Image-guided Surgery and Therapy: Current Status and Future Directions

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ABSTRACT

Image-guided surgery and therapy is assuming an increasingly important role, particularly considering the current emphasis on minimally-invasive surgical procedures. Volumetric CT and MR images have been used now for some time in conjunction with stereotactic frames, to guide many neurosurgical procedures. With the development of systems that permit surgical instruments to be tracked in space, image-guided surgery now includes the use of “frame-less” procedures, and the application of the technology has spread beyond neurosurgery to include orthopedic applications and therapy of various soft-tissue organs such as the breast, prostate and heart. Since tracking systems allow image-guided surgery to be undertaken without frames, a great deal of effort has been spent on image-to-image and image-to-patient registration techniques, and upon the means of combining real-time intra-operative images with images acquired pre-operatively. As image-guided surgery systems have become increasingly sophisticated, the greatest challenges to their successful adoption in the operating room of the future relate to the interface between the user and the system. To date, little effort has been expended to ensure that the human factors issues relating to the use of such equipment in the operating room have been adequately addressed. Such systems will only be employed routinely in the OR when they are designed to be intuitive, unobtrusive, and provide simple access to the source of the images.

Keywords: Image-guided surgery; image-guided therapy, registration, tracking, robotics, virtual reality, simulation, software

1. INTRODUCTION:

Image-guided surgery and therapy has its roots in the field of stereotactic neurosurgery. While this approach was not specifically “image-guided” in the beginning, it nevertheless provided the means to introduce probes into the brain at precisely defined locations. At the advent of truly three-dimensional imaging, first with CT and later with MRI, volumetric images were used with stereotactic frames to guide many neurosurgical procedures. Upon the development of systems that permitted surgical instruments to be tracked in space, image-guided surgery began to include the use of “frame-less” procedures, and the application of the technology spread beyond neurosurgery to include orthopedic applications and therapy of various soft-tissue organs such as the breast, prostate and heart.

This paper begins with an overview of stereotactic technology and follows with examples of applications in common use or in development. Current problems and limitations of current practice are identified, and the paper concludes with a glimpse into the future of image-guided surgery.

2. STEREOTACTIC SURGERY

2.1 Frame-based

Computerized planning systems made their debut in the early 1980’s with simple programs that established coordinate systems in the brain based on frame-based fiducial markers. This approach rapidly evolved to allow images from multiple modalities to be combined so that surgical planning could proceed using information from a combination of MRI, CT and angiographic images. Such multi-modality imaging was considered important for certain procedures, such as the insertion of probes or electrodes into the brain. The ability to simultaneously visualize the trajectory with respect to images of the blood vessels (either using orthogonal projections or stereoscopic image pairs), enabled the pathway to be planned with the confidence that it traversed within a vascular-free zone. [1,2,25,26] Much of stereotactic surgery was concerned with procedures involving the introduction of probes, cannulae or electrodes into the brain. However, in 1986, Kelly[3-5] proposed an innovative approach, based on stereotactic principles for the treatment of tumors. Instead of a narrow cannula, he approached a tumor volume via a cylindrical retractor integrated with a stereotactic frame. Such tumors could be stereotactically biopsied and treated by implantation of radionuclide sources, or resected using computer-assisted stereotactic laser microsurgical techniques. Kelly's work was a bridge between conventional frame-based stereotactic neurosurgery, and the frameless approaches that subsequently evolved.

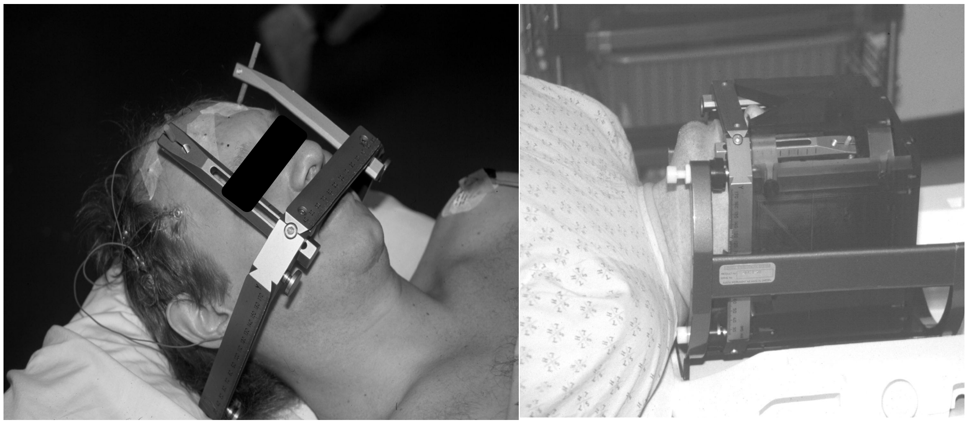

Figure 1. Typical Stereotactic frame. a) fastened to the patient's head prior to surgery; b) with fiducial marker plates attached prior to the scanning procedure.

2.2 Frameless stereotaxy

In spite of the advantages of the stereotactic frame, most involve a surgical procedure to fasten them to the patient, either through the creation of 3-4 1-2 mm deep holes in the skull with a twist-drill to accept blunt pins, or sharp pins applied to the skull under pressure. The frame (or in some cases just the base-ring which can be separated from other structures) may also present unnecessary clutter in the operating room. Hence, there is a general desire to be rid of the frame if possible. However, without the frame to provide the fiducial markers, some other sort of reference system must be employed to register the patient to the image(s). Commonly used registration methods are discussed below.

2.3 Point matching

The most common method of registering an image to the patient involves the identification of common landmarks both in the images and on the patient. For example, a tracked pointer may identify landmarks such as the outer canthi of the eyes, the tragus of the ears, and the nasion, while these same structures are identified within the three-dimensional images of the patient. Unfortunately there is bound to be some variation in the identified locations of the landmark points on the patient, as well as some difficulty in identifying exactly the same locations within the patient's three-dimensional image. Generally, a least-squares approach is used to obtain an approximation to the correct registration. However, unless all of the registration points are appropriately distributed about the surgical site, small inaccuracies in registration in the region containing the homologous points can be magnified for more remote points.[6-7]

2.4 Surface matching

Some systems employ a surface-matching approach to complement the point matching method. This technique involves using the probe to sample points on the surface of the patient, and then determining the best match of this point-cloud to an extracted surface from the 3-D patient image. This combined approach using both points and surfaces is described by Maurer[8] and is incorporated in several commercial image-guided neurosurgical systems. Under ideal conditions, (i.e. in phantom tests where homologous structures are easily identified and there is no movement of the markers with respect to the object), accuracy approaching that of stereotactic frames can be achieved.[9] However, under clinical conditions, where natural features on the patient's skin are identified, the accuracy obtainable from his type of approach decreases due to the subjective identification of homologous point-pairs on the patient and in the images. While this may be adequate for many neurosurgical purposes, it is not appropriate for procedures requiring great precision.

2.5 Bone-mounted markers

The accuracy and precision of point matching procedures can be improved by using surface markers glued to the patient's skin. In this case their location can be more precisely determined using the pointer, and they can be automatically identified within the patient's three-dimensional images. While this improves the precision of the matching, there remains the problem that skin mounted markers can move with respect to the underlying bony anatomy, and therefore add additional error. Maurer *et al.*[10] have demonstrated convincingly that the only way to achieve patient-to-image registration with the same accuracy as can be obtained with a stereotactic frame is by using bone-mounted fiducial markers. Even though the implantation of these reference markers constitutes a procedure that is approximately as invasive as the installation of a stereotactic frame, it can nevertheless be performed under local anesthetic and represents a level of invasiveness that is minor compared to the surgical procedure that is to follow. Maurer *et al.*[10] show that the accuracy and precision obtainable with properly designed markers is in the order of 0.5 to 1.5mm.

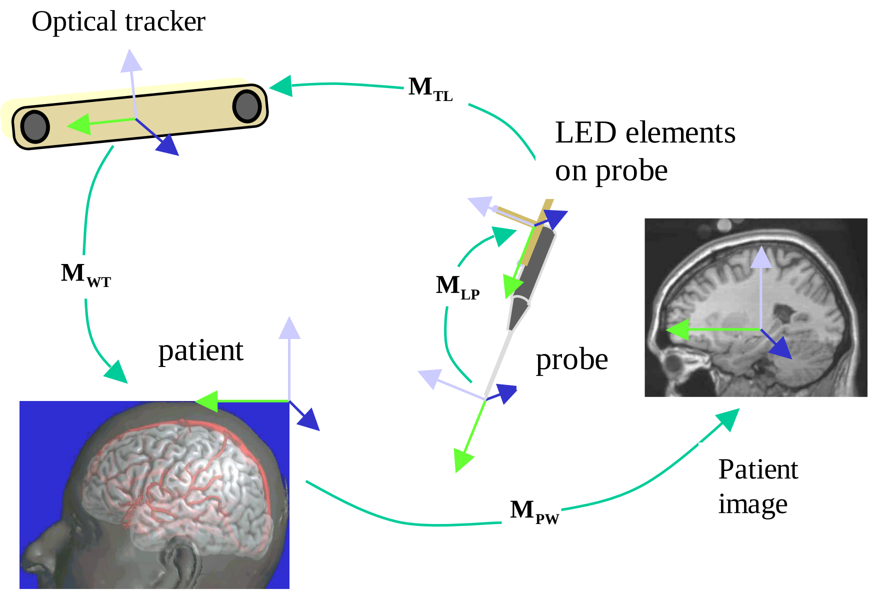

Figure 2. Typical instrument tracking scenario. The symbols M_{xx} represent the transformation matrices relating various coordinate systems. The transformation matrix describing the relationship between the probe and the patient image is a concatenation of these transformation matrices.

2.6 Tracking Systems

Tracked probes provide the key to image-guided surgery. Mechanical,[9,11] ultrasonic, magnetic,[12] or optical[13] methods have all been employed to determine the probe's position, but the use of optical trackers (both active and passive) has now become almost universal. Until recently there was no satisfactory means of tracking an object (for example a catheter tip or a flexible endoscope) within the body unless one employed a real-time imaging system like MRI,[14-16] ultrasound,[17] or fluoroscopy. Recently, miniature magnetic sensors[a][b] have become available that can be inserted in a catheter, which opens the door to tracking flexible instruments within the body. Most of the devices in routine use currently report accuracies and precisions of better than 1mm, which is generally accepted as a target performance standard for tracking devices. Whatever process is employed at the registration and instrument tracking phases of the procedure, a number of coordinate transformation calculations must be made to relate the coordinates of "image-space" to those of "patient space", as illustrated by Figure 2.

2.7 Intra-operative imaging.

Although tracking systems allow image-guided surgery to be undertaken without frames, and permit dramatic expansion in the scope of procedure to which it could be applied, the move to encompass open-craniotomy procedures brought other problems. The absence of the frame compromised the accuracy with which the images could be registered to the patient, and the fact that the tissue could move during the procedure meant that the pre-operative images did not necessarily represent the state of the tissue accurately during surgery. A great deal of effort has been spent on image-to-image and image-to-patient registration techniques, and means of combining real-time intra-operative imaging with images acquired pre-operatively. Approaches to this problem include the use of "open" MR magnets, which allow the patient to be imaged dynamically during the procedure,[18,19] and intra-operative imaging using standard magnets that can be employed to image the patient at several time-points during the surgical procedure.[20] These approaches are expensive and somewhat unfriendly with respect to the OR environment. In response to this problem, the use of intra-operative ultrasound has been employed either alone,[21,22] or in conjunction with pre-operative MRI.[23,24]

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[a] http://www.ndigital.com/aurora

[b] http://www.ascension-tech.com/products/minibird

3. MULTI-MODALITY IMAGING

Although CT was the primary imaging modality originally employed for stereotactic surgical planning, it soon became evident that it could be complemented by other imaging modalities. In particular, the combination of MRI and digital subtraction angiography provides both anatomic and vascular information; while MRI (or CT) and PET (or Spect / fMRI) provided anatomical and functional data in the same image volume. For this reason, multi-modality image display and analysis systems were developed to allow the planning and guidance operation to take place using multiple image data sets simultaneously.[25-27] Many of these techniques are discussed in a recent comprehensive review on image registration.[28]

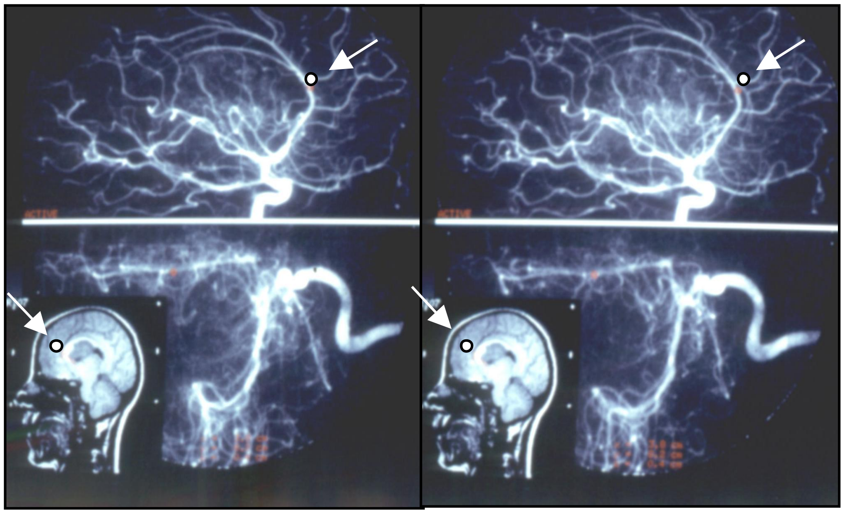

Figure 3. Stereoscopic (crossed-eye) view of lateral (top) and anterior-posterior (bottom) angiograms along with registered MR image. A 3-D cursor (arrows) driven through the volume defined by the angiograms is tracked in the appropriate slice of the MR volume.

Although MRI and CT are three-dimensional imaging systems and digital subtraction angiography is two-dimensional, it is nevertheless possible to display the projection of a point identified in the 3-D modality within the 2-D angiogram. Likewise a point within the planar angiogram can be represented as a line within the MRI or CT volume. By employing orthogonal or stereoscopic angiogram pairs, three-dimensional localization can be achieved within the angiogram-defined space (Figure 3). This multi-modality approach was particularly important when planning trajectories to deep brain structures, or when implanting EEG recording electrodes during a procedure to localize the foci of epileptic seizures.[29,30] In both cases, it is important to ensure that the trajectory follows a path that is free from major blood vessels. This can be easily achieved by verifying the trajectory that is planned on the basis of the MRI or CT images by examining its projection within the angiogram images.

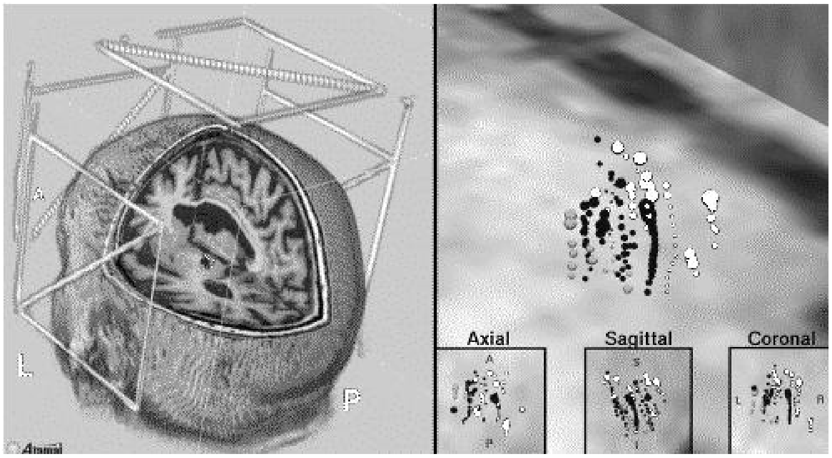

Figure 4 Atlas of Facial, Finger, and Foot paresthesias evoked by microstimulation (300Hz stimulus, < 100µA, 0.2ms) derived from 26 patients. Left: Location of stimuli coordinates within deep brain region of individual patient. Right: magnified region showing somatatopy (facial responses in white, finger responses - black, foot responses - grey)

3.1 Physiology

Physiological information is often useful as a complement to the anatomical data furnished by MRI, CT or angiography. In addition to the information derived from PET or fMRI some neurosurgical procedures (such as the therapy of Parkinson's disease) rely heavily on electrophysiological information, recorded from deep-brain electrodes. Mapping the electrophysiological responses recorded during such procedures onto the 3-D anatomical images of the patient helps the surgeon navigate towards the desired target. Moreover, a database of such responses, normalized through non-linear image registration to a standard data space, can be integrated with the patient's 3-D MRI to assist the surgeon by predicting the likely target for creating a therapeutic lesion[31] (Figure 4).

3.2 Video

Intra-surgical video images can add a great deal of information to an image guided surgical procedure. The integration of the real and modeled worlds in this manner is often referred to as augmented or enhanced reality visualization. Kikinis[32] and Davey[33] demonstrated the efficacy of integrating a video image of the operative site with the graphical representation of a tumor or other target structure. In this manner, the surgeon can "see-through" the patient's skin into the operative site, to facilitate the planning of an optimal approach to the surgical target. More recently, other investigators have achieved similar results by integrating virtual images (derived from 3-D medical imaging) into the same space occupied by the physical object, through the use of half-silvered mirrors suspended above the operative site[c], or head-mounted displays.[34,35] Using stereoscopic visualization and appropriate head-tracking, this approach can place a realistic 3-D virtual image of the organ in the same physical space occupied by the actual organ.

3.3 Microscopes

Since many surgical procedures involve the use of an operating microscope, the integration of the microscope images with those obtained from preoperative MRI and CT scans is a natural application of augmented reality. In this case the images from a tracked microscope can be integrated electronically in a digital or analog fashion, with the combined images being displayed on a video or computer monitor. Alternatively, the images from the preoperative scans can be projected into the visual field of the microscope.[36] This technology has also been incorporated into head-mounted displays where the position of the surgeon wearing such a display is tracked and the preoperative image corresponding to the viewpoint of the surgeon is projected on his field of view.[37]

3.4 Endoscopes

While an operating microscope can "see" into an operating site through a skull opening greater than about 2 cm in diameter, when we seek to visualize the target directly through a smaller opening, other means must be employed. The endoscope has been used for many years to gain visual access to body cavities, and has been employed in neurosurgery to assist in surgical procedures within the ventricles. A technique that has become popular recently is "virtual-endoscopy,"[38,39] which uses computer graphics to simulate the view of an endoscope placed in a particular body cavity, based on the representation of the cavity derived from preoperative MRI or CT images. With the increasing emphasis on minimally invasive surgery, there has recently been an active interest in combining the video images from standard endoscopy with the computer-generated images of virtual endoscopy. The aim here is to place the endoscope image observed during a minimally invasive surgical procedures, in its proper context by merging it with the equivalent surface extracted from the preoperative images. Several authors have recently reported on the clinical application of combining images of the ventricle wall obtained from a tracked endoscope, with the equivalent images from CT or MRI.[40-42] The simplest mode of operation of this approach is to simply track the tip of the endoscope, and display the tracked point on orthogonal image slices derived from the original data. The most convenient means of achieving this goal is to display the three slices that intersect at the tracked point. However, in order to place the endoscopic image in its proper context, a surface rendition of the cavity within which the endoscope resides is constructed, onto which the video image produced by the endoscope may be mapped. Figure 5 is an example of an endoscopic image after proper rectification to remove lens-induced distortions, as well as those due to the

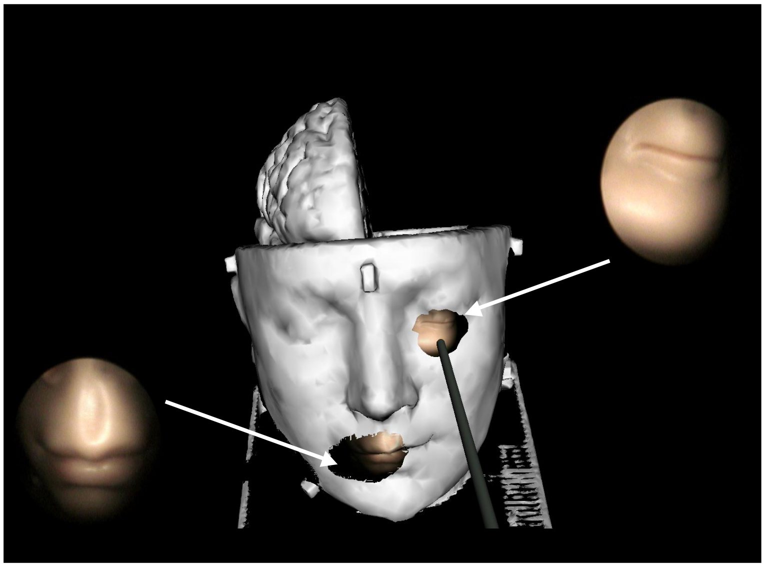

Figure 5. Endoscopic images from a tracked endoscope, mapped onto the surface defined by a 3-D digital model of the original object.

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[c] http://www.mrcas.ri.cmu.edu/projects/overlay /system.html

arbitrary shape of the organ surface, that has been accurately mapped onto the surface of the image derived from a 3-D CT volume.

4. NON NEUROLOGICAL APPLICATIONS

4.1 Orthopedics

Computerized image-guidance of spinal and orthopedic procedures has lagged somewhat behind its application in neurosurgery, but it is rapidly growing in popularity. Lavalée *et al.*[43] discuss a computer-assisted surgical system for navigation during spinal surgery, using CT images as guidance. Their approach follows closely that outlined for IGNS. This same group[44] describes a similar technique for anterior cruciate ligament reconstruction. This system uses a workstation and a three-dimensional optical localizer to display images that recreate knee kinematics. In the future, it is expected that standard arthroscopy will be combined with a tracking system and “virtual arthroscopy” based on high quality MR and/or CT images of the joint to assist in such procedures.

Foley *et al.*[45] point out the limitations of 2-D conventional imaging techniques for spinal navigation, and describe a three-dimensional image-space representation of the surgical volume, using a specially designed referencing system and computer workstation, while Nolte[46] discusses the use of interactive navigation of surgical instruments for the fixation of spinal implants. The use of rapid 3-D MRI was investigated by Martel *et al.*[47] to acquire images suitable for image guided surgery of the spine. They employ a very fast 3-D MRI sequence, with a wide bandwidth and short echo time (TE) to minimize susceptibility distortions, along with MRI/CT compatible fiducial landmarks. This permits the validation of the MR approach against CT, and demonstrates that the registration can be undertaken with an accuracy of 0.4 mm using 3-D MRI. They show that MR can effectively be as accurate as CT for spinal imaging in this context, and conclude that MRI shows promise for use in computer assisted surgery of the spine.

4.2 Breast

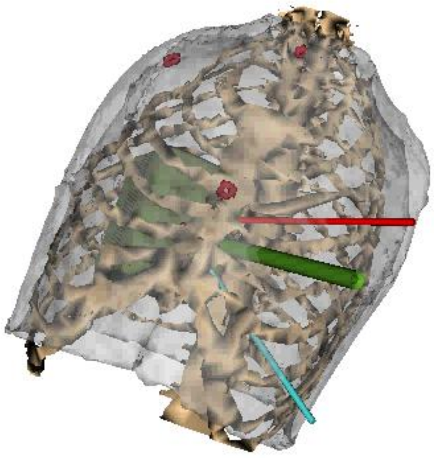
Using the GE intra-operative magnet discussed above, Gould *et al*.[48] demonstrated that interventional MRI is an effective tool for accurately identifying palpable breast tumors and guiding their surgical excision. The use of radiographic and ultrasonic techniques for image-guided breast surgery is increasing, but is currently restricted to fine needle aspiration and core biopsy, as discussed by Staren *et al.*[49,50] They comment that future care of patients with diseases of the breast will continue to be increasingly dependent on image-guided breast biopsy techniques. This approach should avoid many unnecessary open biopsies for benign lesions and facilitate therapeutic planning for malignant lesions. The increasing use of computer assisted stereotactic radiographic and ultrasound breast imaging is also reviewed by Burns,[51] who suggests that such techniques to guide percutaneous core sampling of the abnormal area are less invasive, less painful, highly accurate, and less expensive than incisional breast biopsy with preoperative needle localization.

4.3 Prostate

Image guidance is common in treatment of prostate cancer, but its application is focused on therapy (via cryosurgery or brachytherapy) rather than surgical removal. The most common modality in use for image-guided therapy of the prostate is ultrasound, and the recent development of 3-D trans-rectal ultrasound (TRUS) imaging techniques[52-54] has had a positive impact on this field. When employing 3-D TRUS for therapy, a series of 2-D US images, uniformly spaced in angle, are reconstructed to form a 3-D volume. This is registered with a therapeutic probe (radio-active seed implant device or cryosurgery probe) and manipulated in much the same manner as a lesioning device is introduced into the brain. Intraoperative 3-D TRUS provides unique, pseudo real-time views of the prostate, which facilitates the optimal placement of the probes.

4.4 Heart

As in other regions of the body, minimally invasive surgery techniques have begun to play an increasing role in cardiac surgery in an attempt to reduce the significant trauma and long recovery time associated with traditional coronary bypass surgery. Conventional coronary bypass surgery requires a sternotomy and a cardiopulmonary bypass procedure that subjects patients to significant trauma and lengthy hospital stays. Over the past few years, minimally invasive direct coronary artery bypass (MIDCAB) procedures have been introduced, performed via instruments introduced into the chest via trochars and guided endoscopically. Such techniques are making a significant impact on cardiac surgery, but because of the extreme difficulty in manipulating the instruments at the distal ends of the trochars, several groups have recently begun to perform coronary bypass surgery on the beating heart in the intact chest using tele-operated robots inserted into the chest via intercostal ports.[55-57] The use of robots increases dexterity and reduces the effect of tremor in the surgeon’s hands.



In spite of the sophistication of these robotically assisted systems, the use of images in the planning of the procedure is presently limited to conventional chest-radiographs and angiograms. The use of such simple images makes it extremely difficult to plan the positions for the entry ports between the ribs, and does not allow for any level of guidance during the procedure. The operation must be carried out solely under the guidance of a 1-2 cm diameter field-of-view delivered by the inserted endoscope. Several laboratories have recently extended the expertise developed in neurosurgical guidance to build a virtual cardiac surgery environment, which combines 3-D CT and 4-D (dynamic) MRI to present the surgeon with a model for planning and guidance during the procedure[58,66] (Figure 6). Initially, these efforts have been based on static cardiac images aimed at planning appropriate inter-costal port locations and robot orientations. This work is however moving rapidly in the direction of virtual dynamic surgical simulation, planning and guidance environments, that will synchronize the dynamics of the modeled cardiac environment with that of the beating heart.

5. COORDINATED APPLICATION DEVELOPMENT

Many groups across the globe are working on problems in image-guided surgery, and many different software and hardware platforms have been employed. This situation not only makes it difficult to share resources across the community, it also raises the problem of legacy software being constrained to a particular (outdated) hardware platform. Nevertheless, over the past few years, many groups have begun to use the rapidly evolving VTk[h] environment for developing medical imaging applications. Working with such a suite of robust tools has significant advantages producing increased development speed, reliability, and reusability of code. In addition, its open source nature encourages contribution from the user community. The development of new applications in medical image visualization and surgical planning requires the completion of many common tasks such as reading, re-sampling and segmenting images, followed by visualization via surface or volume rendering, etc. The intra-operative use of such tools requires that images be registered to the patient, and that tools and probes are tracked. For such systems to be employed by someone other than the original author, the user must be provided with basic, easy to understand user interface components. Computer and end-application hardware changes rapidly, as do operating systems and network environments. Such factors emphasize the advantages of having access to an independent collection of reusable software components that are hardware and operating system independent, and which can be assembled rapidly to prototype new applications.

In our lab, we have developed a set of such components that address some of the above-mentioned concerns.[59] They are written in both C++ (some as VTk classes) and Python, but all are accessible from Python, a byte compiled scripting language that is gaining rapid acceptance. Applications built using these components have been used on the Red Hat Linux, Silicon Graphics Irix, Microsoft Windows, and Mac OS X platforms. Rigorous object oriented software design methods have been applied to ensure hardware independence and a standard application programming interface (API). There are components to acquire, display and register images from MRI, MRA, CT, Computed Rotational Angiography (CRA), Digital Subtraction Angiography (DSA), 2D and 3D ultrasound, video and physiological recordings. We have also implemented interfaces to various tracking systems for intra-operative use. Over the past two years, these components have been used to create general image manipulation and viewing tools, a deep brain functional atlas[31] (Figure 5), a 3D ultrasound acquisition and display platform[24], a tracked neuroendoscope guidance system[61] (Figure 6), a prototype minimally invasive robotic coronary artery bypass graft planning system[58] (Figure 7), and a frame-based stereotaxy neurosurgery planning tool[59]. We believe that by following this approach, new applications can be developed more rapidly, they can be readily tailored towards the needs of users, and the transition from a research to a clinical/commercial environment can be facilitated. Further details of this approach can be found in Starreveld *et al.*[59]

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[h] http://www.kitware.com

6. CHALLENGES IN IMAGE-GUIDED SURGERY

The current emphasis on the use of minimally invasive therapies in all parts of the body has made image-guidance for therapy and surgery a rich area for research and development. Many of these applications present fascinating problems, and one of the most challenging is in the area of minimally invasive robotically-assisted cardiac surgery, where therapy is performed on the beating heart through several small holes between the ribs. In order to adequately provide full intra-operative image-guidance to the surgeon during the procedure, not only must pre-operative dynamic images be matched to the intra-operative anatomy of the patient but proper account must be taken of the complex relative motion undergone by the heart and thorax during the procedure. Currently, the efficacy of this procedure is limited by the lack of sophistication of the robotic end-effectors, allowing only single accessible coronary vessels to be bypassed using this procedure. Improvements to the dexterity of these robots will enable more complex procedures to be performed using these minimally-invasive approaches.

Factors currently limiting the wide acceptance of image-guided surgery include the lack of universal image standards, less than intuitive user interfaces, differences in image-registration protocols, incompatibility of surgical tools with guidance systems, lack of adaptation of systems to user preferences, and inherent errors in imaging and tracking systems. While it is true that the introduction of ACR-NEMA followed by DICOM-3 has gone a long way towards the creation of a universal image format standard, there nevertheless remain many DICOM "flavors". In addition, DICOM does not directly support 3 and 4-dimensional datasets or 3-D objects. Images are still treated as a serried as "byte-slices" rather than as samples of some parameter within a multi-dimensional space. Some of these limitations have been addressed by the MINC (Medical Image Net-CDF) format, based on Net-CDF and extended at the Montreal Neurological Institute by Neelin *et a.*[60d] MINC adopted by many groups in the neuroscience imaging community and beyond as an effective format/environment for medical imaging reseach. The need to evolve coherent user interface and interconnectivity standards that could be adopted by multiple manufacturers was expressed by Bucholz in his recent keynote address at the MICCAI-2000 meeting. To this end he has proposed the SurgON standard[e], that, if adopted universally, could solve many of the inter-connectivity and user interface problems that exist with current systems.

7. SIMULATION

The development of tools for image-guided surgery and therapy has led to the need for an environment to accurately represent the patient using computer methods, to simulate surgical and therapeutic procedures in as realistic a manner as possible, without involving human subjects. This approach becomes particularly important as surgical procedures become minimally invasive and robotically assisted. The need for accurate simulation in this environment can be likened to the need for simulation in the aviation industry, i.e. exposing the pilot/surgeon to realistic scenarios and monitoring their responses.

Simulation fulfills the needs to compare alternative procedures, develop and refine interventions, reduce complications, increase predictability, train practitioners, customize instruments and devices, and improve outcomes. The input data for such a simulator are acquired from multiple imaging modalities, including CT, ultrasound, and MRI, and can be in the form of pre-, intra- and post-operative three-dimensional images. In reality, simulation is part of the continuous spectrum that already exists for image-guided surgery. The level of realism in the presentation of the data allows us to progress from simple guidance of the procedure to realistic simulation. Models of the skeleton and soft tissue may now be synthesized from volumetric images, and visualized and modified interactively. Individualized electronic regional body atlases may also be created using deformable templates or by applying image fusion/registration methods. Once modeled and visualized, simulation is accomplished with various interactive devices, both visual and tactile, that mimic biopsy, minimally invasive, and open surgical and therapeutic procedures, tele-surgery, intraoperative navigation, virtual endoscopy, gene therapy, and can provide the necessary training. Glombitza *et al.*[62] recently presented an overview of the state of the art of virtual surgery, citing its use in a variety of environments.

An important aspect of realistic simulation is the force feedback sensed by the operator conveying realism at the tactile level. This probably represents the most difficult aspect of the simulation cycle. While sophisticated multi-degree of freedom force-feedback (haptic) devices exist (Sensable Technologies Inc[f], MPB Technologies[g]), they are limited to applying linear or

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[d] The MINC Format. MNI Website .http://www.bic.mni.mcgill.ca/software/minc/minc.html

[e] http://Thalamus. slu.edu/SurgON/

[f] http://www.sensable.com/products/6dof.htm

[g] http://www.mpb-technologies.ca/space/p_freedom6s.html

rotational force feedback to the operator, are not able to provide textural information (to the fingertips for example), and may be limited with respect to the rate at which they can respond to input. It is likely that in some instances, physical models (registered spatially with the virtual model) could be employed to provide the appropriate haptic feedback when performing such procedures as cutting and probing tissues. An example might be an Agar or Poly-vinyl alcohol cryogel[63] phantom that has been manufactured to simulate the mechanical properties of the tissue being modeled. If the underlying finite element model that is driving the mechanical simulation and visualization is sufficiently sophisticated to mimic the behavior of the phantom (when cut for example), the physical model could provide much of the necessary mechanical feedback to the operator.

8. FUTURE DIRECTIONS

Although image-guided procedures are commonplace in neurosurgery, there have been few efforts to quantify their effectiveness, either in terms of patient outcome or cost savings. One study that has attempted to do so was presented recently by Paleologos *et al.*,[64] who demonstrate some benefit (in terms of reduced complication rates, shorter hospital stays) through the use of image-guidance for meningioma surgery via craniotomy vs. conventional approaches. They point out that it is difficult to construct robust studies to validate such procedures, and that many of the advantages relate to the increased comfort of the surgeon performing the procedure. While difficult to generalize from this small study, they acknowledge the additional benefits of integrating multi-modality imaging and correcting for intra-operative brain shift would be expected to significantly enhance the acceptance of such techniques. While image-guide surgery systems are becoming increasingly sophisticated perhaps the greatest challenge to the successful adoption of image-guided surgery systems in the operating room of the future, relates not to the technology, but to the user interface and the acceptance of the technique. Over the last few years, inexpensive high-speed computing hardware has become available to allow interactive surgical image-guidance to be performed in real time, with the images presented to the surgeon in a “virtual-reality” format. However, little effort has been expended to date on ensuring that the human factors issues relating to the use of such equipment in the OR have been adequately addressed. Visarius *et al.*[65] point out that the majority of image-guided surgical systems in clinical use still require the involvement of a “systems engineer” to ensure that the procedure runs smoothly. It is incumbent on all who develop such systems that they focus on reducing the cost of the equipment, making it available on demand, and designing it so that it can be used by OR staff as a routine item of surgical equipment. Patient images must be automatically available in the OR in the appropriate format; patient-image registration steps must be trivial and robust, all tools should be recognized and trackable by the system, and images need to integrated with the actual patient view so that the surgeon is not constantly changing his visual field. It will only be when such systems are unobtrusive, provide simple access to the image sources and can be operated in an intuitive manner by traditional operating room staff, that they will be employed routinely in the OR.

Beyond neurosurgery, minimally-invasive image-guided techniques will continue to play increasingly important roles in cardiac surgery, breast, orthopedic surgery, prostate therapy, and brachytherapy of various organs. The use of tele-robotic control will increase the precision of these procedures through tremor control and dexterity enhancement, and permit more procedures to be performed under direct image guidance (in conventional MR scanners or high dose-rate x-ray fluoroscopy). In adition, many of the techniques discussed here are finding application in conventional external beam radiation therapy.

9. CONCLUSION

Image-guided approaches have evolved significantly over the past 20 years and stand to make further important contributions to a variety of surgical and therapeutic procedures, rendering them less invasive and less traumatic to the patient. There are many challenges in the path of the general acceptance of these techniques by the surgical community. In addition to the general lack of quantifiable evidence regarding the demonstrable efficacy of these approaches, there is a natural reluctance of many practitioners to embrace technology-based approaches, particularly when faced with the prospect of having to learn on a new paradigm, or to place reliance on an additional level of “engineering” support during the surgical procedure. For this reason, the key developments in this field must include the provision of a largely automated and “bullet-proof” infrastructure, where image-management becomes a trivial operation, the delivery of user interfaces that are intuitive and non-threatening and the ability to make systems available to the surgeon on demand with a minimum of additional planning.

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