Medical Robotics

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The evolution of robotics in surgery is a new and exciting development. Surgical robotics brings together many disparate areas of research such as: design, development and modeling of robotic systems, nonlinear control, safety in medical robotics, ergonomics in minimally invasive procedures, and last but not the least, surgery. Over the past decade there have been significant advances in basic research and technology that have made it possible for the development of robots for surgery. One of the main advantages of robots is the increased precision and repeatability in carrying out surgical procedures, which were not possible in the past by a human surgeon. Robots and computers in conjunction can perform complex computations at much higher speeds compared to humans. On the other hand, humans are more adept in integrating diverse sources of information and making decisions based on their past experience of working in that field. They are also dexterous on the "human" scale, have very strong hand-eye coordination and an excellent sense of touch. Robots on the other hand have very good accuracy in carrying out pre-specified tasks, are not prone to fatigue or boredom, can carry out fast computations for surgical planning based on 3-D imaging data and other sensory feedback, and can also be designed for a wide range of operating conditions and scales. There are however severe limitations of robots and humans. One of the main disadvantages of robots is that they have poor judgment capability, limited dexterity and poor hand-eye coordination. Humans on the other hand cannot operate beyond their physical capability (their natural scale of operation) and are prone to tremor and fatigue [Taylor96]. Robots are thus seen more as augmenting human capabilities rather than replacing surgeons. The strengths and weaknesses of humans and robots are summarized in Table 1.

Several robotic systems have been developed for surgical procedures. Some of the key areas where robotics has made a significant impact are orthopaedics, neurosurgery, laparoscopic procedures, opthalmic surgery, and cardiac surgery.

Humans	Robots
Strengths	*Strengths*
• Strong hand-eye coordination	• Good geometric accuracy
• Dexterous (at human scale)	• Stable and untiring
• Flexible and adaptable	• Can be designed for a wide range of scales
• Can integrate extensive and diverse information	• May be sterilized
• Able to use qualitative information	• Resistant to radiation and infection
• Good judgment	• Can use diverse sensors (chemical, force, acoustic, etc.) in control
• Easy to instruct and debrief	
Limitations	*Limitations*
• Limited dexterity outside natural scale	• Poor judgment
• Prone to tremor and fatigue	• Limited dexterity and hand-eye coordination
• Limited geometric accuracy	• Limited to relatively simple procedures
• Limited ability to use quantitative information	• Expensive
• Large operating room space requirement	• Technology in flux
• Limited sterility	• Difficult to construct and debug
• Susceptible to radiation and infection	

Table 1. Strengths and Limitations of Humans and Robots (adapted from Taylor and Stulberg [Taylor96].)

Developments in science and technology have facilitated rapid development of robotic technologies for surgical applications. Before we go into various application areas of robotics for surgery, it is important to understand some of the common techniques used in robotic surgery. One of the most rapidly evolving techniques is minimally invasive surgery, whereby small incisions made into the body of the patient are used to guide the surgical instruments and perform the surgery. These incisions are used for guiding a light source, video camera and

various surgical tools, which are required for the procedure. One of the examples of minimally invasive surgery is knee arthroscopy involving the removal of meniscus cartilage. In this procedure, the surgeon resects the cartilage without making large incisions in the tissue surrounding the knee joint. This leads to faster recovery times, lower hospitalization costs, and reduced post-operative complications. Other minimally invasive procedures such as those in neurosurgery involve preoperative image analysis and surgical planning for accurate localization and removal of the brain tumor. Image based procedures is another technique used in robot assisted surgery. Image based procedures are broadly classified into three stages: planning, registration, and navigation. In the planning phase, the preoperative images are used to plan a surgical strategy such that during the procedure, the healthy tissue and blood vessels surrounding the tumor are not traumatized. Navigation on the other hand is the actual execution of the surgical strategy after planning and registration is accomplished. Registration is one of the most important steps in a minimally invasive procedure and we will describe this in greater detail.

Registration is the process of matching the points in the preoperative image data with those in the patient's anatomy. Some of the common imaging modalities are: computed tomography (CT), and magnetic resonance imaging (MRI) for anatomical information of the operative site, positron emission tomography (PET) and single photon emission computed tomography (SPECT) for obtaining functional information of the operative site which can be combined with the CT or MRI data to obtain richer information. Often registration procedures involve multimodal image data for accurate correlation. Registration involves matching the imaging data from two independent coordinate systems. Hence, it differs from calibration where two coordinate systems are attached to the same object and the problem is to find a relation between the two. There are two basic approaches to registration. It is either fiducial based or shape based. In the fiducial based approach, fiducials or markers are placed on the anatomical structure and imaging data is obtained of the location of these fiducials. During surgery, the robot by means of a probe, for example, contacts these fiducials and obtains their location in its own coordinate system. By means of suitable matrix transformations, complete correlation between the image data and the robot data can be obtained. However, fiducial based approaches can cause substantial discomfort to the patient as in the total hip replacement (THR) surgery using the ROBODOC system, since the fiducials have to be present throughout the procedure. In the total hip replacement procedure,

the fiducials or pins are inserted at the proximal and distal end of the femur. In addition, fiducial based registration technique also adds significant operating time as the robot tip has to contact each of these fiducials during the initialization phase and if there is a slight movement of the operative site, the system needs to be reinitialized. In THR surgery using the ROBODOC system, the femur of the patient is fixated to the table to prevent its movement. In the shape-based approach, the problem is to fit the preoperative image data with the anatomical structure during the procedure. This is computationally time consuming and the goal is to obtain the best fit of the intraoperative data with the preoperative image. This method does not track the changes in the anatomical structure during the procedure. To summarize, the primary task is to match the information from various sources for accurate localization of the lesion. In most surgical procedure, precision is of great importance and hence registration techniques need to be very accurate compared to standard diagnosis done by the surgeon. Registration need not necessarily be limited to imaging data. It can also involve registering the operating room environment.

Registration process involves three sets of data: a) Preoperative data, whereby the imaging system consisting of computed tomography (CT), magnetic resonance imaging (MRI), positron emission tomography (PET), single photon emission computed tomography (SPECT), etc. provides 2D or 3D information of the operative site. This information is useful for planning the surgical procedure. b) Intraoperative data, whereby the imaging system continuously monitors the progress of the surgical strategy and gives information to the surgeon for online planning of the path to be followed to prevent damage to the adjacent tissue, and also help the surgeon see newer tissues and/or vascular structure which was not present prior to the incisions. Intraoperative registration also provides active guidance to the localizers or robotic instruments and helps locate the instrument in the image. This helps to prevent damage to the tissues and vascular structure during surgery. c) Postoperative data helps the surgeon to update the information of the anatomical structure and obtain information about the success of the surgery. This information is useful for follow-up visits and monitoring the progress of the healing process or detecting new lesions in the future. In this chapter, we will explore the various applications of robotic technologies for performing surgery.

1 ORTHOPAEDIC SURGERY

Orthopaedics was one of the first areas where robotic applications were developed. This is partly due to the fact that bones are rigid and hence registration problems are simpler and make image-guided procedures relatively straightforward. The development of the ROBODOC system began in the mid-1980's as there was a need for improved precision in forming the femoral cavity for hip implants in total hip arthroplasty. The HipNav system for accurate acetabular cup placement in total hip arthroplasty is another such application of robotics to orthopaedic surgery. There have been a variety of robotic systems developed for total knee replacement surgery (TKR), which involve increasing the accuracy of prosthetic alignment. In this procedure, the robot guides the jig to the correct location so that the surgeon can make accurate bone resections. Robotics has also been applied in spine surgery where significant emphasis has been on developing systems for accurate pedicle screw placement. There are a variety of systems developed for a specific clinical procedure. Since the diversity of these systems is large, they have been classified into three main categories according to the independence given to the surgeon in performing a surgical task. These systems for orthopedic surgery are broadly classified as: active, semi-active and passive systems [DiGioia98]. Active systems are generally autonomous although under the supervision of the surgeon such as the ROBODOC system. In these systems the robot performs the task autonomously without any external guidance from the surgeon. These systems typically use various sensing modalities and multiple images of the operative site to ensure the required accuracy and safety of the procedure. Since these systems do not work in cooperation with the surgeon, the safety requirements for these systems for clinical use is very demanding. Semi-active systems such as the ACROBOT (see Figure 4(b)) system work under direct supervision and guidance of the surgeon. In total knee replacement (TKR) surgery using the ACROBOT system, the surgeon guides the cutting tool and the necessary cutting force, while the robot actively monitors the movement of the cutting tool so that it does not cut unnecessary material. Semi-active systems have active motors and encoders, however they cannot perform the procedure without human guidance. As a result, the safety requirement for these systems is less stringent compared to the active systems. Passive systems provide the surgeon with feedback of what he/she does by comparing the planned strategy and its actual execution without any direct intervention. An example of a passive system is the

PADyC system developed by Troccaz et al, for guided execution of potentially complex strategies while providing increased accuracy and ergonomics [Troccaz93].

To illustrate the various applications of robotics in orthopaedic surgery, we will now go through a few of these in greater detail.
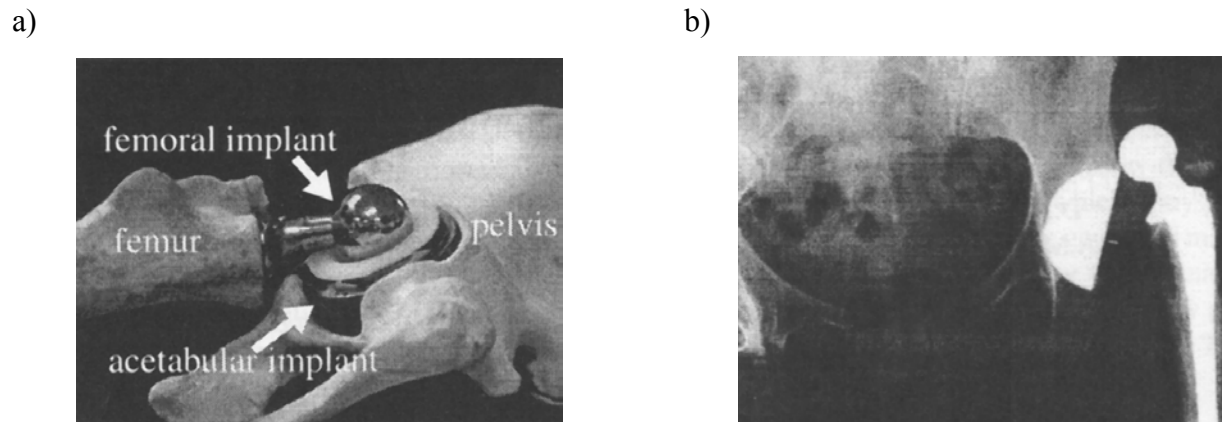
a)   b)

Figure 1. a) Femoral and acetabular implant in a total hip replacement surgery and b) X-Ray image of femur head dislocation from the acetabular cup. (Figures 1(a) and 1(b) from "Development and validation of a navigational guidance system for acetabular implant placement", D. A. Simon, B. Jaramaz, M. Blackwell, F. Morgan, A. M. DiGioia, E. Kischell, B. Colgan, and T. Kanade. *In First Joint Conference on Computer Vision, Virtual Reality and Robotics in Medicine and Medical Robotics and Computer Assisted Surgery.* Editors: J. Troccaz, E. Grimson, R. Mosges, pages 583-592, 1997. Springer Verlag). **Do not reprint these figures without obtaining the appropriate permissions.**

Total Hip Replacement (THR): The Total Hip Replacement procedure involves replacing the hip joint through a surgical process. The hip joint is comprised of two parts: the acetabulum, which is a cup shaped bone in the pelvis and the head of the thigh bone (femur), which is like a "ball". About half a million total hip replacement surgeries are performed annually in the United States comprising of primary or revisited cases. The primary post-operative complication is the dislocation of the femoral implant and in some cases disassociation of the femoral implant from the acetabular implant as shown in Figure 1(b). During the surgical procedure, the acetabulum and the head of the femur are removed and replaced by a smooth artificial socket and an artificial

ball with a long stem made of stainless steel as shown in Figure 1(a). These artificial parts are put together with bone cement. However, over a period of time the cement can crack and loosen the fit. An alternative treatment procedure is to use cementless total hip replacement. In this procedure there is a possibility of bone growth into the metal for maintaining a good fixation. This approach overcomes the deleterious effects of a cemented hip replacement procedure. However, the cementless procedure requires a close proximity between the bone surface and the implant (about 0.25mm or less). Since precision in the THR procedure is very important, robotic technology has played a key role in the development of the ROBODOC system for performing the THR procedure.

Femoral cavity: The procedure begins with the insertion of three titanium pins through small skin incisions into the greater trochanter and condoyles of the patient's femur. Next, a CT scan of the leg is made and the location of the pins is identified in the coordinate system of the CT images. The surgeon then decides the implant size from a library of implants based on the kinematics of the leg and the density of the bone. After this, the acetabular cup and the femoral cap are removed from the patient in the normal process. To ensure accurate spatial location, the femur of the patient is fixated to the table by means of a specially designed fixator. The titanium pins are exposed and the robot tip contacts the pins to determine the transformation between the CT images and the robot coordinate frame. A high speed milling cutter then cuts the desired implant shape in the femur while the surgeon is continuously monitoring the process. After the cavity is cut, the fixator is removed and the robot moves out of the way. The surgeon completes the remaining part of the procedure in the normal way. Although the advantages of using a robotic system are clear in this procedure, one of the main disadvantages is the trauma caused to the patient due to pin placement in the femur and the rigid fixation of the femur to the operating table to maintain accurate registration.

Acetabular cup placement: Since, disassociation of the femoral implant from the acetabular cup is one of the primary causes for hip dislocation in post-operative complications, it is vital to accurately position the femoral implant with the acetabular cup. The current manual alignment devices configure the implant with respect to the gross body axis of the patient without taking into account the pelvic orientation or its geometry. The HipNav system has been

developed by [Simon97] to reduce the occurrence of this complication. The system consists of a preoperative planner, a range of motion simulator, and an intraoperative tracking and guidance system. The preoperative planner allows the surgeon to select the correct implant size and its placement based on the CT scan of the patient's pelvis. The surgeon specifies the position and orientation of the implant based on orthogonal views of the pelvis and using 3D rendering techniques. The range of motion simulator (see Figure 2) helps the surgeon to determine the range of orientations at which there is a possibility of impingement of the femoral implant with the acetabular cup. This information combined with the preoperative planning and CT images, aids the surgeon in determining the accurate positioning of the acetabular cup. Finally, the tracking and guidance system monitors the location of the pelvis with the preoperative plan and aids the surgeon in accurately placing the cup.
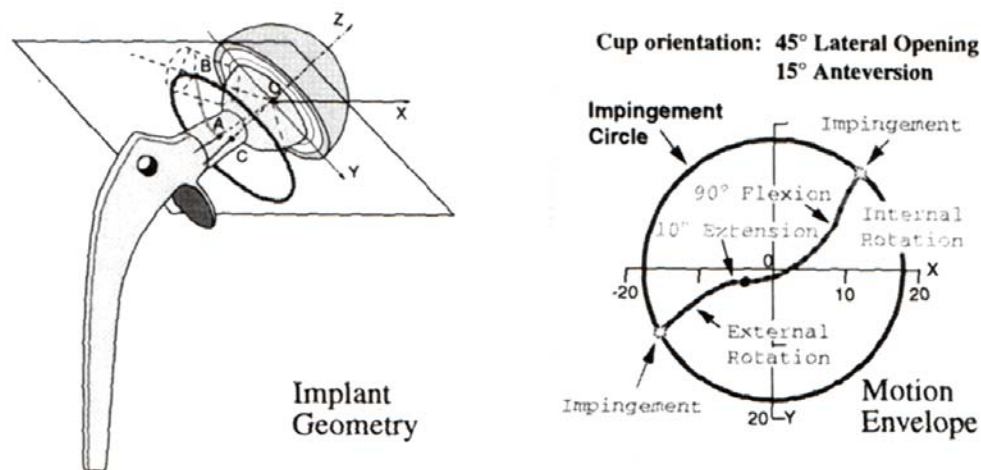

Figure 2. Kinematic range of motion simulator to determine the orientation of the implant at which impingement will occur between the femoral neck and the acetabular cup. (From "Development and validation of a navigational guidance system for acetabular implant placement", D. A. Simon, B. Jaramaz, M. Blackwell, F. Morgan, A. M. DiGioia, E. Kischell, B. Colgan, and T. Kanade. *In First Joint Conference on Computer Vision, Virtual Reality and Robotics in Medicine and Medical Robotics and Computer Assisted Surgery.* Editors: J. Troccaz, E. Grimson, R. Mosges, pages 583-592, 1997. Springer Verlag). **Do not reprint these figures without obtaining the appropriate permissions.**
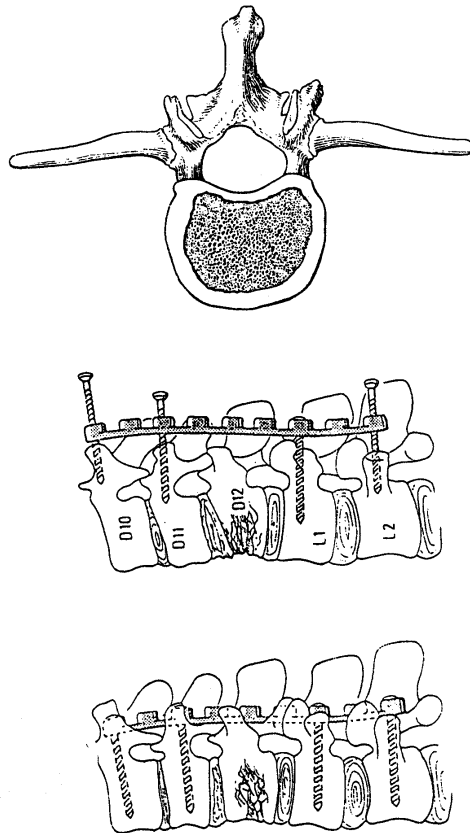
Figure 3. Anatomy of the vertebrae and the placement of the pedicle screws. (From "Computer assisted spinal surgery using anatomy-based registration", S. Lavallee, J. Troccaz, P. Sautot, B. Mazier, P. Cinquin, P. Merloz, and Jean-Paul Chirossel. In *Computer-Integrated Surgery: Technology and Clinical Applications*, Editors: R. H. Taylor, S. Lavallee, G. C. Burdea and R. Mosges, pp. 425-449. MIT Press, Cambridge, MA, 1996.) **Do not reprint this figure without obtaining the appropriate permission.**

Spine surgery: Transpedicle screw insertion is a common procedure to prevent relative motion between the adjacent vertebrae by achieving a rigid segmental fixation. This procedure is performed for various spinal procedures due to fracture, scoliosis, spondylolisthesis, etc. with limited visual feedback at times. The primary difficulty in carrying out this procedure is that the screw must be passed down the long axis of the vertebral bone with great accuracy without damaging the surrounding nerve tissue. This procedure requires a great deal of experience to perform with marginal accuracy. Good fixation of the screws requires insertion of the screw through the axis of the pedicle. The exact location and orientation of the pedicle axis is crucial

for such intervention. The anatomy of the vertebrae and the placement of the pedicle screws are shown schematically in Figure 3. Since the surgeon, based on his/her experience inserts the screws manually, this procedure is especially difficult for a young surgeon since a slight error in the orientation of the inserted screw results in a larger error when the screw is inserted completely. This procedure is performed by opening the back of the patient and exposing the underlying vertebrae. This significantly increases the trauma to the patient and also leads to an increased recovery time. An approach using minimally invasive techniques is currently under development whereby this procedure can be performed percutaneously with the aid of intraoperative ultrasound or radiograph images [Lavallee96b].

Total knee replacement (TKR): In knee replacement surgery, it is important to obtain an accurate alignment of the prosthetic components to regain normal functioning of the knee joint and the leg. Typically, for this procedure, two prosthetic components are used with one component mounted on the proximal tibia and the other on the distal femur. This procedure typically requires 6 flat planes to be cut from the bone ends, along with two circular holes and two locating slots. The relationship between these holes, planes and slots is crucial to obtaining a good mating between the various components in a typical TKR. This procedure is typically performed by mounting templates and the surgeon performs the cutting task using these templates. However, surgeons do not have any force feedback from the cutting tool and hence changes in the bone density can lead to excessive cutting and a corresponding misalignment of the prosthetic components. Also the sequential application of many templates can lead to a cumulative error in the task performance and deteriorate the performance of the implant. In addition, it can also cause significant trauma to the patient and may need postoperative treatment to correct the problem.

Robots are ideally suited for performing this task in cooperation with the surgeon. One such robotic system has been developed by [Harris97] where the surgeon guides the robot to perform the cutting task while continuously monitoring the cutting force by direct interaction with the robot. Since it is a semi-active robotic system, the safety requirements are less demanding than an active robotic system. This system allows the surgeon to change the cutting speed as desired based on the "feel" of the operative site while the surgeon performs the bone cutting with the

robot. This robot, called the ACROBOT (Active Constraint ROBOT) can also be programmed to check the movement of the surgeon so that the surgeon does not deviate from the workspace and cut unwanted material. The robot is linked to a computer system into which preoperative CT images are loaded. Based on the CT data, the surgeon can manipulate this image in 3D to choose the correct prosthesis for the patient. This also helps in aligning the chosen model with the CT image and evaluating the efficacy of the fit and the areas to be machined. The computer is also programmed to compute the various cutting planes to obtain a better fit. Figure 4(a) shows the overlay of the prosthesis with the actual CT image to help the surgeon preoperatively plan the entire task before an actual procedure. Figure 4(b) shows the photograph of the ACROBOT.
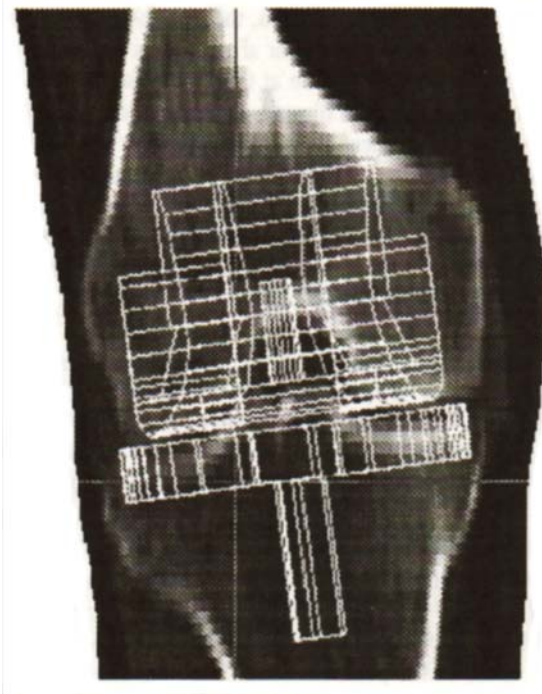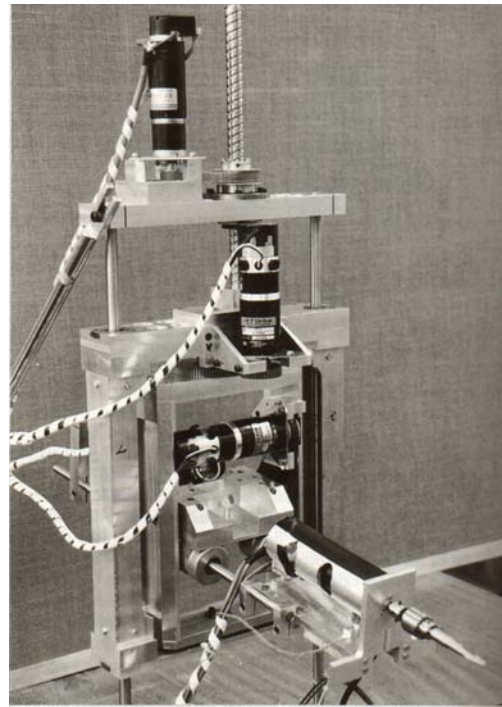
a) b)

Figure 4. a) Overlay of the computer model of the prosthesis components superimposed on the actual CT image for preoperative planning and b) the ACROBOT system for TKR surgery. (Figures 4(a) and 4(b) from "Experiences with robotic systems for knee surgery", S. J. Harris, W. J. Lin, K. L. Fan, R. D. Hibberd, J. Cobb, R. Middleton, and B. L. Davies. *In First Joint Conference on Computer Vision, Virtual Reality and Robotics in Medicine and Medical Robotics and Computer Assisted Surgery.* Editors: J. Troccaz, E. Grimson, R. Mosges, pages 757-766,

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2 NEUROSURGERY

Neurosurgery was the first area to employ image-guided techniques. Image-guided procedures are non-invasive since CT, MRI, and fluoroscopy, provide an image on the monitor, which can then be used for planning, registration and navigation of the robotic system.   For example, in the removal of brain tumors in neurosurgery, the MRI image locates the tumor precisely in the brain and this information is used to guide the robot correctly to the right location with minimal damage to the surrounding tissue. Some other robotic systems have also been developed which use image-guided techniques to make the neurosurgical procedures as minimally invasive as possible, reduce the intervention time   and cause minimal trauma to the surrounding healthy tissue [Lavallee96a].

In the planning phase of any image-guided procedure, the preoperative and intraoperative images are processed to reveal the essential information that is required to design efficient path planning algorithms. This information is used during execution of the planned trajectory so that the robot tip does not damage the surrounding tissue, blood vessels, nerves, etc. In the registration phase, it is essential to establish a correspondence between the preoperative image data such as that obtained from a CT scan or MRI with the operating room coordinate system. This is established by matrix transformations between the operating room coordinate system (or the robot coordinate system) and the preoperative image. This is performed by a calibration procedure, whereby at least three points on the patient's head (for neurosurgical procedure) are identified in the CT coordinate system and in the robot coordinate system. Once this identification is achieved, a coordinate transformation is performed to accurately locate the robot tip in the CT coordinate system. This information can be used intra-operatively by the surgeon performing the procedure. Finally, in the navigation phase, the information from the registration process is used to either navigate the robot or help the human surgeon. If the robot navigates autonomously, then the sensors onboard the robot continuously monitor its motion to ensure that the movement of the robot tip is within the acceptable range. Similarly, if the surgeon carries out the procedure

with the aid of a robot guiding the movement, the sensors onboard the robot can track the movement of the surgeon holding the instruments. In this phase of an image-guided procedure, safety is of primary concern and the decision of autonomous vs. manually guided robots is governed primarily by safety considerations.

In neurosurgery, minimally invasive surgical techniques, less intervention time and reduced trauma are the most important requirements. Stereotactic neurosurgery is an example of a procedure that satisfies these requirements. Stereotactic surgery is operating in a three-dimensional anatomic space by using a reference system. Horsley and Clarke first used this approach in 1908 for physiologic examination. Stereotactic surgery in humans was only developed much later in 1947 when Spiegel and Wycis first used this approach for identifying the target location based on internal landmarks by using a positive contrast ventriculogram (based on 2-D X-ray imaging techniques). With the advent of computer and rapid increase in technology, surgeons can now view and analyze the 3-D information from CT, MRI, DSA (Digital subtraction angiography), PET and other imaging modalities, in real-time and visualize, plan, and verify their surgical strategy before the actual intervention. One example of this work is the Compass system (manufactured by Compass International, Inc., Rochester, Minnesota), which provides computerized image, an interactive surgical positioning system, and volumetric stereotactic procedures. Volumetric stereotactic procedures involve localization, reconstruction, and integration of volumetric information in stereotactic space. This group has also developed Regulus (Compass International, Inc.), a hardware and software device that allows the surgeon to perform the procedure with or without a stereotactic frame.

3 MINIMALLY INVASIVE SURGERY

Minimally invasive surgical procedures are gaining rapid acceptance in the surgical workplace with more research focus towards inventing novel minimally invasive techniques for accomplishing a "major" surgical task with "minor" incisions in the body. The advantages of this procedure are: considerably shortened recovery times, lesser hospitalization costs, less postoperative pain, and reduced trauma during the procedure. Though the advantages of this procedure are several for the patient, it poses additional requirements from the surgeon. Since the

surgeon is used to working without workspace constraints, they may find it difficult to manipulate surgical tools through small incisions and observe the results of their work on a monitor across the operating table. Minimally invasive procedures also lead to repetitive stress injuries resulting from small workspace volume. Though the research efforts are directed towards making laparoscopic techniques more surgeon friendly with the development of various sensing modalities and endoscopic guidance systems, the surgical tools for minimally invasive procedures are far from natural for the surgeon.

Laparoscopy was approved for cholecystectomy or gallbladder removal a few years back and this procedure is almost exclusively performed through minimally invasive techniques. In this procedure, the surgeon makes tiny incisions about 5 to 10 millimeters in length and these holes are used to pass a video camera, a light source and precision surgical instruments such as laparoscopic scissors. The video camera provides the surgeon with a complete view of the internal operating field on a color monitor, which is located across the operating table. The surgeon can see the movements of the surgical instruments on the monitor and perform the procedure appropriately. Recently, there have been trends to provide the surgeon with a 3D view of the internal operative site rather than 2D information on a monitor. This allows the surgeon to view the internal operative site in greater detail during the procedure. However, the task of working through small incisions in the body places severe limitations on the surgeon and the dexterity in manipulation of the surgical instruments. In order to perform a minimally invasive procedure, the surgeon needs a lot of training to be able to naturally perform complex mental transformations by looking on the monitor across the table and moving the surgical instruments. This is tedious and complex since surgeons are used to observing the operative site directly while their hands are working on it. Minimally invasive procedures also place greater challenges in terms of instrumentation development for performing dexterous manipulation. With smaller incisions, the surgeon can only move the instrument along the direction of insertion or rotate it. Lateral movement is not possible since the point of incision acts as a fulcrum. Minimally invasive procedures also deprive the surgeon of one of their most important ability, the sense of touch. Many surgical procedures are best performed by "feeling" the tissue or the surrounding vessels.

Minimally invasive surgery also poses severe physical limitations. The task of holding the laparoscope lasts for almost the entire duration of the procedure and it is very tiring for the surgical assistant. Secondly, with the human performing the holding and manipulation task over a larger period of time can lead to repetitive stress injuries. Since the procedure requires positioning and orientating the scope continuously, a mechanical clamp for holding the scope is not a feasible solution. Thus a robotic system, which will hold and manipulate the scope for the surgeon is an excellent example of the use of robotics for this procedure. The AESOP system (Automated Endoscope System for Optimal Positioning) developed by Computer Motion is an example of such a system [Sackier96]. The AESOP system is shown in Figure 5. This is a voice-activated system whereby the computer follows the voice commands of the surgeon and guides the robot to position the laparoscope appropriately for the surgeon.
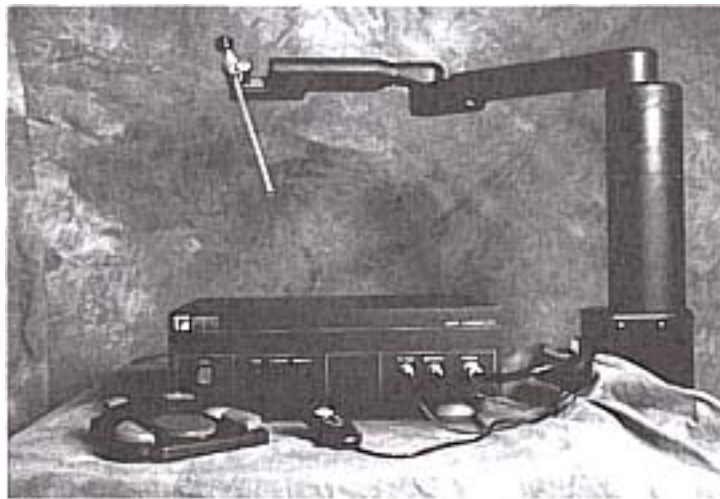

Figure 5. The AESOP robot with the computer control unit and the positioning arm. (From "Robotically assisted laparoscopic surgery: From concept to development", J. M. Sackier and Y. Wang. In *Computer-Integrated Surgery: Technology and Clinical Applications*, Editors: R. H. Taylor, S. Lavallee, G. C. Burdea and R. Mosges, pp. 577-580. MIT Press, Cambridge, MA, 1996.) **Do not reprint this figure without obtaining the appropriate permission.**

Another example of a minimally invasive procedure performed with the aid of a robot is the transurethral resection of the prostrate. The prostrate gland is located between the base of the penis and the bladder neck. In some people, the urinary tract can become blocked with adenomatous tissue, which obstructs the flow of urine. The growth of this tissue, which occurs

with age, is normally benign. In the past this obstruction was removed by an open procedure. However, in recent years the obstruction removal procedure is performed through minimally invasive techniques. In this procedure, an endoscope is inserted down the center of the penis and is located at the base of the penis. This endoscope contains the tools for observation, illumination and the necessary cutting tools. The resectoscope consists of a tungsten wire loop. With the aid of the endoscopic camera, direct visualization of the operative site is possible. The resectoscope employs a high frequency current that is used to remove the excess growth. As in most minimally invasive procedures, a saline liquid bloats the interior cavity surrounding the operative site. The harvested tissue floating in this liquid is then sucked out through the suction channel in the resectoscope. Davies et al, performed an initial feasibility study of a robotic system for performing this procedure and the system is shown in operation in Figure 6(a). The manual safety frame used in the procedure is shown in Figure 6(b). The area of resection in this procedure needs to be specifically confined between the bladder neck and the verumontanum. However, since the required motion is very complex to be performed by an industrial robot, [Davies96a] developed a passive guiding system for performing this procedure. This aids the surgeon to confine the movement to a well-defined workspace while manually guiding the resection tool. This also ensures the safety of the patient since the system is passive and not actively controlled.
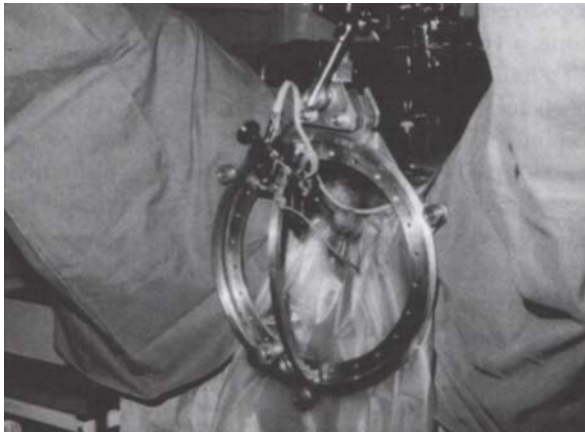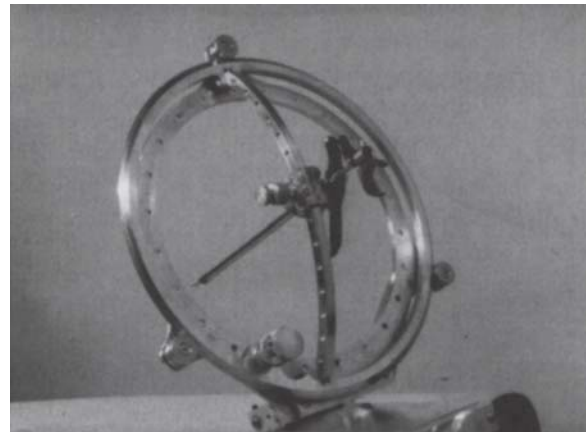
a)   b)

Figure 6. a). Safety frame in position for transurethral resection of the prostrate and b) Manual safety frame. (Figures 6(a) and 6(b) from "A clinically applied robot for prostatectomies", B. L. Davies, R. D. Hibberd, A. G. Timothy, and J. E. A. Wickham. In *Computer-Integrated Surgery: Technology and Clinical Applications*, Editors: R. H. Taylor, S. Lavallee, G. C. Burdea and R.
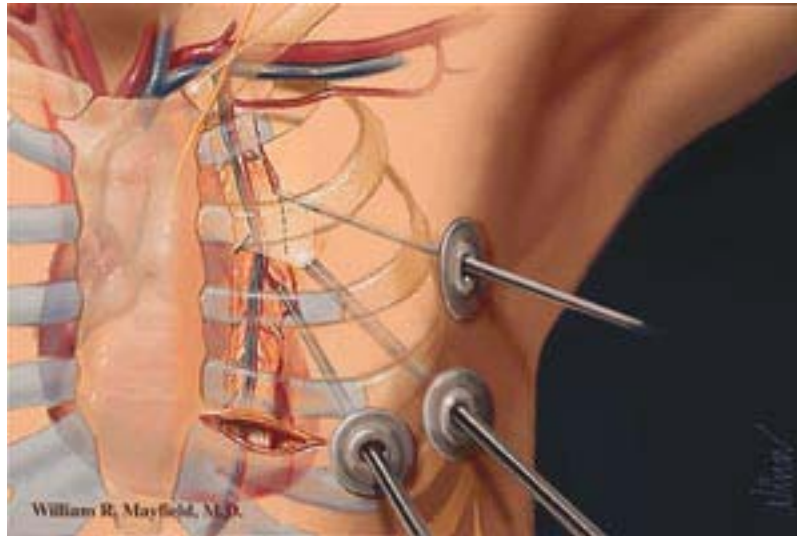
Figure 7. Access ports for minimally invasive cardiac surgery. (From *Minimally invasive cardiac surgery*. R. G. Cohen, M. J. Mack, J. D. Fonger, and R. J. Landreneau. Quality Medical Publishing, Inc. 1999, page 129, St. Louis, Missouri) **Do not reprint this figure without obtaining the appropriate permission.**

Minimally invasive surgical techniques are being actively developed for cardiac surgery with significant collaboration between the industry and academia. One of the examples of such a robotic system is developed by Intuitive Surgical Systems. In this system, tiny ports or holes are made in the skin such as those shown in Figure 7. Through these holes, the surgical tools are inserted along with a 3 dimensional video imaging system, which provides real-time feedback to the surgeon sitting on the console. The surgeon moves the telerobotic arms of the robot from the console and continuously monitors the progress of the slave robot. This system has been used for various cardiac procedures such as valve repair and coronary artery bypass graft. The system is superior to the human surgeon performing a similar task since it is performed through tiny incisions rather than a sternotomy (cutting the chest bone to expose the surgical site of the heart).

a)   b)
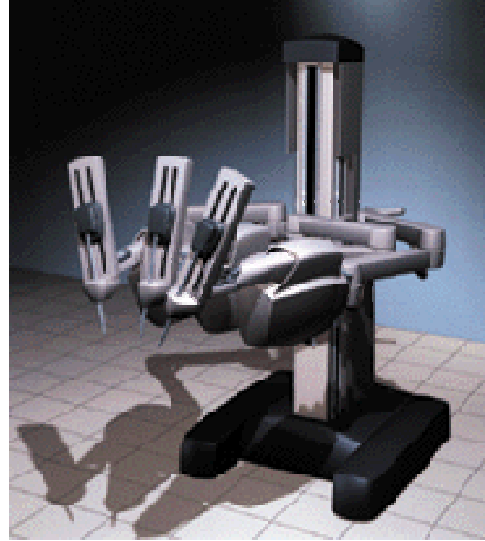
Figure 8. a) The Endo Wrist developed by Intuitive Surgical Systems for minimally invasive cardiac procedures and b) The Slave robotic system with various surgical tools for performing the surgery. (Figures 8(a) and 8(b) From "The heart of microsurgery", J. K. Salisbury, Jr. In *Mechanical Engineering, American Society of Mechanical Engineers*, 1998.
Website: http://www.memagazine.org/contents/current/features/microheart/microheart.html). **Do not reprint these figures without obtaining the appropriate permissions.**

The configuration of the whole system is similar to any other regular telerobotic system where there is a master manipulator and a slave manipulator. In a telerobotic system, the movements of the master robot, which could be controlled by a human, are reproduced on the slave manipulator with or without any time delay. Typically, in a surgical robotic system, which is teleoperated such as the one of Intuitive Surgical Systems, the surgeon is in the same operating room as the robot and hence there is no time delay in replicating the actions of the master on the slave and obtaining 3 dimensional information of the operative site. However, if this were performed over a larger distance, time delay issues would become important since there is limited bandwidth and it becomes necessary to prioritize the information transmitted between the master and the slave robots. Compared to conventional telerobotic systems where there is no human in the control loop, the telerobotic system developed by Intuitive surgical and other such telerobotic systems have an advantage over conventional systems. Human judgment and cognitive skills are acquired with experience and they are too complex to replicate in a robot. On the other hand, robots have high dexterity and precision in performing a task. Thus involving a human surgeon in the control

loop has led to better precision in performing cardiac surgery with this system, which was not previously possible. In conventional minimally invasive procedure, one of the main disadvantages is the absence of natural view and feel of the operative site since the surgeon has to look at the monitor across the operating table to observe the movements of the laparoscopic instruments manipulated by him/her. The Intuitive system overcomes this limitation by "immersing" the surgeon in the operative field. The surgeon immerses himself / herself in the operative field by directly visualizing the movements and teleoperatively controlling the movements of the slave. This also overcomes the counterintuitive motion of the surgical tools as in conventional laparoscopic surgery. In conventional minimally invasive surgery, the surgical tools have fewer degrees of mobility, thereby limiting the procedures performed with those techniques to simple procedures. But procedures such as heart valve repair are far more complex and require efficient and dexterous manipulations with a robotic hand. This led to the development of the Endo Wrist shown in Figure 8(a), which is a key component of this system. The Endo Wrist allows the surgeon to reach around and behind the tissues, which would not be possible by a human due to limited mobility range of our joints. The Endo Wrist has cable transmission and gives the surgeon seven degrees of freedom for each hand. The Slave robotic system, which can hold various surgical tools for performing the surgery, is shown in Figure 8(b).

Figure 9. The Intuitive Surgical System for minimally invasive cardiac procedures. (From "The heart of microsurgery", J. K. Salisbury, Jr. In *Mechanical Engineering, American Society of Mechanical Engineers*, 1998.

Website: http://www.memagazine.org/contents/current/features/microheart/microheart.html). **Do not reprint this figure without obtaining the appropriate permission.**

Thus, in the Intuitive system, the surgeon sits on the console such as that shown in Figure 9. During the procedure the surgeon can control the movement of the camera mounted on the robot to have a better view of the surgical site. Through sufficient magnification and force feedback, the surgeon can manipulate the Endo Wrist to achieve complex movements during surgery. The three dimensional video imaging system provides real-time feedback to the surgeon of the surgical site.

4 MICROSURGERY

Robotics has also played a key role in opthalmic microsurgical procedures. In microsurgical procedures, the presence of tremor causes imprecision. An Opthalmic surgeon typically works under an operating microscope for the entire duration of the procedure and this could be stressful. Since the forces encountered in microsurgical procedures are very small, it is necessary to amplify the forces to give a realistic feel of the applied force and the sensed forces to the surgeon performing the procedure for a better control over the operation. [Taylor99] are currently working on developing a robotic system called the "Steady Hand Micromanipulation" system for opthalmic procedures. The goal of this system is to augment the capabilities of the surgeon by aiding the surgeon in performing sub-millimeter manipulation tasks. The Steady Hand system is a cooperative robotic system whereby the strengths of both the robotic system and the human surgeon are combined for performing the procedure. The surgeon has better hand-eye coordination, and sensory integration capability while the robot is good for accurate positioning of the instrument tip. The robot's controller senses the interaction forces, both by the operator on the tool and by the tool on the environment. This force information is used by the controller architecture of the robot to produce a smooth, tremor-free, position control and force scaling.
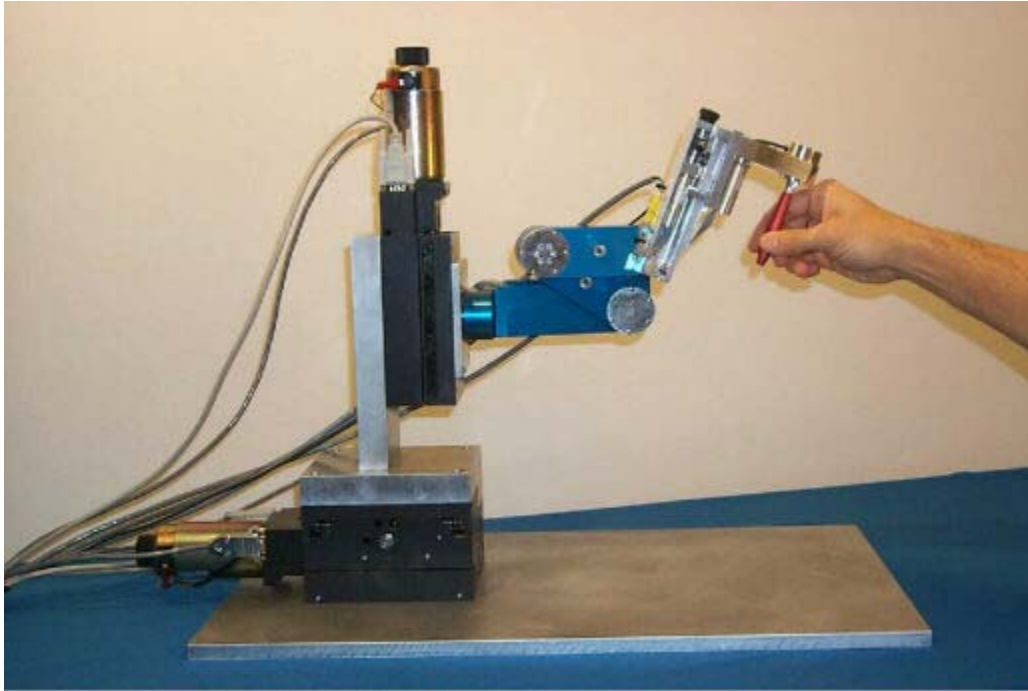
Figure 10. The Steady Hand Micromanipulation system. (From "A Steady-Hand robotic system for microsurgical augmentation", R. H. Taylor, P. Jensen, L Whitcomb, A. Barnes, R. Kumar, D. Stoianovici, P. Gupta, Z. Wang, E. deJuan, and L. Kavoussi. In *International Journal of Robotics Research*, vol. 18, No. 12, December 1999, pp. 1201-1210, Sage Publications.)

Website: http://cisstweb.cs.jhu.edu/web/research/MicrosurgicalAssistant/Mic

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In the Steady-Hand micromanipulation system shown in Figure 10 developed by [Taylor99], there is decoupling between the manipulator orientation and translational motions. The device consists of four modular components:

- XYZ translational assembly gives the ability to move the assembly in any of the coordinate directions.

- Orientation assembly, which consists of a remote center of motion linkage providing two rotations about a remote motion center, located approximately 100mm from the robot. This assembly maintains the remote center point once it is programmed into the robot controller.

- A combined end-of-arm motion and guiding assembly, which provides one additional rotation and translation about the tool axis passing through the remote center of motion.

This subassembly also has a 6-degree of freedom (Fx, Fy, Fz, Tx, Ty, and Tz) force and torque sensor and a tool holder for mounting the micromanipulator tool. The force sensor is along the axis of the tool and it measures the amount of force exerted by the surgeon on the tool and also by the tool on the environment.

- Specialized tools such as microgrippers, scissors, and needle holders are placed in the tool holder. The microgrippers with force sensing capability, for example, can be used to measure the interaction forces.

The modular design facilitates improvements in individual components and their testing without constructing an entirely new system. The system and technologies developed in the Steady-Hand system can also be applied to other areas of surgery such as neurosurgery, ENT, and spine surgery.

Figure 11 shows another example of a robotic system for microsurgical applications. This is the robot assisted microsurgery (RAMS) system with six degrees of freedom [Schenker95]. The robot has a cable driven mechanism and has the capability to position within 25 microns in a workspace volume of 20 cubic centimeters. It can be used for both microsurgical tasks and handling larger surgical tools in a minimally invasive procedure. One of the potential areas of application of this robotic system is in telesurgery where image guided techniques are used. The RAMS has position scaling in the ratio 1:3, larger work angle for surgical access, very low force sensitivity, and mechanically stiff with precision tracking at low speeds and higher payloads. Due to a cable driven system, the robot has negligible friction and very low backlash.
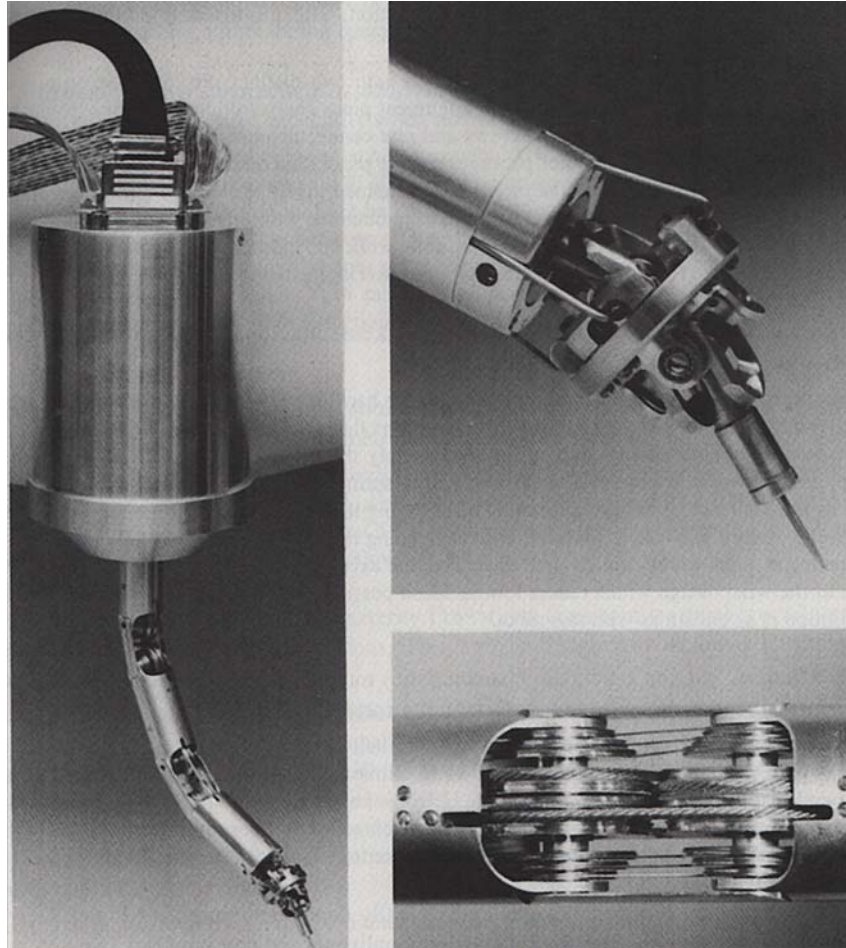
Figure 11. The Robot Assisted Microsurgery (RAMS) manipulator. On the left is the six degree of freedom cable driven robot arm. On the top right is the wrist with three degrees of freedom and on the bottom right is the cable driven mechanism. (From "A new robot for high dexterity microsurgery", P. S. Schenker, H. Das and T. R. Ohm. In *Computer Vision, Virtual Reality and Robotics in Medicine*, Editor: Nicholas Ayache, pages 115-122, 1995, Springer Verlag.) **Do not reprint this figure without obtaining the appropriate permission.**

There has been significant amount of work done in the area of robot-assisted surgery where telerobotic principles have been applied. In general, telesurgical systems attempt to regain the tactile and kinesthetic information that is lost when the surgeon does not directly manipulate the instruments. Minimally invasive surgical procedures pose additional limitations in terms of workspace for manipulation and in giving the "feel" of the operative site. Some of the main issues in the design of a telesurgical system are the incorporation of force-feedback since the surgeon looses the feel of the operative site that is so critical for inspection and manipulation of

tissues and blood vessels. The incorporation of force-feedback and their benefits have been studied in other areas of teleoperation. One of the most important issues in telesurgical systems is the right balance between fidelity and stability of the system Time delay is also a critical issue in most teleoperation tasks, however if the procedure is performed in the same operating room where the surgeon is present, these delays are insignificant to affect the performance of the system.
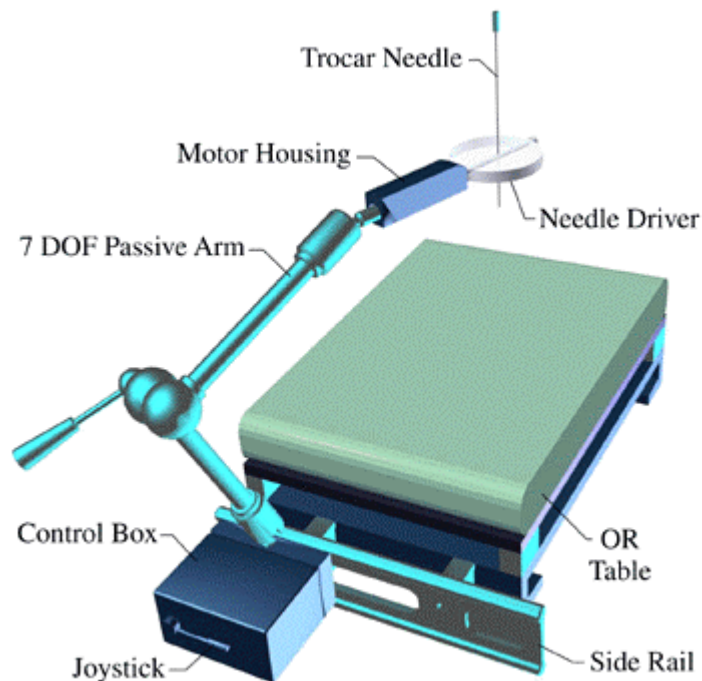
5 PERCUTANEOUS PROCEDURES

Figure 12. The PAKY device. (From "A Novel Mechanical Transmission Applied to Percutaneous Renal Access", D. Stoianovici, J. A. Cadeddu, R. D. Demaree, S. A. Basile, R. H. Taylor, L. L. Whitcomb, L. R. Kavoussi. In *Proceedings of the ASME Dynamic Systems and Control Division*, DSC-Vol.61, pp. 401-406, 1997.)

Website: http://prostate.urol.jhu.edu/research1/urobotics/projects/paky/

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There are several advantages of percutaneous (through the skin) needle access procedures. Some of the advantages are reduced invasiveness of the procedure, shorter recovery time, and morbidity. These procedures are inherently difficult since the surgeon does not have three-

dimensional information of the operative site by an imaging device. To accomplish this task several robotic systems have been proposed, however, the cost of these systems makes them prohibitive for regular use. The PAKY (Percutaneous Access of the KidneY) device developed by [Stoianovici97] is a simple robotic system optimized for percutaneous procedures. This system is shown in Figure 12. The system utilizes the radiological needle alignment procedure, improves accuracy compared to a manual placement procedure and enables lateral fluoroscopic monitoring of the needle without the need for a vision or imaging system during the procedure. This reduces the overall cost of the system.

In a typical manual renal access procedure, the urologist positions the C-arm over the site and aligns the needle entry point and the needle target so that they are superimposed in the image. This defines the needle trajectory and the information is memorized by the C-arm. Next, the urologist holds the needle in the desired position and orientation along the desired trajectory line. The surgeon then inserts the needle manually into the patient, while simultaneously viewing the superimposed C-arm image to ensure the correct trajectory. Since there is no lateral image information available through the C-arm, which is monitoring the axial direction, the urologist has no knowledge of the depth of penetration. The surgeon relies on experience and trial and error to ascertain the correct depth of travel. The PAKY system developed above can be locked along the desired axis of needle insertion. The C-arm can then be realigned to obtain a lateral view for the surgeon.

The PAKY device employs a passive six degree of freedom manipulator comprising of three revolute joints and one spherical joint. The joints do not have motors or position encoders. The joints can be locked into any desired position by vacuum operated brakes. The device is mounted on a rigid side rail since the needle has to maintain the trajectory under the insertion force. The insertion mechanism is on the end of the device as shown in Figure 12. The insertion mechanism is made of plastic and is disposable. A novel feature of the insertion device is that it grasps the barrel of the needle and not the needle head thereby reducing the unsupported length of the needle and also flexure of the needle due to the insertion force.

6 SAFETY

Finally, safety has primarily been one of the most important factors in the acceptability of a robotic device in the surgical workplace. Over the years, there has been significant development of safety systems, which have led to the acceptability of the robot in the operating room. A detailed account of the issues involved with safety in robotic systems is presented in [Davies96b]. Currently, redundant internal and/or external sensors are used in some systems as a means of verifying the executed trajectory by the robot. It is equally important to address the issue of unexpected breakdown of the robot control algorithm and the corresponding high velocities generated at the robot tip. One possible way to increase the safety in such systems is to have an independent force monitoring at the robot end-effector through a separate computer. Other approaches for increasing the safety of the robotic system include   high   reduction ratios   in   transmissions   used   by [Lavallee92] for stereotactic neurosurgery.   Here slow movements and irreversibility employed in various phases of the surgical task gives the operator sufficient time to push the power-off button and reinitialize the   system.   Similarly, in the system developed by [Taylor89] for cementless total hip replacement surgery, the safety system continuously monitors the cutter force and prevents excessive forces from being applied to the cutting site. In summary, the safety systems for each robot are unique to the task specification and the design of the robotic system.

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Assignment for the "Medical Robotics" module

Prof. Jaydev P. Desai

1. Discuss the various imaging techniques for image-guided surgery. Explain the differences between the various techniques.

2. Discuss the advantages of minimally invasive surgery.

3. Discuss one surgical procedure that could use a robotic device to improve the performance in surgery. You can also search on the Internet for various surgical procedures that use robotic technologies and suggest improvements to the existing design for one robotic system of your choice.

4. Discuss the main challenges in neurosurgery and cardiac surgery for minimally invasive procedures.