussed within curricula to avoid the risk of divorcing technique from clinical context and the hazards of ionizing radiation.

Incorporation of objective measures of assessment of training will introduce reproducible and reliable skills assessment as a part of examination, accreditation and revalidation. While objective methods are available in relation to assessment of surgical training [MRR*97, TSJ*98, Eur94, FRMR96, MMSD03], these do not yet exist for interventional radiology. Given that the interventional training environment will undergo significant change over the next decade, the relevant assessment methods needed require development and validation with a degree of urgency. The metrics used can be distilled from data obtained by performance of cognitive task analysis and will be applicable to objective assessment of performance in simulator models, as well as in the clinical scenario, and will ultimately be incorporated into certification processes.

4.7. Augmented Reality

Augmented Reality (AR) is a technology that dynamically integrates pictures of virtual objects into real scenes. Unlike the concept of *virtual environments*, in which the user's visual field is entirely synthesised, AR superimposes computer-generated artifacts onto the existing view of the real world, correctly orientated with the viewing direction of the viewer who typically wears a suitable *head-mounted display*, HMD, or similar device [Micc]. AR is a technology growing in popularity, with applications in medicine (from as early as 1988 [YYHY88]), manufacturing, architectural visualization, remote human collaboration, and the military [Azu97]. However, such systems make the already onerous systems integration tasks associated with VE systems even more difficult and so acutely highlight present limitations associated with spatial tracking systems and other VE peripherals.

Video cameras can be attached to the front of an otherwise normal (scene occluding) HMD and the video feeds mixed with the computer generated data before being displayed to the user via the HMD's active display panels and optics. Such systems are referred to as "Video-through" AR systems. The alternative is to use "See-through" displays in which the synthetic computer generated images are injected into the display to impinge on the user's view, for example the Varioscope AR [FBH*01]. Such systems allow uninterrupted and unaltered views of the real world, which appear very important as far as user acceptance is concerned for medical applications. The central problem in AR is the correct alignment of the viewer's coordinate system (*i.e.* the position and orientation of the viewer's eyes, *e.g.* the endoscope) with the virtual coordinate system of the augmented images. Without establishing the spatial transformation between object and observer coordinate frames, it is impossible to correctly augment the view of a scene. This in itself is a registration problem and, for AR to be effective, the registration must be both accurate enough to keep discrepancies between the real and virtual visual stimuli to a minimum, and fast enough to be used in real-time. Latency or "jitter" of the display of virtual objects in the real environment can degrade the quality of the AR experience severely. There are additional problems which must be addressed, such as occlusion and *radiometry*, that is matching the lighting models of real and virtual worlds.

AR is a new technology, and as a result there are few commercial or clinical AR systems in widespread use. Of those that are currently available, interesting systems that attempt to fuse the visual and haptic displays from the user's perspective are being developed at KDSL in Singapore, and ReachIn Technologies AB. Also of note is recent work to develop the MEDical Augmented Reality for Patients (MEDARPA) workstation [Hir], which uses AR without the need for a HMD or restrictive cables. Instead, the augmented information is located on a free-positionable, halftransparent display, the "virtual window" that can be positioned over the patient. It is likely that with increasing robustness of the technology and availability of HMD and other suitable hardware, use of AR will grow in those areas where the technology can succeed. Unfortunately for many clinical applications, particularly those involving deformable anatomical structures, the registration problem has proven to be a difficult barrier to overcome.

4.7.1. AR Surgery

In surgery, AR offers a natural extension to the image-guidance paradigm and offers great potential in enhancing reality in the operating room [LCK*93]. Rather than having to refer constantly to a computer monitor, images can be augmented in real-time onto the surgeon's field-of-view. This 'X-ray vision' quality of AR is especially useful to the restricted-view realm of minimally invasive surgery. From the outside, we could augment an internal view of the patient based on preoperative or intra-operative data, presenting the surgeon with a large and information-rich view of the surgical field whilst entirely preserving the benefits of minimal invasion. For example, a doctor would be able to view the exact location of a lesion on a patient's pancreas as they move around the patient in three dimensions, and without making a single incision. In endoscopic procedures, it would be possible to project the image of unseen blood vessels obscured from view onto the video display, reducing the risk of accidental damage. Or in neurosurgery, rather than displaying the location of cranial drill-holes on a separate monitor, the targets can be augmented directly onto the surgeon's view of the patient. Clearly, the enhanced visualization characteristic offered by AR can be beneficial to a wide range of clinical scenarios.

One of the first medical AR systems was designed to display individual ultrasound slices of a foetus onto the pregnant patient [BFO92, Ack]. Ultrasound data was combined with video from a head-mounted display. Initially, due to inaccurate tracking, the alignment between the ultrasound and video was poor and the foetus lacked 3D shape. However, the research group at UNC has improved the technology and is now developing the system for visualization during laparoscopic surgery [FLR*98]. The innovative work of this group also includes an AR system for ultrasound-guided biopsy of breast lesions [SLG*96].

Many medical AR systems concentrate on the head. This is because the task of alignment and tracking of the patient is minimized, as the motion of the patient and organs is rigid and constrained. One such system is the Microscope-Assisted Guided Interventions (MAGI) [EKM*00, KEM*00]. The system projects a reconstructed 3D vessel tree from pre-operative data onto the surgical microscope view. The aim of the system is to allow the surgeon to view structures that are beneath the observed surface, as if the tissue were transparent. Figure 15 is an image from MAGI being used to guide the surgeon when removing a tumour (acoustic neuroma). A moving texture map is used here as the display paradigm and very good 3D perception was reported by the surgeon.

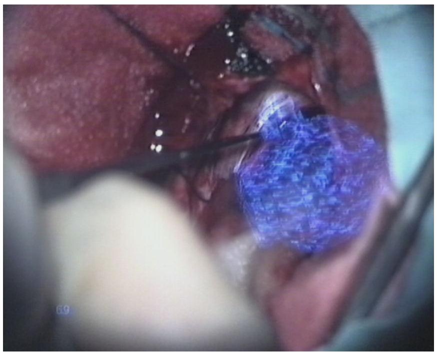


Figure 15: *Overlay of an acoustic neuroma after resection, showing how it had entered the internal auditory meatus - from the MAGI project. Image courtesy of Computational Imaging Science Group in the Division of Radiological Sciences of Guy's Hospital, London.*

Systems are also being developed for planning surgery. [SFW02] is designed for intra-operative planning of extended liver resection. This system relies on the knowledge and skill of a radiologist to manually align the pre-operative data with the intra-operative information. The overlays are produced from two sets of image modalities: pre-operative CT and intra-operative ultrasound data sets. 3D vessel trees are reconstructed from the CT scans and with the aid of the intra-operative ultrasound, the radiologist registers the graphics with video from the head-mounted display worn by the surgeon.

4.8. Robotics and Telemedicine

Medical robotics is a relatively new and promising field of study, which aims to augment the capabilities of surgeons by taking the best from robots and humans. Microscopic surgery and endoscopic surgery are revolutionary techniques in surgery. They are minimally invasive, *i.e.* the operation is performed with instruments inserted through small incisions rather than by making a large incision to expose the operation site. The main advantage of this technique is the reduced trauma to healthy tissue, which is the major reason for post-operative pain and long hospital stay. However, the dexterity of the surgeon is significantly reduced because of the loss of degrees of freedom (DOF) and motion reversal due to the fulcrum at the entry point. Force-feedback is almost completely lost due to the friction at the airtight port and stiffness of the inflated abdominal wall and there is a lack of tactile sensation on which surgeons are highly dependent in open surgery to locate vessels and tumours within areas of complex anatomy.

Minimal invasive surgery is an example of tele-manipulation, as the surgeon is physically separated from the workspace. Tele-robotics is a natural approach to address the shortcomings of laparoscopic surgery. The goal in developing a tele-surgical workstation is to restore the manipulation and sensation capabilities of the surgeon, which were lost in conventional minimally invasive surgery. A slave manipulated control, through a spatially consistent and intuitive master will replace the dexterity lost. Force feedback to the master will give back the fidelity of the manipulation, and tactile feedback will replace lost tactile sensation. Based on the role they play in medical applications and stressing the role of robots as tools that can work cooperatively with physicians to carry out surgical interventions, robots in medicine have been classified as follows [Tay97]:

1. Intern replacements
2. Telesurgical systems (master-slave)
3. Navigational aids
4. Precise positioning systems
5. Precise path systems

While this classification is technology oriented, it is also possible to divide the field by clinical application area: Neurosurgery, Orthopedic, Gynaecology, Urology, Maxillofacial, Radiosurgery, Ophtalmology and Cardiac. The application of robots in surgery developed mostly in the fields of neurosurgery and orthopaedics [BB95]. They were the major focus for surgical robotic systems because the anatomy provides relatively fixed landmarks that simplify the process of registration.

In neurosurgical procedures, neuro-navigators, stereotactic localizers and robotic assistants have been developed to improve spatial accuracy and surgical precision [GFB93, KHSG92]. Initial studies have shown that robotic systems can achieve a positional accuracy in the region of 1-2 mm [TCCe99].

In orthopaedics, the RoboDoc^{TM} system [Inta] was designed to address potential human errors in performing cement-less total hip replacements. It produces cavities 10 times more accurate than can be achieved by manual reaming and does not produce gaps [PBM*92].

In microsurgery, a robot-assisted microsurgery system (RAMS) has been developed for microsurgical procedures of the eye, face and hand. The system consists of a laptop computer, a joystick, a mouse and a slave robot arm simulating movements of the human arm with six DOF. Early results suggest that microsurgical manipulations with RAMS are more rapid and precise than the surgeon can achieve [SOSe00].

In obstetrics and gynaecology, the Zeus robotic system [Com] has been used to perform laparoscopic tubal ligation reversal. The Zeus is a master-slave system with three essential components: a surgeon's console, a computer control translating the surgeon's movements from the console to the robotic arms, and three interactive robotic arms. The robotic arm that holds the laparoscope is directed by voice commands.

Cardiac surgery has requirements similar to gynaecology for micro-suturing and the da Vinci^{TM} surgical system [Intc] has been used in human studies for cardiac procedures. The da Vinci is another master-slave telemanipulator with three robotic arms mounted on a heavy-duty mobile cart that can be wheeled into the operating theatre. It has three main components - a surgeons console, a laparoscopic stack and the robotic arms. The surgeons console can be placed within or outside the operating area. It is linked to the robot via cables. One of the robotic arms serves as the mount for the 12 mm endoscope, while the other two hold the 8 mm laparoscopic instruments or dissectors. They mimic the surgeons right and left hands. The endoscope contains two separate optical channels which relay images to two high-resolution cameras. These images are transmitted to a binocular display at the surgeon console providing the surgeon with a 3-D image of the operative field. The laparoscopic instrument tips are equipped with Endowrist technology. This is a computer enhanced mechanical wrist that contains cable-driven joints allowing for 7 degrees of freedom at the tip of the instrument compared to 4 degrees with a standard laparoscopic instrument. The computer interface between the surgeons console and the robotic arms filters out tremors and also allows for motion scaling. With the da Vinci system, the surgeon's movement can be scaled down by up to a factor of 5:1.

While it has been over 15 years since the first recorded use of a robot for a surgical procedure, the field of medical robotics is still an emerging one that has not yet reached a critical mass. Although robots have the potential to improve the precision and capabilities of physicians, the number of robots in clinical use is still very small. However, it is expected that demographic change, pressure for cost effectiveness and cost containment in healthcare, growth in minimal access surgery and day treatment, growth of intra-operative imaging enabling accurate robotic positioning without a fixed datum and increasing specialisation: leading to demand for expert assistance via tele-surgery and tele-mentoring will broaden the application area of medical robotics leading to a significant improvement in their cost effectiveness.

4.8.1. Telemedicine

The extraordinary developments in fields such as computing, communications and medical technologies are now making possible long-foreseen advances in telemedicine and telecare. By making use of computers and communication technologies, it is possible for an increasing range of medical services to be available locally.

Current telemedicine activities can be classified according to the technology used, the type of activity or the target group. One of the most important aspects of classification is the distinction between real time and store and forward. In real time telemedicine, the interaction between the participants is "live" and they can interact immediately. The advantage of this approach is that it enables optimum transfer of information between the participants. The disadvantages are that it is logistically difficult to manage large-scale services and they tend to be relatively expensive. Store and forward telemedicine is less expensive and easier to manage, as there is no "live" interaction. One participant gathers information (text, data, images, *etc.*) in electronic form and sends it to the other participant, who views it at a subsequent convenient time and reports back. Choice as to which of the above approaches is preferable varies with the type of service required; neither is universally preferable.

Telecare or telemonitoring can enable a patient's home to become a virtual hospital ward. Using advanced telemetry and sensor technologies, vital signs can be measured and transmitted to monitoring centres, which can detect possible problems and record them for future study. A nurse, based in the monitoring centre could be available 24 hours a day to provide reassurance and advice. A GP or specialist could be contacted if there are signs causing concern. Telemonitoring is a wide and fast-growing field with many implications on how healthcare will be delivered in the future. Over the next few years, as telemedicine is deployed more widely, one of the main challenges will be to manage the change that this will cause.

The development of tele-manipulators linked to high bandwidth telecommunications systems opens the possibility for tele-surgery, where an intervention can be carried out by a surgeon remote from the patient. A number of teams around the world have demonstrated the feasibility of this technique, but further sophistication is needed to give the remote surgeon a real sense of being there - or tele-presence. Amongst the applications lined up for tele-surgery are the ability to carry out surgery in remote areas, battlefield situations and disaster sites, and the ability to allow a scarce expertise to be widely disseminated using a small number of experts.

It is hoped that these and other advances in telemedicine may be able to help address the chronic problems of geographic maldistribution of healthcare resources, uneven distribution of quality, and the spiraling cost of care, but it evidently clears that the key to successful telemedicine is not the technology but the effective delivery of care [Yel99]. The technology itself is simply a means to an end.

4.9. Nanotechnology in Medicine

Nanomedicine has been defined as the monitoring, repair, construction and control of human biological systems at the molecular level, using engineered nanodevices and nanostructures [Fre]. In the future, use of 3D visualization and medical virtual environments will certainly expand and also have key roles in emerging areas such as microsurgery and nanotechnology applications. Micro-robots and even nanobots designed for use within the human body will need supervision by skilled operators equipped with advanced visualization equipment. There already exist "microsubmarines" powered by an induction motor; at 4 mm long and 650 µm in diameter, it is small enough to pass down a hypodermic needle and has the potential for various diagnostic or therapeutic applications [micb]. We envisage that the device will be tracked within the human body and referenced to a patient-specific data set to allow the supervisor to navigate using virtual images. This potential is already being demonstrated by the nanoManipulator (nM), an immersive virtual-environment interface to a Scanning Tunneling Microscope (STM) [Tay]. A head-mounted display presents an image of the surface being scanned by the STM at a scale of one million to one in front of the user while a force-feedback manipulator allows the user to feel contours on the surface.

4.10. Commercial Products

This section presents a brief overview of the currently available commercial products, from both hardware and software sides, that implement a medical virtual environment. Note that the majority of commercial products today focus on laparoscopy training. A comprehensive overview of surgical simulators in this field is more specifically given in [SJ03b].

4.10.1. Immersion Medical

Immersion Medical (formerly HT Medical) has been developing simulation platforms including both software and hardware solutions for i) needle and catheter insertion, ii) endoscopy, iii) endovascular procedures, and iv) laparoscopy [Immb].

CathSim^{TM} Vascular Access Simulator was developed to help nursing and phlebotomy students to acquire skills in needle and catheter insertion. The system includes a hardware device, *AccuTouch^{TM} Tactile Feedback* device, which enables the student to feel the insertion, by providing haptic feedback, from the needle or catheter entry through the skin to the entry into the vein lumen. In order to challenge the user to possible real scenarios, intravenous catheterization procedures can be performed in adult, pediatric or geriatric patients and, can include phlebotomy, IV catheterization and peripherally inserted central catheters (PICC) [UTN*99].

AccuTouch^{TM} Endoscopy Simulator supplies simulations of multiple flexible endoscopic procedures such as flexible bronchoscopy, upper and lower gastrointestinal flexible endoscopy. To teach and assess skills in a safe environment, the system uses anatomic models developed from real patient data, and incorporates a flexible endoscope which feels and performs like the real tool. The force is consequently transmitted through this endoscope to give the real sensations of the procedure.

AccuTouch^{TM} Endovascular Simulator allows the simulation of cardiac pacing or catheterization, and interventional radiology techniques. It provides the user with tactile feedback. In cardiac pacing, for instance, the trainee manipulates the required surgical accessories as in real procedures, and can feel the resistance of the lead when it moves in and out of the heart. Visual feedback is also integrated. Indeed, a computerized fluoroscopic view is displayed in real-time on a monitor.

Immersion Medical has also been developing hardware platforms, *Virtual Laparoscopic Interface* (VLI) and *Laparoscopic Surgical Workstation* (LSW), which are used in *LapSim^{TM} Basic Skills* and *LapSim^{TM} Dissection* by Surgical Science AB (see below). With VLI, the motions of two surgical instruments are optically tracked. Therefore haptic feedback is not provided. On the other hand, tools implemented in LSW reproduce standard laparoscopic tools supporting four haptic degrees of freedom, or five with the standard scissor-type handle.

4.10.2. Surgical Science AB

Surgical Science AB develops a series of software solutions, called *LapSim^{TM}*, for the training and assessment in minimally-invasive surgery skills of medical professionals [Sur]. *LapSim^{TM}* support haptic and non-haptic hardware devices by Immersion Medical (see above). It is available in three versions, *LapSim^{TM} Basic Skills*, *LapSim^{TM} Dissection* and, *LapSim^{TM} Gyn* which assess basics of laparoscopy, dissection and gynaecological laparoscopy respectively.

LapSim^{TM} Basic Skills provides general exercises to learn the basics of laparoscopy. For example, in the camera navigation exercise, the user must handle a camera with the left instrument to find a red ball on the tissue surface, and zoom up to it. Other exercises include instrument navigation, coordination, grasping, lifting, grasping, cutting, clip applying, suturing, precision and speed. In practice, graphic complexity and level of difficulty can vary. It let teachers able to create or modify courses depending on student's needs.

LapSim^{TM} Dissection, an extension of the previous tool, is dedicated to the simulation of dissection and subsequent clipping and cutting of the gall bladder's bile ducts and blood vessels performed in laparoscopic cholecystectomy procedures.

LapSim^{TM} Gyn is specific to gynaecological laparoscopy procedures. It includes sterilization, ectopic pregnancy removal and the final suturing stage of the myomectomy procedure.

4.10.3. Xitact

Xitact SA has developed *LS500^{TM}*, a laparoscopic cholecystectomy training platform available since 2002 [Xit]. It contains an operation table which includes the abdomen of the virtual patient, endoscopic instruments, and the endoscopic camera. These instruments provide force feedback with five degree of freedom. The hardware platform is compatible with laparoscopic surgery simulation software from various vendors. The validity of such a simulator has been questioned for the training in the surgical preparation of laparoscopic cholecystectomies as well for groups of novice surgeons as of experts. Training using *LS500^{TM}* has been reported as beneficial for both groups of surgeons [SJ02, SJ03a].

Xitact SA has also been developing tracking and USB force feedback devices for interventional (*xitact ITP^{TM}*) and endoscopic procedures.

4.10.4. Mentice

Mentice supplies various medical virtual environment applications, particularly in the field of minimally invasive surgery such as i) laparoscopy, ii) endovascular intervention, and iii) arthroscopy [Men].

Procedicus^{TM} MIST, formerly known *MIST/VR* developed by Virtual Presence (Sale, UK), is composed of two standard laparoscopic instruments linked to a personal computer to display the movement of the instruments in real-time. It was not developed to simulate the actual procedure, it was designed to teach, train and assess psychomotor skills in minimally invasive surgery through a series of abstract exercises using simple geometrical shapes, *e.g.* putting balls in boxes. The system supplies performance feedback on exercises, whose level of difficulty grows. The software design is modular to incorporate additional procedures such as the suturing module developed in collaboration with SimSurgery A/S (par. 4.10.5).

Procedicus^{TM} KSA (Key Surgical Activities) is devoted to laparoscopic training. It provides simulation of various types of procedures, such as triangulation, scope navigation, cutting, suturing, needle passing, diathermy and other essential key skills. The patient model corresponds to an abdomen made of stomach, gallbladder, liver, and the surrounding anatomies.

The virtual arthroscopy product family, *Procedicus^{TM} VA*, is available in two modules for shoulder and knee arthroscopic procedures.

Procedicus^{TM} VIST (Vascular Intervention System Training) is a generic system dedicated to endovascular simulations. It consists of the simulation of the physics and physiology of the human cardiovascular system (hemodynamics, blood flow and dye contrast media mixing and, catheter-vasculature physical interaction), the haptic device, and two monitors to display simulated fluoroscopic images used by interventional cardiologists to guide them during the intervention, and to display the instructional system. *Procedicus^{TM} VIST* is available in three modules: i) *Procedicus^{TM} VIST - Cardiology* dedicated to angioplasty and coronary stenting, ii) *Procedicus^{TM} VIST - Electrophysiology* to the training of biventricular lead placement, and iii) *Procedicus^{TM} VIST - Radiology* to carotid and renal stenting.

4.10.5. SimSurgery AS

SimSurgery AS [Simb] has developed medical simulation software tools for virtual training (*SimMentor^{TM}* [RKW*02]) and procedural planning in minimally invasive surgery, such as laparoscopy like the *Procedicus^{TM} MIST* suturing modules (see above).

4.10.6. Simbionix

Simbionix is specialized in the development of minimally invasive therapy training systems. Their simulation solutions imitate the tactile sensations given by laparoscopic instruments. They supply a range of four simulation platforms [Sima].

GI Mentor I^{TM} and *GI Mentor II^{TM}* provide hands-on training in endoscopic procedures.

URO Mentor^{TM} provides hands-on training in diagnostic and therapeutic procedures in the field of endourology.

PERC Mentor^{TM} provides training in percutaneous access procedures done under real-time fluoroscopy.

The last platform, *LAP Mentor^{TM}*, is a multi disciplinary simulator which enables hands-on training in basic and generic laparoscopy. The whole laparoscopic surgery procedure can be simulated using such a platform.

4.10.7. Medical Simulation Corporation

SimSuite^{TM} System by Medical Simulation Corporation aims to provide a realistic simulated clinical environment [Meda, MM03]. It combines haptic systems with real patient scenarios and images. It allows individual or team training with varying levels of complexity in several fields, such as cardiac, endovascular and general programs, as well as custom device manufacturer programs. It also introduces the user to the patient history, diagnosis, risk assessment and intervention preparation. Each intervention can be recorded for debriefing.

4.10.8. Select-IT Vest Systems AG

Select-IT VEST Systems AG has been developing a simulator for minimal invasive surgery, *VEST system* (Virtual Endoscopic Surgery Trainer) [Sel]. It is based upon a 3D-simulation development environment, *KISMET 3D-Simulation Software* by Forschungszentrum Karlsruhe [For]. The *VEST system* hardware platform consists of an artificial cavity, and a modified version of *Laparoscopic Impulse Engines* force feedback device by Immersion Medical (par. 4.10.1).

Currently, three software applications are available: i) *Basic Tasks Training* to become familiar with the system and with laparoscopic techniques, ii) *VSOne Cho* for the training in the gall bladder removal (laparoscopic cholecystomy) and, iii) *VSOne Gyn* which is devoted to laparoscopic surgery in gynecology.

4.10.9. Reachin

In 2002, Reachin introduced its first medical product, *Reachin Laparoscopic Trainer* (RLT) [Rea]. This platform allows the training in basic dexterous skills and in cholecystectomy procedures. It supports both LSW haptic and VLI non-haptic devices by Immersion (par. 4.10.1). Training courses composition can be modified to vary difficulty levels, from a number of basic and progressively more advanced skill training courses to specific procedures. Every movement performed by the user can be recorded in order to measure and assess the progress of the trainees. In *Unique Forceback* training mode, the user is guided by the simulator by pre-recorded movements and the tutor's speech.

Reachin has been implementing an original immersive visualization technology, *Reachin Display*, which is composed by a CRT monitor capable of stereo refresh rates, CrystalEyes StereoGraphics shutter glasses [Ste], a *PHANTOM*^{TM} haptic device by SensAble Technologies [Sen], Magellan/SpaceMouse [3Dc] and a semi-transparent mirror. The monitor, which is rotated through 45 degree, projects images onto the mirror placed above the haptic device. Looking through the mirror, the user can see and feel 3D models floating in the space. In addition to its *Reachin Display*, a proprietary application programming interface (API), *Reachin API*, is also supplied to create scientific visualization or medical applications like surgical simulators with force feedback. It integrates C++, Python, VRML, OpenGL with their haptic rendering technology.

4.10.10. Digisens

Digisens has developed a tool family, *HaptikFURL*, to teach dental medicine using stereoscopic glasses and a *PHANTOM*^{TM} haptic device to improve the tactile feeling of students [Dig]. Teeth models are reconstructed from micro-CT volumes to accurately reproduced the surface and especially the inside of teeth in order to allow students to mill these virtual teeth.

4.10.11. Trends in Commercial Products

Early simulators aimed at realism, but they were unsuccessful. Indeed, graphics hardware was too expensive, which prevented large-spread use, or was too slow, which did not make real-time simulations possible. One of the first successes probably was *MIST/VR* by Virtual Presence (par. 4.10.4). Its originality consisted of the task abstraction approach: manipulating simple 3D shapes using a laparoscopic user-interface.

Nowadays, simulating realism is becoming possible although many research challenges still remain, such as realistic physical behavior of deformable tissue, fluid flow, haptic modelling, *etc.* Indeed, the sensation is a key issue in surgery skills learning or training by simulation. The future will also undoubtedly see more variety of solutions, not only confined to the field of laparoscopy surgery, such as interventional radiology, open surgery techniques, and other specialist domains such as dental surgery.

5. Future Challenges and Conclusions

Medical applications that use computer graphics techniques are becoming commonplace. As the field begins to mature, we note that there are still many research challenges remaining including:

- Further integration of human, machine and information,
- Continuing strives for improved realism.
- Integration of computationally intensive tasks with Grid resources and high performance computing
- New application areas will emerge.
- Reducing cost will continue to be a priority.
- Validation of training simulators and computer graphics algorithms must be demonstrated.
- Moral and ethical issues will need to be addressed.

While we have no doubt that as these items are progressed the impact will be significant, a sea change in medical opinion will still be required. A significant learning curve has to be overcome by today's medical profession if the advances already achieved, never mind those to come, are to be translated into realities in health care and benefit to patients. The positive collaborations between computer scientists, clinicians, medical physicists and psychologists that are present in the majority of the projects described in this report augur well that this will happen.

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