Computer-Integrated Surgery and Medical Robotics

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1. Introduction: coupling information to surgical action

The growing demand for complex and minimally invasive surgical interventions is driving the search for ways to use computer-based information technology as a link between the pre-operative plan and the tools utilized by the surgeon. Computers, used in conjunction with advanced surgical assist devices, will fundamentally alter the way that are procedures are carried out in 21st Century operating rooms.

Computer Integrated Surgery (CIS) systems make it possible to carry out surgical interventions that are more precise and less invasive than conventional procedures, while judiciously tracking and logging all relevant data. This data logging, coupled with appropriate tracking of patient outcomes, will make possible a totally new level of quantitative patient outcome assessment and treatment improvement analogous to “total quality management” in manufacturing.

The goals of CIS systems are to enhance the dexterity, visual feedback, and information integration of the surgeon. While medical equipment is currently available to assist the surgeons in specific tasks, it is the synergy between these capabilities that gives rise to a new paradigm. The goal is to complement and enhance the surgeon's skills and always leave him in control, never to replace him.

CIS systems are instances of an emerging paradigm of human-computer cooperation to accomplish delicate and difficult tasks. In some cases, the surgeon will supervise a CIS system that carries out a specific treatment step such as inserting a needle or machining bone. In other cases, the CIS system will provide information to assist the surgeon’s manual execution of a task, for example through the use of computer graphic overlays on the surgeon’s field of view. In some cases, these modes will be combined.

From an engineering systems perspective, the objective can be defined in terms of two inter-related concepts:

- ***Surgical CAD/CAM systems*** transform preoperative images and other information into models of individual patients, assist clinicians in developing an optimized interventional plan, register this preoperative data to the patient in the operating room, and then use a variety of appropriate means, such as robots and image overlay displays, to assist in the accurate execution of the planned interventions.
- ***Surgical assistant systems*** work interactively with surgeons to extend human capabilities in carrying out a variety of surgical tasks. They have many of the same components as surgical CAD/CAM systems, but the emphasis is on intraoperative decision support and skill enhancement, rather than careful pre-planning and accurate execution.

Two other concepts related to CIS are ***Surgical Total Information Management (STIM)*** and ***Surgical Total Quality Management (STQM),*** which are analogous to "total information management" and "total quality management" in manufacturing enterprises.

Table 1 summarizes some of the factors that must be considered in assessing the value of CIS systems with respect to their potential application. Although the main focus of this article is the technology of such systems, an appreciation of these factors is very important both in the development of practical systems and in assessing the relative importance of possible research topics.

The CIS paradigm started to emerge from research laboratories in the mid 1980's, with the introduction of the first commercial navigation and robotic systems in the mid 1990's. Since then, a few hundreds of CIS systems have been installed in hospitals and are in routine clinical use, and a few tens of thousands of patients have been treated with CIS technology, with their number rapidly growing. The main clinical areas for which these systems have been developed are neurosurgery, orthopedics, radiation therapy, and laparoscopy. Preliminary evaluation and short-term clinical studies indicate improved planning, execution precision, which results in a reduction of complications and shorter hospital stays. However, some of these systems have in some cases a steep learning curve and longer intraoperative times than traditional procedures, indicating the need to improve them.

To make our discussion more concrete, we briefly present two examples of deployed CIS systems: ROBODOC® (Integrated Surgical Systems, Davis, Ca.) an active medical robotics system, and the StealthStation® (Medtronic Surgical Navigation Technology, Boulder, Colo.) an intraoperative navigation system used in neurosurgery and orthopaedics.

The ROBODOC system [1-7] is active medical robot developed clinically by Integrated Surgical System from a prototype developed at the IBM T.J. Watson Research Center in the late 1980's (Figure 1).

ROBODOC is a computer-integrated system for cementless primary total hip replacement. In primary total hip replacement procedures, a damaged joint connecting the hip and the femur is replaced by a metallic implant inserted into a canal broached in the femur. ROBODOC allows surgeons to plan preoperatively the procedure by selecting and positioning an implant with respect to a Computer Tomography (CT) study and intraoperatively mill the corresponding canal in the femur with a high-speed tool controlled by a robotic arm. It consists of an interactive preoperative planning software, and an active robotic system for intraoperative execution. Pre-clinical testing showed an order-of-magnitude improvement in precision and repeatability in preparing the implant cavity. As of 2001, about 40 systems were in clinical use, having performed an estimated 8,000 procedures, with very positive results documented in follow-up studies.

The StealthStation [8] is representative of current surgical navigation systems (Figure 2). It allows surgeons to intraoperatively visualize the relative locations of surgical tools and anatomy in real time and perform surgical actions accordingly. The anatomical model used for navigation is constructed from preoperative CT or MRI data. The instruments and rigid anatomy location are obtained in real time by attaching to them frames with light-emitting diodes that are accurately tracked with a stereoscopic optical tracking camera. The preoperative model is registered to the intraoperative situation by touching with a tracked probe predefined landmarks or points on the anatomy surface and matching them to their corresponding location on the model. Intraoperative navigation allows for less invasive surgery and more precise localization without the need of repeated intraoperative X-ray or ultrasound two-dimensional imaging. For example, to perform a biopsy of a tumor on the brain, the surgeon directs the instrumented drill on the patient's skull with the help of the images, and drills directly towards the tumor instead of making an incision on the skull and visually looking for the tumor.

The key technical enabling factors that lead the development of CIS systems were the increasing availability of powerful imaging modalities, such as CT, MRI, NMT, and live video, powerful computers with graphics capabilities, novel algorithms for model construction and navigation, and integrative systems and protocol development. This article reviews the main technical issues of CIS systems. It is organized as follows: the next section presents an overview of CIS systems, their main elements architecture, and information flow. The following section describes the main enabling technologies of CIS systems: imaging devices, image processing, visualization and modeling, preoperative analysis and planning, registration, tracking and sensing, robotics, human-machine interfaces, and systems integration technology. Then, we describe in detail examples of CIS systems including navigation systems, augmented reality navigation systems, and virtual reality systems. We conclude with perspectives and possible directions for future development.

2. An overview of CIS systems

Figure 3 shows a generic block diagram of a CIS system. At the core is a computer (or network of computers) running a variety of modeling and analysis processes, including image and sensor processing, creation and manipulation of patient-specific anatomical models, surgical planning, visualization, monitoring and control of surgical processes. These processes receive information about the patient from medical imaging devices about the patient and may directly act on the patient through the use of specialized robots or other computer-controlled therapy devices. The processes also communicate with the surgeon through a variety of visualization modules, haptic devices, or other human-machine interfaces. The surgeon remains at all times in overall control of the procedure and, indeed, may do all of the actual manipulation of the patient using hand tools with information and decision support from the computer. The modeling and analysis processes within the computer will often rely upon databases of prior information, such as anatomical atlases, implant design data, or descriptions of common surgical tasks. The computer can also retain nearly all information developed during surgical planning and execution, and store it for post-operative analysis and comparison with long term outcomes.

Essential elements of CIS systems are devices and techniques to provide the interfaces between the "virtual reality" of computer models and surgical plans to the "actual reality" of the operating room, patients, and surgeons. Broadly speaking, we identify three inter-related categories of interface technology: 1) imaging and sensory devices; 2) robotic devices and systems; and 3) human-machine interfaces. Research in these areas draws on a broad spectrum of "core" engineering research disciplines, including materials science, mechanical engineering, control theory, device physics, and others. The fundamental challenge is to extend the sensory, motor, and human-adaptation abilities of computer-based systems in a demanding and constrained environment. Particular needs include compactness, precision, biocompatibility, imager compatibility, dexterity, sterility, and human factors.

Figure 4 illustrates the overall information flow of CIS systems from the surgical CAD/CAM paradigm perspective. The CIS systems combine preoperative and intraoperative modeling and planning with computer-assisted execution and assessment. The structure of the Surgical Assistant systems is similar, except that many more decisions are made intraoperatively, since preoperative models and plans may sometimes be relatively less important. Broadly speaking, surgery with a CIS system comprises three phases, all drawing upon a common technology base.

- ***Preoperative*: *phase:*** A surgical plan is developed from a patient-specific model generated from preoperative images and *a priori* information about human anatomy contained in an anatomical atlas or database. Planning is highly application-dependent since the surgical procedures are greatly different. In some cases, it may be simple interactive simulations or the selection of some key target positions, such as performing a tumor biopsy in neurosurgery. In other cases, such as in craneofacial surgery, planning can require sophisticated optimizations incorporating tissue characteristics, biomechanics, or other information contained in the atlas and adapted to the patient-specific model.
- ***Intraoperative phase:*** The images, patient-specific model, and plan information are brought into the operating room and registered to the patient, based on information from a variety of sensors, usuch as a spatial tracking system and/or intraoperative imaging device. In some cases, the model and plan may be further updated, based on the images. The computer then uses a variety of interface devices to assist the surgeon in executing the surgical plan. Depending on what is most appropriate for the application these interfaces may include active devices such as robots, "smart" hand tools, and information displays. As the surgery proceeds, additional images or other measurements may be taken to assess progress and provide feedback for controlling tools and therapy delivery. Based on this feedback, the patient model may be updated during the procedure. This updated model may be used to refine or update the surgical plan to ensure that the desired goals are met. Ideally, intraoperative imaging and other feedback can ensure that the technical goals of the surgical intervention have been achieved before the patient leaves the operating room. Further, the computer can identify and record a complete record of pertinent information about the procedure without significant additional cost or overhead.
- ***Postoperative phase:*** The preoperative and intraoperative information are combined with additional images and tests, both to verify the technical results of the procedure and to assess the longer-term clinical results for the patient. Further, the results of many procedures may be registered back to an anatomical atlas to facilitate statistical studies relating surgical technique to clinical outcomes.

Note that the above description is of an idealized CIS system: specific systems do not necessarily require all these capabilities, and some of them are beyond the current state of the art. However, we will use this generic description to organize the technical discussion in the following section.

From a surgeon's perspective, the key difference between advanced medical equipment and a CIS system is the information integration, both between phases and within each phase. This new capability requires in most cases modifications to existing surgical protocols, and in a few cases radically new protocols. It could also enable more surgeons to perform certain difficult procedures that require much coordination and knowledge available to only a few experienced specialists, or perform procedures that are currently not feasible.

3. The technology of CIS systems

This section describes the main technical elements of CIS systems. We begin with a brief summary of medical imaging devices, and then present methods for image processing, visualization, and modeling. We describe next preoperative planning and analysis, followed by registration of data from various sources. Then we discuss tracking and sensing, robotics, man-machine interfaces and systems integration technology.

3.1 Medical imaging

Medical images, both preoperative and intraoperative, are the main source of information of CIS systems. Since they are used in all CIS systems, we briefly discuss their technical characteristics and typical uses.

We distinguish between preoperative and intraoperative imaging devices. Preoperative imaging devices, such as film and digital X-rays, Computed Tomography (CT), Magnetic Resonance (MRI), and Nuclear Magnetic Tomography (NMT) in various forms, are used to obtain images for diagnosis and surgical planning. In most cases, the imaging devices are large and are located outside the surgical suite. Two-dimensional film X-ray images are the most common, with superb spatial resolution, gray-value range, and contrast, and negligible noise and geometric distortion. However, they are two-dimensional projections of spatial structures, and are not amenable to processing for further use unless scanned. CT and MRI images are used to visualize anatomical structures, with CT best suited for bony structures and MRI best suited for soft tissue. They consist of a series of two-dimensional parallel cross-sectional images with high spatial resolution, little geometric distortion and intensity bias, good signal to noise ratio, and a wide field of view. Typical data sets consist of 80-150 images of size 512x512 12-bit gray level pixel images with pixel size of 0.4x0.4mm at 1-2mm intervals. They can be used to visualize anatomical structures, perform spatial measurements, and extract three-dimensional anatomical models. NMT images show functional anatomy, such as nerve activity, and are mostly used in the brain. They also consist of a series of two-dimensional parallel slices, although their quality is lower. They are usually viewed in conjunction with MRI images. The main drawback of preoperative images is that they are static and don't always reflect the position and orientation of anatomical structures which have moved between the time the images were taken and the surgery is performed.

Intraoperative imaging devices include fluoroscopic X-ray, ultrasound, and video image streams from endoscopes, laparoscopes, and surgical microscopes. Fluoroscopic X-ray is widely used in orthopedics to visualize and adjust the position of surgical instruments with respect to bones, or to locate kidney stones. The images are obtained from a mobile C-arm unit, which allows capturing two dimensional projection images from different viewpoints while the patient lies on the table. The circular images are usually displayed on a video monitor. They have a narrow field of view (6 to 12", 400 pixels in diameter), limited spatial resolution and contrast, and present varying, position-dependent intensity and geometric distortions. They are mostly used for qualitative evaluation, and have cumulative radiation as a side effect. Ultrasound images (both static and as sequences) are used to obtain images of anatomy close to the skin. Unlike X-ray images, they have no harmless radiation, but present significant imaging artifacts, such as speckling, noise, and spatial distortion. They also have a narrow field of view and have the resolution and image quality of the standard video monitor where they are displayed. Video image streams became commonplace with the introduction of minimally invasive surgery in the 1980's. They are used to support tumor biopsies, gall bladder removals, and colon explorations, among many others. They allow the surgeon to visualize in real time anatomy and surgical instruments inserted in a body cavity. The limitations of these imaging devices are that they have a narrow field of view (about 3"), have no depth perception, uneven illumination, distortion due to the use of wide-angle lenses, and require direct line of sight. Surgeons must learn how to move and point the camera while respecting various point-of-entry and location constraints. The main advantage of intraoperative images is that they provide an up-to-date image of the surgical situation. However, the field of view and image quality are far inferior to preoperative images. More recent intraoperative imaging devices include surgical Open MRI, surgical CT, and 3D ultrasound, which overcome some of the limitations of the more common imaging devices.

The main limitation of current practice is that there is no quantitative correlation between high-quality preoperative images and intraoperative images. The surgeon must mentally establish the spatial correlation between the images and make decisions based on this correlation.

3.2 Image processing, visualization, and modeling

After image acquisition, the first task is usually visualization for diagnosis, evaluation, and planning. The visualization can take place on displays other than those of the devices where they were acquired, and can require various image processing techniques for better evaluation. These include image balancing and enhancement, distortion and contrast correction, de-noising, and spatial aggregation. For example, individual two-dimensional X-ray and ultrasound images can be processed using an array of standard image processing techniques to improve their clinical value. They can be visualized using zooming, cropping, and other imaging techniques. They can also be combined to create new, multimodal images.

Visualization of CT, MRI, and nuclear medicine images can greatly benefit from specialized visualization techniques, since they are series of two-dimensional cross sections. Instead of having the surgeon mentally correlate consecutive slices and create a mental three-dimensional view, it is desirable to directly reconstruct the three-dimensional information and show it as a new computed image. There are two families of visualization algorithms: volume visualization and surface visualization. We describe them briefly next.

Volume visualization algorithms [9] take as input slices and produce a three-dimensional image from any desired viewpoint. The most common method of generating the three-dimensional images is ray casting (Figure 5). The data set is viewed as a volumetric data set, in which the space is divided into small volume units, called voxels. The voxels are rectangular blocks whose upper and lower faces are consecutive slice pixels in the vertical direction, and whose height is the slice interval distance. To each voxel is associated an intensity value, which is interpolated from the nearby pixel intensity values. To obtain the three-dimensional image, rays emanating from the viewpoint's location towards the image plane are cast on the volume. The pixel intensities in the new image are computed according to an attenuation function, which indicates how to compose the voxel intensity values that the ray traverses. Different choices of attenuation function produce various effects, such as opaque bodies, semi-transparency, or anatomy isolation according to predefined intensity ranges. For example, if only bony surfaces are to be shown, only voxels whose intensity values are within the range of bone intensity are considered in the attenuation function. The advantage of this method is its simplicity, as no previous segmentation or surface extraction is necessary. However, it is computationally expensive, as hundreds of thousands of voxels need to be examined for each new image. Various hardware (Z-buffering) and software techniques (precomputed views, ray arrays) have been developed to speed up the rendering process. Another disadvantage is that no model of the anatomy is created, restricting the type of analyses that can be performed on it. Volume visualization is best suited for complex anatomy with fine details, such as the brain gray matter.

Surface-based visualization algorithms rely on geometric surface models of the anatomy to be visualized. The inputs are usually objects described as triangular meshes extracted from the original data representing the surface of the anatomical structures of interest, such as the skull, femur, kidneys, colon, etc. The objects are then displayed as CAD models on viewers that can take advantage of standard graphics hardware. The main advantage of surface-based visualization is that it has to handle smaller data sets and is thus computationally much more efficient than volume visualization, allowing for near real-time positioning and manipulation on standard computers. Another advantage is that CAD models of implants and surgical instruments can be readily incorporated into the image. However, surface-based visualization requires extracting the surface models, which can be difficult for complex anatomical structures with many fine details and complex geometry. Surface-based algorithms are best suited for anatomy with relatively large and clearly defined surfaces, such as bones and intestinal conduits.

Model construction algorithms are a prerequisite to surface-based visualization and for all tasks that require a geometric model of the anatomy: preoperative planning, contour-based registration, anatomical atlas construction and matching. Their input is a series of slices, and a predefined intensity threshold interval that defines the image intensity ranges of the anatomy of interest. The output is one or more triangular meshes describing the geometry of the surfaces. Mesh extraction algorithms can be divided into two families: 2D contour extraction algorithms and 3D surface reconstruction algorithms. Contour extraction algorithms work by segmenting (manually or automatically) the contour of the anatomy of interest in each slice, and then connecting the resulting successive 2D contours to form a 3D surface. A point *p1* on the contour extracted in slice *i* is connected to the next point *p2* on the same contour at a predefined distance, and both are connected to the closest point *p3* in slice *i+1* to form a triangle *p1p2p3* which represents a surface element. By alternating between consecutive slices, a triangulated ribbon is created between the boundary contours. The drawback of this method is that ambiguities can arise as to how point should be selected to create triangles, resulting in topologically inconsistent surfaces (holes, self-intersections, etc).

To alleviate this problem, surface reconstruction algorithms work directly on the volumetric data to identify the voxels, which are intersected by the object surface and determine its geometry. The most commonly used algorithm in this category is the so-called “marching cubes algorithm” [10]. The algorithm proceeds as follows: a moving cube whose vertices are the pixels of two subsequent slices is formed. The eight vertices of the cube have associated with it a binary number (0 or 1), which indicates if the corresponding to pixel intensity value is above or below a pre-specified threshold (Figure 6). When all eight vertices have a value of 0 (1), the voxel is entirely outside (inside) the anatomical object of interest. Cubes with mixed values (one or more zero and one) are at the boundary of the object. Depending on which vertex values are zero or one, one or more triangular surfaces cutting the cube can be constructed. There are $2^8 = 256$ cases, which can be reduced by symmetry to 14 cases and stored in a lookup table for reference. The algorithm proceeds by moving the cube from the topmost, upper corner of the first two slices to the lowest, bottom corner of the last two slices in sequence. Depending on the vertex values, the table is accessed and the corresponding triangles are constructed. The advantage of this algorithm is its locality, and that the surfaces constructed are topologically consistent (ambiguities in surface construction can be resolved locally). Variants of this algorithm include a tetrahedron instead of a cube, for which there are only two cases with no ambiguities, but which produce two to five times more triangles. The resulting meshes are typically several tens to several hundreds of thousands of triangles, depending on the slice spacing on the original data set. Mesh simplification algorithms can then be applied to the resulting models to reduce their complexity with minimal loss of accuracy.

While surface models are the most commonly used in CIS systems, they are by no means the only types of models. Functional models, containing relevant information specific to an anatomical structure or procedure can also be extracted with custom techniques. For example, a kinematic model of the lleg bones and joints is of interest when planning a total knee replacement. To construct this model, geometric entities such as the mechanical axis of the femur, the center of the femoral head, and other anatomical landmarks should be extracted. Each surgical application requires the construction of its model and the simulation associated with it.

Another type of model used in CIS is a digital atlas. Digital atlases are constructed from detailed imaging data of a person and are used for visualization, planning, and educational purposes. An example of this type of data is the Visible Human Project, which has detailed CT, MRI, and photographic data of a male and a female. This data is carefully segmented and labeled, and a database of organs is constructed from it. The model can then be inspected, for example using the VOXEL-MAN software [11], or used to match to other patient data.

3.3 Preoperative analysis and planning

Once the diagnosis has been made and it has been decided that surgery is necessary, the next step is to carry preoperative analysis and elaborate a surgical plan of action. This plan can range from simple tasks such as determining the access point of a biopsy needle, to complex gait simulations, implant stress analysis, or radiation dosage planning. Because the analysis and planning is specific to each surgical procedure and anatomy, preoperative planning and analysis software is usually custom to each clinical application. These systems can be viewed as medical CAD systems, which allow the user to manipulate and visualize medical images, models of anatomy, implants, and surgical tools, perform simulations, and elaborate plans. To give the reader an idea of the current scope of these systems, we will briefly describe two planning systems, one for orthopaedics and one for radiation therapy.

In orthopaedics, planning systems are generally used to select implants and find their optimal placement with respect to anatomy. For example, a planning system for spinal pedicle screw insertion shows the surgeon three orthogonal cross-sections of the acquired CT image (the original *xy* slice and interpolated *xz* and *yz* slices) and a three dimensional image of the vertebrae surfaces. The surgeon selects a screw type and its dimensions, and positions it with respect to the anatomy in the three cross sectional views. A projection of the screw CAD model is superimposed on the images, and its position and orientation with respect to the viewing plane can be modified, with the result displayed in the other windows. Once a satisfactory placement has been obtained, the system stores it with the screw information for use in the operating room. Similar systems exist for total hip and total knee replacement, which, in addition, automatically generate in some cases machining plans (cut files) for intraoperative surgical robots. Other systems also extract kinematic or fine-element models and perform gait and stress analysis that help surgeons estimate the effectiveness of the proposed solution.

Another example of a complex planning system is in the field of radiation therapy. The goal of radiation therapy is to kill tumor cells by exposing them to a radiation beam while affecting as little as possible the surrounding healthy cells. One way of achieving this is to expose the tumor cells to radiation beams from different directions so that the cumulative radiation effect on the tumor cells destroys them while preserving the surrounding healthy cells. The planning task consists of identifying the tumor and the critical areas where no radiation should be present from MRI images, and then selecting the number of beams, their radius, intensity, duration, and placement that maximizes the radiation to the tumor cells while minimizing the radiation to other cells, especially those in the critical areas. This problem is formulated as a geometric minimum-maximum constrained optimization problem, and solved with a combination of geometric and non-linear optimization techniques. The planning system includes a data visualization and volume definition module, and outputs a series of location commands to the robotic arm carrying the radiation source, and the beam information at each location.

3.4 Registration

Multimodal registration is one of the key steps for information integration in CIS systems. The goal of the registration process is to allow the combination of data from several modalities, possibly taken at different times, so that they can be viewed and analyzed jointly. Registering two data sets consists of finding a transformation that aligns common features in two modalities, so that their spatial locations coincide. Registration is necessary for many tasks such as:

- Combine information of the same patient taken with different modalities, such as CT and MRI, MRI and PET
- Combine information of the same patient before, during, and after surgery, such as preoperative CT and intraoperative X-ray fluoroscopy, preoperative MRI and intraoperative video from a microscope or an endoscope, CT or X-rays from before and after surgery
- Create real-time virtual reality views of moving anatomy and surgical tools by matching preoperative models from CFT or MRI with intraoperative tracking data
- Perform a statistical study of patient data

Most CIS applications require more than one transformation to link two data sets, and thus have more than one registration problem. For example, in the ROBODOC system, the preoperative plan has to be registered to the intraoperative position of the bone so that the robot tip can machine the desired canal shape in the planed position. To obtain this transformation, we must compute the transformation from the bone coordinate system to the implanted fiducials, then from the fiducials to the robot tip, to the robot coordinate system, and then to the cut volume. The series of mathematical transformations that align one data set with another is called the *registration chain*.

The registration task is in fact not one but many different problems. There are great differences on technical approaches depending on the type of data to be matched, the anatomy involved, and the clinical and technical requirements of the procedure. There is a vast body of literature on registration, which is comprehensively surveyed in [12, 13] and can be classified according to the following characteristics:

- *Modalities:* refers to the sources from which data is acquired, e.g. X-ray, CT, MRI, PET, video, tracker, etc. The combinations can be unimodal (same data source) or multimodal (different data sources), which can be two images, an image to a model, or an image to a patient (tracker data).

- *Dimensionality*: refers to the spatial and temporal dimensions of the two data sets to be matched (two or three-dimensional, static or time-varying). The registration dimensionality can be static 2D /2D (X-ray images), 2D/3D (ultrasound to MRI), 3D/3D (PET to MRI),or time-varying, such as digital subtraction angiography (DSA).

- *Registration basis:* refers to the image features that will be used to establish the alignment. These can be extrinsic registration objects, such as a stereotactic frame, or fiducials markers, or intrinsic, such as anatomical landmarks, anatomical contours, or pixel intensity values.

- *Nature and domain of mathematical transformation*: refers to the type of mathematical transformation that is used to perform the alignment. The transformation can be rigid, affine, projective, or generally curved (deformable registration), and can be applied to parts of the image (local) or to the entire image (global).

- *Solution method:* refers to how the transformation is computed. This can include direct solutions when an analytic solution or an appropriate approximation is found, or iterative solutions, where there is a search and numerical optimization methods are used.

- *Type of interaction*: refers to the type of input that the user has to supply. The registration is interactive when it is performed entirely by the user, automatic when no user intervention is required, or semi-automatic when the user supplies an initial estimate, helps in the data segmentation, or steers the algorithm by accepting or rejecting possible solutions.

- *Subject:* refers to the patient source from which the images are taken: it can be the same patient (intra-subject), two different patients (inter-subject), or a patient and an atlas.

- *Anatomy*: refers to the anatomy being imaged. This can be the head (brain, skull, teeth, nasal cavities), the thorax (heart, breast, ribs), the abdomen (kidney, liver, intestines), the pelvis and the perineum, or the limbs (femur, tibia, humerus, hand).

The main steps of registration algorithms are summarized in Table 3. Before attempting to match the datasets, each data set should be corrected for distortions so that the errors resulting from imaging artifacts do not affect the accuracy of the registration process. Next, *what* should be matched is identified in each image. This can be point landmarks, contours, surfaces, pixel values and their gradients, or regions of interest. The pairwise correspondence between these is established so that a measure of similarity between the data sets can be established. The more the features are apart, the larger the dissimilarity is. The similarity is usually formulated as a constrained minimization problem whose minimum is the transformation T that reduces the dissimilarity the most. If no closed form solution exists, the local minimum is found by numerical optimization. One of the data sets is moved by the transformation, and the process is repeated until the match is sufficiently good or no further improvement is possible.

Technically, registration techniques can be classified as rigid or deformable, and geometry or intensity-based. Rigid registration computes a transformation of position and orientation between two data sets. It is applicable to rigid structures that change their position but not their shape, such as bones, implanted fiducials and stereotactic frames, as an approximation to quasi-rigid structures, such as tumors or brain white matter. It is also used as the first step of deformable registration, which computes a general global or local curved map. Deformable registration is necessary for matching soft tissue organs (e.g., brain images before and after brain shift) for time-dependent comparisons (e.g., tumor growth evaluation), and for cross patient and atlas comparisons. The main difficulties of deformable registration are that the problem is ill posed, since there are usually infinitely many transformations that match the data, and that error measurements and comparisons are difficult. The geometric approach uses the spatial disparity (usually the distance) between geometric entities, such as points, contours, or surfaces. The intensity-based approach uses the pixel intensity values and the intensity gradient between pixels to maximize the image correlation.

Examples of common registration tasks are:

- Rigid geometric registration between a surface model obtained from preoperative CT and intraoperative surface data on the same anatomy obtained by touching landmarks or collecting sample points with a tracker. This method is widely used in CIS orthopaedics systems, such as pedicle screw fixation, total hip and knee replacement, and trauma
- Deformable intensity-based registration between brain MRI data sets before and after brain shift

3.5 Positional tracking and other sensing

An important feature of many CIS systems is the ability to accurately determine in real time the location of selected anatomical structures, surgical instruments, and implants during surgery. This information is necessary for visualization, navigation, and guidance. The component that delivers this information to the CIS system is called a tracker or a localizer.

There are many technologies available for positional tracking, including: encoded mechanical linkages; acoustic tracking; electromagnetic tracking; optical tracking using specialized devices; and optical tracking using conventional computer vision methods. Typically, these systems measure the motion relative to some base device of individual elements (which we will call "markers") attached to the objects to be tracked. Several excellent surveys are available on this subject, including [14, 15]. Each method has advantages and drawbacks. The main comparison parameters include setup requirements, work volume characteristics, number of objects that can be tracked simultaneously, the update frequency, the static and dynamic accuracy, the variability and repeatability of the readings, and cost.

Currently, the most commonly used position tracking approaches are based on specialized optical devices such at the Optotrak® and Polaris® systems (Northern Digital, Waterloo, Canada) and Pixsys® and FlashPoint® systems (Image Guided Technologies, Boulder, Colo.). These devices use two or more optical cameras to identify light-emitting diodes or reflective markers in the camera image and compute their location by stereo triangulation. They can be quite accurate, providing 3D localization accuracies ranging from 0.1 mm to about 0.5 mm in typical applications. Their drawbacks include cost and the necessity of maintaining a clear line-of-sight between the sensors and the markers. Magnetic tracking systems such as the Polhemus® (Rockwell International, Milwaukee, Wis.), Flock-of-Birds® (Ascension Technology, Burlington, Vt.) and Aurora® (Northern Digital, Waterloo, Canada) systems are also widely used. These systems no not have line-of-sight constraints, but may be subject to field distortion from materials in the operating room.

Force sensors are commonly used in medical robotic systems to measure and monitor tool-to-tissue and tool-to-surgeon interaction forces (e.g., [16-21]). Generally speaking, the technology used in these sensors is the same as that used in other applications, although specific issues of sterility and compactness often present unusual design strategies.

More broadly, a very wide variety of sensors may be used to determine any number of local tissue properties. Examples include electrical conductivity, optical coherence tomography, near infrared sensing, and temperature sensing, to name a few.

3.6 Robotics

Medical robot systems have the same basic components as any other robot system: a controller, manipulators, end-effectors, communications interfaces, etc.). Many of the design challenges are familiar to anyone who has developed an industrial system. However, the unique demands of the surgical environment, together with the emphasis on cooperative execution of surgical tasks, rather than unattended automation, do create some unusual challenges.

Table 2 compares the strengths and weaknesses of humans and robots in surgical applications.

Safety is paramount in any surgical robot, and must be given careful attention at all phases of system design. Each element of the hardware and software should be subjected to rigorous validation at all phases ranging from design through implementation and manufacturing to actual deployment in the operating room. Redundant sensing and consistency checks are essential for all safety-critical functions. Reliability experience gained with a particular design or component adapted from industrial applications is useful but not sufficient or even always particularly relevant, since designs must often be adapted for operating room conditions. It is important both to guard against both the effects of electrical, electronic, or mechanical component failure and the more insidious effects of a perfectly functioning robot system correctly executing an improper motion command caused by improper registration between the computer's model of the patient and the actual patient. Further excellent discussion may be found in [22, 23] and in a number of papers on specific systems.

Sterility is also a crucial concern. Usually, covering most of the robot with a sterile bag or drape and then separately sterilizing the instruments or end-effectors provide sterility. Autoclaving, which is the most universal and popular sterilization method, can unfortunately be very destructive for electromechanical components, force sensors, and other components. Other common methods include gas (slow, but usually kindest to equipment) and soaking.

Manipulator design is very important in medical robots. Several early systems (e.g., [24]) used essentially unmodified industrial robots. Although this is perhaps marginally acceptable in a research system that will simply position a guide and then be turned off before any contact is made with a patient, any use of an unmodified robot capable of high speeds is inherently suspect. Great care needs to be taken to protect both the patient and operating room personnel from run-away conditions. It is generally better to make several crucial modifications to any industrial robot that will be used in surgery. These include:

- Installation of redundant position sensing;
- Changes in gear ratios to slow down maximum end-effector speed; and
- Thorough evaluation and possible redesign for electrical safety and sterility.

Because the speed/work volume design point for industrial and surgical applications are very different, a more recent trend has emphasized design of custom manipulator kinematic structures for specific classes of applications. Some examples may be found in [25-30].

Many surgical applications (e.g., in laparoscopy or neuroendoscopy) require surgical instruments to pass through a narrow opening into the patient's body. This constraint has led a number of groups to consider two rather different approaches in designing robots for such applications. The first approach (e.g., Figure 8 right, Figure 9, Figure 10 and Figure 12) and references [25, 26, 31, 32]) uses goniometers, chain drives, parallel 5-bar linkages, or other means to decouple instrument motions about an "isocenter" which is placed at the entry portal. The second approach (e.g. Figure 8 left and [33-35]) relies on passive compliance to cause the surgical instrument to comply with the entry portal constraint. In this case, the robot's "wrist" typically has two un-actuated, but encoded, rotary axes proximal to the surgical instrument holder. Both approaches have merit, and they can be combined fruitfully, as described in [36]. The first approach is usually more precise and provides a more stable platform for stereotactic procedures. The second approach has the advantages of being simple and of automatically accommodating patient motions. A fuller discussion of the tradeoff can be found in [36].

Surgical manipulators are not always active devices. Often, the human surgeon provides some or all of the motive power, while the computer provides real time navigational or other assistance (e.g., [25, 27, 32, 37-39]).

Because medical robots are often used together with imaging, materials are also an important concern in surgical manipulator design equipment (e.g., [27, 40]). Figure 10 shows one example of a simple 1-degree-of-freedom radiolucent mechanism that can be used to drive needles into soft tissue [27]. This device is designed for use with fluoroscopic x-rays or ct scanners, and it can be employed either with a simple support clamp or as the end effector of an active robot. Fiducial geometry can be added easily to the robot or end-effectors to assist in registration of the robot to the images (e.g., Figure 11 and also references [41-45]).

Development of robotic devices for use with magnetic resonance imaging (MRI) poses special challenges, because of the strong magnetic fields and RF signals involved. Figure 15 and Figure 16 show two typical systems. Other examples include [40, 46].

3.7 Human-machine interfaces

Computer-based systems that work cooperatively with humans must communicate with them, both to provide information and to receive commands and guidance. As with surgical robots, surgical human-machine interfaces (HMI) have much in common with those for other application domains, and they draw upon essentially the same technologies (speech, computer vision and graphics, haptics, etc.) that have found use elsewhere. In many cases, HMI subsystems that have been developed for other uses may be adapted with little change for surgical use. However, attention must be given to the unusual requirements of surgical applications [47]. Surgeons tend to have very high expectations about system responsiveness and transparency, but have very low tolerance for interfaces that impede their work. On the other hand, t can also be quite willing to put up with great inconvenience if the system is really performing a useful function that truly extends their capabilities.

Surgeons overwhelmingly rely on vision as their dominant source of feedback during surgery. Indeed, the explosion in minimal access surgery over the past decade has very largely been the result of the availability of compact, high-resolution video cameras attached to endoscopic optics. In these cases, the surgeon's attention is naturally focused on a television monitor. In such cases, it is often possible for the computer to add computer graphics, text, and other information to the video stream (e.g., [48, 49]). Similarly, surgical navigation systems (e.g.,[8, 9, 45-52]) provide computer graphic renderings and feedback based on tracked surgical instrument positions and preoperative images. The so-called "virtual fluoroscopy" systems (e.g., [58-61]) show predicted x-ray projections based on intraoperative fluoroscopic images and tracked instrument positions. One very important challenge in the design of such systems is the providing useful information about the *imprecision* of the system's information, so that the surgeon does not make decisions based on a false determination of the relative position of a surgical instrument and target anatomy. One common approach is to display a circle or ellipse representing likely registration uncertainty, but significant advances are needed both in the modeling of such errors and in the human factors associated with their presentation.

One limitation of video overlay systems is the limited resolution of current-generation video cameras. This is especially important in microsurgical applications, where the structures being operated on are very small, or in applications requiring very good color discrimination. Consequently, there is also interest in so-called optical overlay methods in which graphic information is projected into the optical path of a microscope (e.g., [62]) or presented on a half-silvered mirror (e.g., [63, 64]) so that it appears to be superimposed on the surgeon's field of view in appropriate alignment. The design considerations for these systems are generally similar to those using video displays, but the registration problems tend to be even more demanding and the brightness of the displays also an be a problem.

All of the common interfaces (mice, joysticks, touch screens, push-buttons, foot-switches, etc.) used for interactive computer applications are used to provide input for surgical systems as well. For preoperative planning applications, these devices are identical to those used elsewhere. For intraoperative use, sterility, electrical safety, and ergonomic considerations may require some design modifications. For example, the LARS robot [48] repackaged the pointing device from an IBM Thinkpad® computer into a 3 button "mouse" clipped onto the surgeon's instruments. As another example, a tracked stereotactic wand has been used to provide a configurable "push button" interface in which functions are selected by tapping the tip of the pointer onto a sterilized template [65].

Surgeons routinely use voice to communicate with operating room personnel. Further, their hands (and feet) are frequently rather busy. Accordingly, there has long been interest in using voice as a 2-way command and control system for surgical applications. Examples include [35, 48, 66-68].

Force and haptic feedback is often important for surgical simulation (e.g., [68, 69] and telesurgery applications (e.g., [19, 21, 70-73]). Again, the technical issues involved are similar to those for other virtual reality and telerobotics applications, with the added requirement of maintaining sterility and electrical safety.

3.8 Systems

Computer-Integrated Surgery is highly systems-oriented. Well engineered systems are crucial both for use in the operating room and to provide context for the development of new capabilities. Safety, usability and maintainability, and interoperability are the most important considerations. We discuss them briefly next.

Safety is very important. Surgical system designs must be both safe, in the sense that system failures will not result in significant harm to the patient and be perceived to be safe. Good system design typically will require careful analysis of potential failure sources and the likely consequences of failures. This analysis is application-dependent, and it is important to remember that Care must be taken to ensure that system component failures will not go undetected and that the system will remain under control at all times. Wherever possible, redundant hardware and software subsystems should be provided and crosschecked against each other. Rigorous software engineering practices must be maintained at all stages. Discussion of general safety issues for surgical robots may be found in [22, 74-77]. An excellent case study of what can happen when good practices are ignored may be found in [78], which discusses a series of accidents involving a radiation therapy machine.

Many discussions of safety in CIS systems tend to focus on the potential of active devices such as robots or radiation therapy machines to do great harm if they operate in an uncontrolled manner. This is a valid concern, but it should not be forgotten that such “run away” situations are not usually the main safety challenge in CIS systems. For example, both robotic and navigation assistance systems rely on the accuracy of registration methods and the ability to detect and/or compensate for patient motion to ensure that the surgical instruments do not stray from the targeted anatomy. A human surgeon acting on incorrect information can place a screw into the spinal cord just as easily as a robot can. This means that analysis software and sensing must be analyzed just as carefully as motion control. Surgeons must be fully aware of the limitations as well as the capabilities of their systems and system design should include appropriate means for surgeon “sanity checking” of surgical actions.

System usability and maintainability are also important design considerations. Clearly, the ergonomic design of the system from the surgeon’s perspective is important (e.g., [79, 80]). However, the interfaces provided for the operating room staff that must set up the equipment, help operate it, and provide routine maintenance are also crucial both for safety and economic reasons. Similarly, CIS systems should include interfaces to assist field engineers trouble-shoot and service equipment. In this regard, the ability of computer-based systems to log data during use can be especially useful in post-failure analysis and in scheduling preventative maintenance, as well as in providing data for improvement in surgical outcomes and techniques. Although most systems make some use of such facilities, they are probably under-used in present-day commercial systems.

System interoperability is currently a major challenge. Commonly accepted open standards permitting different equipment to work together in a variety of settings are badly needed. Several companies have proposed proprietary standards for use by alliances of vendors, and there has been some academic and government-supported work to provide tool kits, especially in software. However, these efforts are still very fragmented.

4. Examples of CIS Systems

There are already a few dozen CIS systems available commercially or as prototypes in research laboratories worldwide. Although it is not practical to present an exhaustive survey, this section describes a few examples of integrated systems that use parts of the technology described above. For the purposes of this overview, we distinguish between four types of systems:

1. Information enhancement systems
2. Robotic systems for precise preoperative plan execution
3. Robotic systems for human augmentation
4. Other robotic systems

Note that many real systems could logically fit in several of these categories.

4.1 Information Enhancement Systems

The purpose of information enhancement systems is to provide the surgeon and his team with accurate, up-to-date, and useful data and images during the surgery so that they can best develop and update their plan of action and perform surgical actions. To achieve this goal, information enhancement systems usually combine information from different modalities, such as preoperative CT and MRI data, real-time tracking data of tools and anatomy, intraoperative images such as ultrasound and fluoroscopic X-ray images, video sequences from endoscopic cameras and more. In some cases, such as virtual diagnostic endoscopy, a simulated environment replaces the actual procedure. Information enhancement systems are by far the most commonly used CIS systems. What distinguishes them from other CIS systems is that it is the surgeon that performs all surgical gestures without any physical assistance from mechanical devices.

We classify information enhancement systems into three categories:

1. Navigation systems
2. Augmented reality navigation systems
3. Virtual reality systems

We describe them briefly next.

4.1.1 Navigation systems

The purpose of intraoperative navigation systems is to provide surgeons with up-to-date, real time information about the location of surgical tools and selected anatomy during surgery. The goal is to improve the surgeon's hand/eye coordination and spatial perception, thereby improving the accuracy of the surgical gestures. They support less invasive procedures, can shorten surgery time, and can improve outcomes.

The basic elements of a navigation system are: (1) a real-time tracking system to follow one or more moving objects (anatomy, surgical tools, or implants); (2) tracking-enabled tools and reference frames; (3) a display showing the intraoperative situation; and (4) a computer to integrate the information (Figure 2). Since the patient is usually not immobilized, a dynamic reference frame is attached to the anatomy to correct the relative position of the tools to the images.

What is displayed depends on the type of images that are available. The navigation systems can be based on:

- Preoperative images, such as CT or MRI augmented with CAD models of tools and implants.
- Intraoperative images, such as fluoroscopic X-ray, ultrasound, or open MR images augmented with projections of tool CAD models and implant axes.
- Intraoperative video streams from an endoscopic camera or a surgical microscope, shown alongside or fused with preoperative CT or MRI images

Navigation systems based on preoperative CT or MRI images are typically used as follows: shortly before surgery, a preoperative CT or MRI study of the anatomy of interest is acquired. In some cases, fiducial markers that will be used for registration are attached to the patient skin or implanted to the anatomy so that they appear in the images. The data is downloaded to a computer and a model of the anatomy is created. When there are fiducials, they are identified and their precise relative spatial location is computed. The surgeon can visualize the data and elaborate the surgical plan. Before the surgery starts, the preoperative data, model, and plan are downloaded to the computer in the operating room. A dynamic reference frame is attached to the patient, and the intraoperative situation is registered with the preoperative data by either touching the fiducials with a tracked tool, or by acquiring a cloud of points on the surface of the anatomy. Once the registration has taken place, a display showing the preoperative images and model with the CAD models of the tools superimposed is created based on the current tool and anatomy position obtained from the tracker (Figure 17). Several commercial systems are currently available for a variety of procedures. Clinical studies report millimetric accuracy on tool and implant positioning. These types of systems have been applied extensively in orthopaedics, (the spine (e.g., [58, 81, 82]), pelvis (e.g., [83, 84], fractures (e.g., [85-89], hip (e.g., [56, 90, 91]), and knee (e.g., [57, 92-94]), neurosurgery, and craneofacial and maxillofacial surgery.

Navigation systems based on intraoperative images combine intraoperative images with position data from surgical tools and implants to create augmented intraoperative views. An example of such system is the FluoroNav system, which uses fluoroscopic X-ray images [61]. During surgery, a tracking device is attached to the fluoroscopic C-arm, and one or more images are acquired with it. Projections of the tools are then superimposed on the original images and updated in real time as the tools move (Figure 18). Since the camera and the tools are tracked simultaneously, there is no need for registration. The advantages of these systems are that they do not require a preoperative study and that no registration is necessary. However, the views remain two-dimensional, requiring the surgeon to mentally recreate the spatial intraoperative situation. Recent clinical studies show that these systems are having excellent acceptance, since they are closest to current practice, and beginning to be used successfully [95].

Other navigation systems combine video stream data obtained from endoscopic cameras or surgical microscopes, with data from preoperative studies, such as CT or MRI. The camera is tracked, so its position and orientation during surgery are known and can be shown, after registration, together with the preoperative images. The video stream can be shown side by side with a preoperative study, as in Figure 19, or selected information from it can be inserted in the video stream. The main advantage of these systems is that they allow surgeons to see beyond the surfaces shown in the video and to obtain spatial location information that overcomes the narrow field of view of the cameras [96]**.**

4.1.2 Augmented reality navigation systems

One of the drawbacks of the navigation systems described above is that they require the surgeon to constantly shift his attention from the patient to the computer display and back. Augmented reality navigation systems attempt to overcome this drawback by bringing the display right where the surgeon needs it. The data is viewed through glasses worn by the surgeon, projected directly on the patient, or displayed on a transparent screen standing between the surgeon and the patient. The surgeon's head is usually tracked, so that the data can be displayed from the correct viewpoint.

Two examples of this type of systems are the augmented reality CIS system for neurosurgery [97] and the CMU image overlay system [63] for orthopaedics. The augmented reality CIS system for neurosurgery projects colored segmented volumetric data of brain tumors and other neural structures directly on the patient's skull (Figure 20). This allows the surgeon to directly see where to start the minimally invasive procedure. The HipNav navigation system was developed to assists orthopaedic surgeons in positioning the acetabular cup in total hip replacement surgery. In this system, a transparent glass that serves as a projection screen is placed between the surgeon and the patient on the operating table. After registration, the hip and pelvis models extracted from the preoperative CT data are projected on the glass screen, thereby providing the surgeon with X-ray like view of what lies beneath.

4.1.3 Virtual reality diagnosis systems

The third type of information enhancing systems is virtual reality diagnosis systems. These systems, typically used in diagnostic endoscopy and colonoscopy, replace an actual exploration on the patient with a virtual exploration on MRI images. A three-dimensional reconstruction of the anatomical structures of interest, typically tube-like, is constructed from the data set, and a fly-through inspection path inside the structure is computed. The clinician is then presented with a virtual movie that simulates the actual endoscopic exploration (Figure 21). Based on these images, the clinician can look for and identify certain pathologies, such as tumors, and then determine if an actual examination or surgery is necessary. Several algorithms have been developed for model construction, fast visualization, and computation of fly-through path [98].

4.2 Robotic systems for precise preoperative plan execution

One of the drawbacks of navigation systems is that they cannot guarantee that a planned surgical gesture, such as screw placement or needle insertion, will be executed precisely as planned. To ensure not only precise positioning but also precise execution, surgical robots have been developed. We describe next two examples of the most common types of active surgical robots: the ROBODOC® system discussed earlier, and the LARS robot for percutaneous therapy.

4.2.1 Robotic orthopaedic surgery

Because bone is rigid and relatively easy to image in CT, and because geometric precision is often an important consideration in orthopaedic surgical procedures, orthopaedic surgery has been an important domain for the development of CIS systems. For example, the ROBODOC® system discussed earlier has been in clinical use since 1992 and combines CT-based preoperative planning with robotic machining of bone. Both ROBODOC and a very similar subsequently introduced system called CASPAR® [99] have been applied to knee surgery [100-102], as well as hip surgery. Other robotic systems have been proposed or (in a few cases) applied for hip or knee surgery include [38, 39, 103-107].

These applications fit naturally within the context of surgical CAD/CAM systems. For example, Figure 22 shows the information flow for the current ROBODOC implementation. The information flow in the CASPAR system is very similar. CT images of the patient's bones are read into a planning workstation and a simple segmentation method is used to produce an accurate surface model of key anatomical areas. After some key anatomical measurements are made from the images, the surgeon selects an implant design from a library and determines its desired placement in the patient by manipulating a CAD model of the implant with respect to selected mutually orthogonal cross-sections through the CT data volume. The planning workstation computes a cutter trajectory relative to CT coordinates and all of the planning information is written to a magnetic tape along with the patient images and model.

In the operating room, robotic hip replacement surgery proceeds much as manual surgery until after the head of the femur (for the case of primary hip surgery) or failing implant (for revision surgery) is removed. Then the femur is fixed to the base of the robot and a redundant position sensor is attached to the bone to detect any slipping of the bone relative to the fixation device. Then a 3D digitizer is used to locate a number of points on the bone surface. These points are used to compute the coordinate transformation between the robot and CT images used for planning and (thus) to the patient's bone. The surgeon then hand-guides the robot to an approximate initial position using a force sensor mounted between the robot's tool holder and the surgical cutter. The robot then cuts the desired shape while monitoring cutting forces, bone motion, and other safety sensors. The surgeon also monitors progress and can interrupt the robot at any time. If the procedure is paused for any reason, there are a number of error recovery procedures available to permit the procedure to be resumed or restarted at one of several defined checkpoints. Once the desired shape has been cut, surgery proceeds manually in the normal manner. The procedural flow for robotic knee replacement surgery is quite similar.

4.2.2 Robotically-assisted percutaneous therapy

One of the first uses of robots in surgery was positioning of needle guides in stereotactic neurosurgery [24, 108, 109]. This is a natural application, since the skull provides rigid frame-of-reference. However, the potential application of localized therapy is much broader. Percutaneous therapy fits naturally within the broader paradigm of Surgical CAD/CAM systems. The basic process involves planning a patient-specific therapy pattern, delivering the therapy through a series of percutaneous access steps, assessing what was done, and using this feed-back to control therapy at several time scales. The ultimate goal of current research is to develop systems that execute this process with robotic assistance under a variety of widely available and deployable image modalities, including ultrasound, x-ray fluoroscopy, and conventional MRI and CT scanners.

Current work at Johns Hopkins University is typical of this activity. Our approach has emphasized the use of “remote center-of-motion” (RCM) manipulators to position needle guides under real-time image feedback. One early experimental system [110, 111], shown in Figure 23, was used to establish the feasibility of inserting radiation therapy seeds into the liver under biplane x-ray guidance. In this work, small pellets were implanted preoperatively and located in CT images used to plan the pattern of therapy seeds. The fiducial pellets were relocated in the biplane x-rays and used to register the preoperative plan to a modified LARS robot [112, 113] used to.implant the treatment seeds. Although this experiment and related work directed at placing needles into the kidney [114, 115] established the basic feasibility of our approach, we concluded that significant improvements in the robot would be needed

Subsequent work has focused on development of a modular family of very compact component subsystems and end-effectors that could be configured for use in a variety of imaging and surgical environments. Figure 10 shows a novel RCM linkage with a radiolucent needle driver (“PAKY”) developed by Stoianovici *et al.* that form key components in this next generation system. Figure 11 shows the RCM device with a novel end-effector developed by Susil and Masamune that permits the computer to determine the needle pose to be computed with respect to a CT or MRI scanner using a single image slice [42, 44, 45]. This arrangement can have significant advantages in reducing set-up costs and time for in-scanner procedures and also eliminates many sources of geometric error. Figure 24 shows another variation of the RCM used as a high dexterity wrist in a system designed for manipulating ultrasound probes for diagnosis and ultrasound-guided biopsies [116].

Related work at Brigham and Women's Hospital in Boston is illustrated in Figure 16. This system [117] is designed to operate in an open-magnet MRI system and uses a common control architecture developed jointly by MIT, Brigham and Women's Hospital, and Johns Hopkins [118, 119]. One early application will be MRI-guided prostate therapy. Figure 15 shows another MRI-compatible robot system, this one designed for breast biopsy [120].

4.3 Robotic systems for human augmentation

The emphasis in surgical assistant robots is the use of these systems cooperatively to enhance human performance or efficiency in surgery. Much of the past and current work on surgical augmentation (e.g., [67, 70, 73, 121-125]) has focused on teleoperation. There is considerable interest in the use of master-slave manipulator systems to improve the ergonomic aspects of laparoscopic surgery. Figure 25 shows a typical example (the DaVinci® system [122] marketed by Intuitive Surgical). In this case, three slave robots are used. One holds an endoscopic camera and two others manipulate surgical instruments. In the case of the DaVinci, the surgical instruments have high dexterity wrists, as shown in Figure 25 (right). Other systems with varying degrees of complexity (e.g., the Zeus® system marketed by Computer Motion) are also in use, and this area of application may be expected to grow in the future.

Although the primary impact of teleoperated robots in surgical applications over the next years will probably be in applications in which the surgeon remains close to the patient, there has also been considerable interest in remote telesurgery (e.g., [70, 126, 127]). In addition to the design issues associated with local telesurgery, these systems must cope with the effects of communication delays and possible interruptions on overall performance.

The manipulation limitations imposed by human hand tremor and limited ability to feel and control very small forces, together with the limitations of operating microscopes have led a number of groups to investigate robotic augmentation of microsurgery. Several systems have been developed for teleoperated microsurgery using a passive input device for operator control. Guerrouad and Vidal [128] describe a system designed for ocular vitrectomy in which a mechanical manipulator was constructed of curved tracks to maintain a fixed center of rotation. A similar micromanipulator [129] was used for acquiring physiological measurements in the eye using an electrode. While rigid mechanical constraints were suitable for the particular applications in which they were used, the design is not flexible enough for general purpose microsurgery and the tracks take up a great deal of space around the head. An ophthalmic surgery manipulator built by Jensen et al. [130] was designed for retinal vascular microsurgery and was capable of positioning instruments at the surface of the retina with sub-micron precision. While a useful experimental device, this system did not have sufficient range of motion to be useful for general-purpose microsurgery. Also, the lack of force sensing prevented the investigation of force/haptic interfaces in the performance of microsurgical tasks.

Many microsurgical robots (e.g., [70, 124, 131-133]) are based on force-reflecting master-slave configurations. This paradigm allows an operator to grasp the master manipulator and apply forces. Forces measured on the master are scaled and reproduced at the slave and, if unobstructed, will cause the slave to move accordingly. Likewise, forces encountered by the slave are scaled and reflected back to the master. This configuration allows position commands from the master to result in a reduced motion of the slave and for forces encountered by the slave to be amplified at the master.

While a force-reflecting master-slave microsurgical system provides the surgeon with increased precision and enhanced perception, there are some drawbacks to such a design. The primary disadvantage is the complexity and cost associated with the requirement of providing two mechanical systems, one for the master and one for the slave. Another problem with telesurgery in general is that the surgeon is not allowed to directly manipulate the instrument used for the microsurgical procedure. While physical separation is necessary for systems designed to perform remote surgery, it is not required during microsurgical procedures. In fact, surgeons are more likely to accept assistance devices if they are still allowed to directly manipulate the instruments.

The performance augmentation approach pursued by the CIS group at Johns Hopkins University, which has also been explored independently by Davies, *et al*. [37-39], and which has some resemblances to the work of Kazerooni [134], emphasizes cooperative manipulation, in which the surgeon and robot both hold the surgical tool. The robot senses forces exerted on the tool by the surgeon and moves to comply. Our initial experiences with this mode in ROBODOC indicated that it was very popular with surgeons and offered means to augment human performance while maximizing the surgeon's natural hand-eye coordination within a surgical task. Subsequently, we incorporated this mode into the IBM/JHU LARS system [26, 36, 49, 135-139]. Figure 21 shows one early experiment using the LARS to evacuate simulated hematomas with a neuroendoscopic instrument [54, 140-142]. We found that the surgeon took slightly longer (6 *vs.* 4 minutes) to perform the evacuation using the guiding, but evacuated much less surplus material (1.5% excess *vs.* 15%).

More recently, we have been exploring the extension of these ideas into microsurgery and other precise manipulation tasks. We have extended our model of cooperative control, which we call "steady hand" guiding, to permit the compliance loop to be closed based on a scaled combination of forces exerted by the surgeon and tissue interaction forces, as well as based on other sensors such as visual processing. The result is a manipulation system with the precision and sensitivity of a machine, but with the manipulative transparency and immediacy of hand-held tools for tasks characterized by compliant or semi-rigid contacts with the environment [18]. We have also begun to develop higher levels of control for this system, incorporating more complex behaviors with multiple sensing modalities [72, 143-146], using microsurgical tasks drawn from the fields of ophthalmology and otology. Figure 22 shows a typical experiment using our current robot to evaluate robot-assisted stapedotomies. Figure 23 shows a comparison of instrument tremor and drift with and without robotic assistance. We have also demonstrated 30:1 scaling of forces in compliant manipulation tasks.

4.4 Other robotic assistants

The use of robotic systems to assist surgeons by performing routine tasks such as laparoscopic camera manipulation is becoming commonplace. Examples include [33, 35, 135, 147]. Some of the manipulator design issues associated with such systems were discussed in Section 3.6. For human-machine interfaces, these systems provided a joystick or foot pedal to permit the surgeon to control the motion of the endoscope. However, other interfaces have include voice, tracking of surgeon head movements, computer vision tracking of surgical instruments, indication of desired gaze points by manipulating a cursor on the computer screen, etc. Figure 8 (left) shows a typical installation of a voice-controlled commercial system (the AESOP(TM, developed by Computer Motion, Inc.).

More recently, there has been interest in robotic systems for manipulating ultrasound probes [116, 148-151]. Figure 12 and Figure 24 show typical current research efforts in development of such robotic systems. Most of this activity has targeted diagnostic procedures such as systematic examination of carotid arteries for occlusions. However, these systems have the potential to become as ubiquitous as the robotic endoscope holders discussed above. Our research group at Johns Hopkins University has begun to explore applications such as precise ultrasound-guided biopsies and other interventional procedures.

There has also been work in the use of flexible robotic devices for intralumenal applications such as colonoscopy and angioplasty. Examples include [152-155] Generally, these devices are snake-like, though there have been a few efforts (e.g., [155]) to develop autonomous crawlers.

5. Perspectives

Computer-integrated surgery is a new, rapidly evolving paradigm that will change the way surgery will be performed in the future. Technical advances in medical imaging, tracking, robotics, and integration are paving the way to a new generation of systems for minimally invasive surgery.

We believe that computer-integrated surgery (CIS) will have the same impact on health care in the coming decades that computer-integrated manufacturing has had on industrial production in the recent past. Achieving this vision will require both significant advances in basic engineering knowledge and the development of robust, flexible systems that make this knowledge usable in real clinical application.

It is important to remember that the ultimate payoff for CIS systems will be in improved and more cost-effective health care. Quantifying these advantages in practice can be problematic, and sometimes the final answer may take years to be demonstrated. The consistency, enhanced data logging, and analysis made possible by CIS systems may help in this process. It will not be easy to figure out how to apply these capabilities. However, we believe that the CIS paradigm is here to stay.

6. Acknowledgments

Any survey or critical summary must necessarily draw upon the work of many people. We would like especially to acknowledge the contributions of many colleagues over the past decade who have helped develop an evolving shared understanding of medical robotics and computer-integrated surgery. We are especially grateful to those individuals who generously provided photographs and other information about the specific systems that we have used as examples. In some cases, these colleagues have also worked with us in developing some of these systems.

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TABLES

Advantage	Important to whom	How quantify	Summary of key leverage
New treatment options	Clinical researchers Patients	Clinical and pre-clinical trials	Transcend human sensory-motor limits (e.g., in microsurgery). Enable less invasive procedures with real time image feedback (e.g., fluoroscopic or MRI-guided liver or prostate therapy). Speed clinical research through greater consistency and data gathering.
Quality	Surgeons Patients	Clinician judgment; Revision rates	Significantly improve the quality of surgical technique (e.g., in microvascular anastomosis), thus improving results and reducing the need for revision surgery
Time and cost	Surgeons Hospitals Insurers	Hours, Hospital charges	Speed OR time for some interventions. Reduce costs from healing time and revision surgery. Provide effective intervention to treat patient condition.
Less invasiveness	Surgeons Patients	Qualitative judgment; recovery times	Provide crucial information and feedback needed to reduce the invasiveness of surgical procedures, thus reducing infection risk, recovery times and costs (e.g., percutaneous spine surgery).
Safety	Surgeons Patients	Complication & revision surgery rates	Reduce surgical complications and errors, again lowering costs, improving outcomes and shortening hospital stays (e.g., robotic THR, steady hand brain surgery).
Real time feedback	Surgeons	Qualitative assessment Quantitative comparison of plan to observation Revision surgery rates	Integrate preoperative models and intraoperative images to give surgeon timelyand accurate about the patient and intervention (e.g., fluoroscopic x-rays without surgeon exposure, percutaneous therapy in conventional MRI scanners). Assure that the planned intervention has in fact been accomplished
Accuracy or precision	Surgeons	Quantitative comparison of plan to actual	Significantly improve the accuracy of therapy dose pattern delivery and tissue manipulation tasks (e.g., solid organ therapy, microsurgery, robotic bone machining).
Documentation and follow-up	Surgeons Clinical researchers	Data bases, anatomical atlases, images, and clinical observations	CIS systems inherently have the ability to log more varied and detailed information about each surgical case than is practical in conventional manual surgery. Over time, this ability, coupled with CIS systems' consistency, has the potential to significantly improve surgical practice and shorten research trials.

Table 1: Key advantages from CIS Systems.

	Strengths	**Limitations**
Humans	Excellent judgment Excellent hand-eye coordination Excellent dexterity (at natural "human" scale) Able to integrate and act on multiple information sources Easily trained Versatile and able to improvise	Prone to fatigue and inattention Tremor limits fine motion Limited manipulation ability and dexterity outside natural scale Bulky end-effectors (hands) Limited geometric accuracy Hard to keep sterile Affected by radiation, infection
Robots	Excellent geometric accuracy Untiring and stable Immune to ionizing radiation Can be designed to operate at many different scales of motion and payload Able to integrate multiple sources of numerical & sensor data	Poor judgment Hard to adapt to new situations Limited dexterity Limited hand-eye coordination Limited ability to integrate and interpret complex information

Table 2: Complementary Strengths of Human Surgeons and Robots

Input: two data sets to be matched**,** image acquisition parameters

Process each data set separately to correct for geometric and intensity distortion and to reduce noise.

While *there is dissimilarity* **and** *there is improvement* **do**

Extract features or regions of interest from both images

Pair features from each data set

Formulate a similarity measure based on pairing

Find the transformation *T* that most reduces the dissimilarity

Transform one of the data sets by *T*

Output: transformation *T*

Table 4: Basic Steps of a Registration Algorithm

FIGURE CAPTIONS

Figure 1: Top: ROBODOC system for orthopaedic replacement surgery (photos by author). Bottom: Early version ROBODOC planning screen (left) and comparative cross sections showing conventionally broached (upper right) and robotically machined (lower left) cadaver femurs [1, 156, 157].

Figure 2: A CIS navigation system in action. The surgeon (left) is performing a brain tumor biopsy with the help of a navigation system. He is holding pointer with light-emitting diodes whose position and orientation is precisely determined in real time by a stereo tracking camera (up). The computer display (center) shows the preoperative MRI and the current position of the pointer. The image shows three orthogonal cross-sections and a three-dimensional reconstruction of the MRI data. The cross hair in each view shows the position of the pointer. The surgeon moves the pointer towards the desired position by watching the pointer location move on the screen as he moves the pointer.

Figure 3: The architecture of CIS systems: elements and interfaces

Figure 4: Major information flow in CIS systems

Figure 5: Volumetric rendering by ray casting (adapted from [9])

Figure 6:: Principle of the marching cubes algorithm: indexes for the marching cube (left) and coding scheme (right). (Reproduced with permission from [10]).

Figure 8: Two robotic assistants for laparoscopic surgery. The AESOP® system (left) is a widely deployed commercial system for manipulating a laparoscopic camera. The robot combines active joints with a 2 degree-of-freedom wrist to achieve 4 controlled motions of the endoscope while preventing lateral forces from being exerted at the entry point into the patient's body. The experimental IBM/JHU LARS system used a 5 bar linkage to decouple rotational and translational motions at the entry point. Both approaches have been used in a number of experimental and clinically deployed surgical robots. (AESOP photo courtesy Computer Motion, Inc.)

Figure 9: Robot system for transurethral prostate surgery [25]. This system used goniometer arcs to provide conical motions about an apex point remote from the mechanism. (Photo courtesy Brian Davies).

Figure 10: RCM robot with radiolucent PAKY end-effector used in percutaneous kidney stone removal [127, 158-162]. (Photo courtesy Dan Stoianovici)

Figure 12: Robotic system for diagnostic ultrasound [148]. (Photo courtesy S. Salcudean)

Figure 11: RCM robot with radiolucent CT-compatible needle driver [42, 44, 45]

Figure 15: MRI-compatible robot for breast biopsy [120]. Photo courtesy Harald Fischer.

Figure 16: Robot system for use in open-magnet MRI system [117].

Figure 17: Typical screen display of a CIS navigation system in action. The top left, right, and bottom windows show orthogonal cross-sectional views of the MRI data set. The cross hair in each shows the position of the tool tip at the center of the tumor. The bottom right window shows the spatial view, with the tool in yellow. (Photo courtesy of BrainLab).

Figure 18: : Screen display of a fluoroscopy-based navigation system during intramedullary nail distal locking. The windows show AP and lateral fluoroscopic X-ray images with the tool (solid green line) and its extension (dotted yellow line). The goal is to align the tool with the nail's hole axis [59, 61](Photo Courtesy of L.P. Nolte).

Figure 19: Typical screen display of a CIS navigation system for endoscopic surgery. The left windows show orthogonal cross-sectional views of the CT data set and the endoscope image. The green line shows the position of the endoscope. The photograph on the right shows the endoscope and the tracking plate (Reproduced from [98]).

Figure 20: Augmented reality CIS system for brain tumor surgery. The tumor image (green) and brain structure (blue) are projected directly on the patient's skull (Photo Courtesy of Ron Kikinis)

Figure 21: Virtual endoscopy: three-dimensional reconstruction of structure to be viewed (left) and view from the inside fly-through. (Reproduced from [98]).

Figure 22: Information flow in a typical orthopaedic robotic system (in this case, the ISS ROBODOC system).

Figure 23: Early percutaneous therapy experiments at JHU using the LARS robot [110, 111].

Figure 21: Cooperative guiding using the LARS for neuroendoscopy experiment [54, 140-142]

Figure 22: Microsurgical Augmentation Experiments with the Johns Hopkins Steady-Hand robot [163]. Shows the current generation of the robot being used to evaluate robotically assisted stapedotomy. The current generation comprises an RCM linkage [164], a custom end-effector assembly [21, 165, 166], and off-the-shelf components. (Photo courtesy Dan Rothbaum, MD).

Figure 23: Comparative performance of human tremor and drift without a robot and with steady-hand manipulation augmentation[167]

Figure 24: Dexterous RCM end-effector for ultrasound and similar applications [116] mounted on an Integrated Surgical Systems Neuromate Robot. (Photo Courtesy Randy Goldberg)

Figure 25: Telesurgical augmentation system: In this "telepresence" system the surgeon sits at a control console (left foreground) and manipulates a pair of "master" robot arms while "slave" robots (left background and right) mimic his motions inside the patient's body [122]. (Photos courtesy Intuitive Surgical Systems).