# CHAPTER 5

# Surgical Robotics

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**Abstract -** The recent introduction of surgical robotics into the operating room offers a significant breakthrough in the way surgery is conducted. It combines technological and clinical breakthroughs in developing new robotic systems and surgical techniques to improve the quality and outcome of surgery. These breakthroughs are based on more than a decade of innovation in the field of robotics in both academia and industry. The scope of this chapter covers the fundamental concepts and approaches utilized in surgical robotics. The surgeon – robot interface along with the robot – patient interface are defined and used for classifying the various surgical robotic systems. Topics such as soft tissue biomechanics, teleoperation, haptics, Time delay, indexing, motion compensation and scaling, image guided surgery, and objective assessment of skill are covered. A detailed review of seven FDA approved and commercially available systems is presented in terms of the clinical procedure conducted by each robot along with the associated problems and needs, as well as the system architecture. The chapter is concluded by describing trends and future directions such as reduction of the system size that leads to minimizing the impact on the surrounding tissues and improving the human machine interaction that may lead to semi-autonomous operations. The revolutionary process involved with the introduction of surgical robotics system into the operating room is still in its infancy. It is anticipated that the number of operations conducted with surgical robotics will continue to grow and the field as a whole will have a profound impacts on surgical outcomes and human health.

**Keywords: Surgery, Robotics, Surgical Robotics, Telesurgery, Telemedicine, Teleoperation, computer aided surgery, Image guided surgery**

## 1. Scope

The scope of this chapter covers the fundamental concepts and approaches utilized in surgical robotics. It is acknowledged that the majority of the commercially available surgical robotic systems are based on scientific foundations and innovations that emerged out of the research community, and many references and pointers are provided to previous publications of these academic efforts. In this chapter, however, the detailed discussions are limted to FDA- and CE-approved surgical robotic systems. The

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reader may refer to additional previously published reviews [1-17]. Recent attempt to define the state of the art was complied in book entitled: Surgical Robotics – Systems Applications and Visions [54]

## 2. Background and Leading Concepts

Surgery may be performed primarily through three main modalities (Figure 1): (a) a surgical procedure in which the surgeon interacts with the tissue directly with his/her fingers as well as through manipulation of surgical tools using an open or minimally invasive approach; (b) a surgical procedure in which the interaction with the tissue is mediated by a surgical robotic system in conjunction with cameras and imaging modalities that provide visual information prior (pre-operative) and during (intra-operative) the operation; and (c) a surgical procedure conducted in a simulation environment in which the operational medium can be either real or simulated tissue. These three modalities have a common human-machine interface in which information is shared between the surgeon and the operation modality. This information-rich layer may be analyzed in order to monitor the surgical process at high levels and to assess the surgeon's operational skills.

The recent introduction of surgical robotics into the operating room offers a significant breakthrough in the way surgery is conducted. It combines technological and clinical breakthroughs in developing new robotic systems and surgical techniques to improve the quality and outcome of surgery. These breakthroughs are based on more than a decade of innovation in the field of robotics in both academia and industry. The promise of surgical robotics is to deliver high levels of dexterity and vision to anatomical structures that cannot be approached by the surgeon's fingers and viewed directly by the surgeon's eyes, while simultaneously minimizing the impact and trauma to the tissue surrounding the surgical site. Making this technology available to surgeons has led to the development of new surgical techniques that would otherwise be impossible. The surgical robot and the various imaging modalities act as mediators between the surgeon's hands and eyes and the surgical site, respectively; however, these two elements are part of a larger information system that will continue to evolve and affect every aspect of surgery and healthcare in general. It is likely that the clinical knowledge accumulated through the use of these new systems, and an understanding of their potential capabilities, will lead to the development of new and more capable surgical robotic systems in the future.

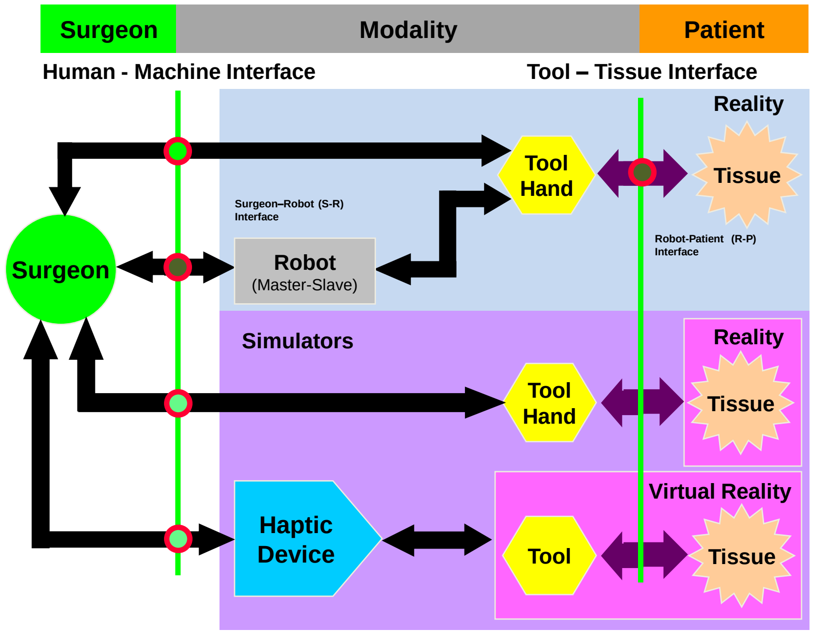


***Figure 1:*** *Modalities and Interfaces of Surgical Procedures*

## 2.1 Human-Machine Interfaces: System Approach

Two human-machine interfaces are established with the introduction of a surgical robotic system: the surgeon-robot interface (S-R) and the patient-robot interface (R-P). Each has a unique set of requirements that dictates its design capabilities and functions. These two interfaces may be used to classify the various surgical robotic systems as depicted in Figure 2.

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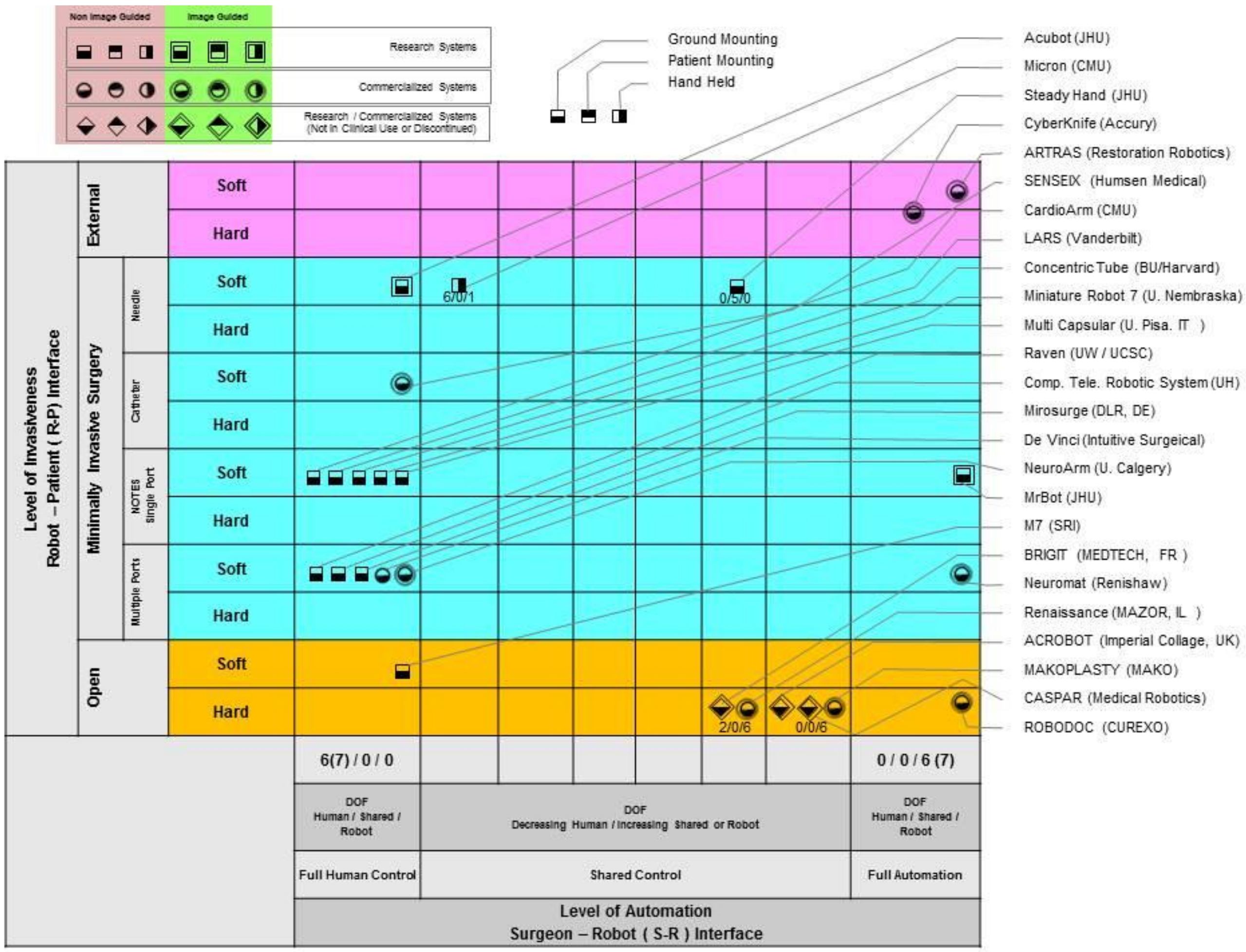


**Figure 2:** Classification of surgical robotic systems based on a Surgeon-Robot (S-R) interface (horizontal axis) defining the level of automation and a Robot-Patient (R-P) interface dictating the level of invasiveness.

### 2.1.1 Surgeon-Robot (S-R) Interface: System Architecture

The S-R interface is defined by a wide spectrum of control levels provided to the surgeon over the surgical robotic system (Figure 1). Assuming a certain level of control required to complete a task, this control level can be distributed between the human operator and the robotic system at different ratios. The distribution of the control level between the surgeon and the robotic system defines the level of automation allocated for the task. Figure 3 depicts how the level of automation affects time delay, the need for imaging modality, accuracy, and the approach to hard and soft tissues.

The level of automation is bounded by two extreme scenarios. The right hand side in Figures 2 and 3 (horizontal axis) describes a scenario in which the surgical robotic system is fully autonomous. In this mode of operation, the surgical robot executes a predefined trajectory, maintaining full control over the execution of a plan that was predefined by the surgeon. This process requires a careful registration that fixes the organ in a specific position and orientation in space while registering it with respect to the base of the surgical robotic system. The surgeon initiates the execution of the process and monitors its progress. Other than to terminate the procedure in case of emergency, the surgeon will not be able to change the preoperative planning during its execution. This surgical approach and control level is suitable for hard tissues such as bone that can be scanned by various imaging modalities, positioned, oriented and registered in space with respect to the surgical robotic system or to soft tissue such as the brain, which is mechanically constrained by the skull. This mode of operation is commonly used in industry assembly lines, in which robots are incorporated to perform preplanned tasks. It is therefore natural that Robodoc, one of the first robotic systems introduced to surgery, followed the same approach. As such, Robodoc was used to mill the femur bone in preparation for a stem implant in a total hip arthroplasty (i.e. total hip joint replacement) [18-21].

The left hand side of Figures 2 and 3 (horizontal axis) describes a scenario in which any movement of the surgical robotic system is in direct response to a real time position command input provided by the surgeon. The system architecture used to enable this approach is *teleoperation*, utilizing a master/slave configuration. The master is defined as the surgical console and the salve serves as the surgical robot itself interacting with the patient's tissue through the surgical tools. Teleoperation in a master/slave configuration is another technology that emerged in the fifties as a safe method for handling radioactive materials. This approach was introduced to surgical robotics via research systems such as SRI's M7 [22], MIT's Black Falcon [23], and commercial systems including Zeus® by Computer Motion and Intuitive Surgical's da Vinci® [24]. These systems were primarily designed to operate on soft tissues. Due to their mechanical properties, soft tissue, unlike hard tissue, changes its geometry during surgical procedures (see section 2.3). As a result, pre-operative scanning and preplanning along with autonomous operation is not the preferred mode of operation. Instead, the teleoperation architecture brings the surgeon back into the surgical scene to control and execute every motion of the surgical robot.

The level of automation incorporated into a robotic surgical procedure varies widely, and is defined by the how the surgical task is shared between the robotic system and the surgeon. At one end of the spectrum, the surgical procedure may be broken down into sub tasks and selected subtasks can be automated. At the other end of the spectrum, an effort is made to develop a control strategy in which both the surgeon and the robot hold a set of surgical tools simultaneously and collaborate during the surgical procedure.

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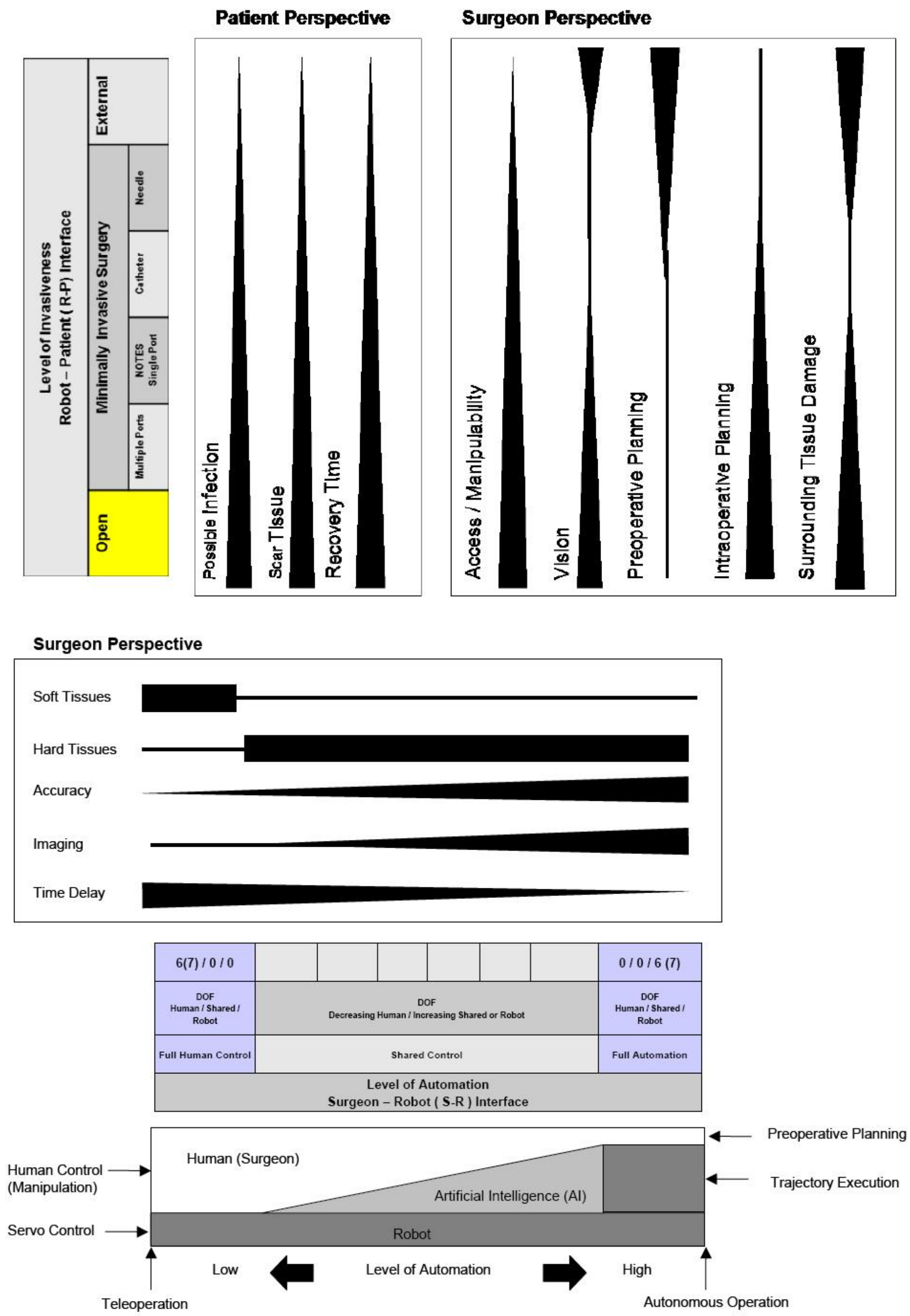


**Figure 3**: Schematic representation of the surgeon-robot-patient domains: (top) level of invasiveness in the Robot-Patient (R-P) interface; (bottom) level of automation in the Surgeon-Robot (S-R) interface, and their impact on various operational parameters from the patient and surgeon perspectives.

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### 2.1.2 Robot Patient (R-P) Interface: Surgical Approach and Levels of Invasiveness

The robot-patient (R-P) interface determines the level of invasiveness (vertical axis in Figures 2 and 3). The level of invasiveness spectrum spans across a range of surgical approaches including (1) the invasive open-procedure approach, which requires a large incision to expose the targeted anatomy, (2) variations of minimally invasive surgical approaches with a gradual reduction of invasiveness, such as multiple tools inserted through ports, NOTES (defined below), catheters and needles and (3) a noninvasive approach in which energy (radiation) is provided by an external source to a localized space to provide a localized therapy. All of these surgical approaches may to some extent be applied to both soft and hard tissues. As the level of invasiveness decreases, the level of manipulation also decreases and, as a result, the surgeon has fewer degrees of freedom to mechanically manipulate the tissues. Figure 3 shows how other factors are affected by a reduction in the level of invasiveness from the patient's perspective: factors such as potential infection, scar tissue, and recovery time; and from the surgeon's perspective: factors related to manipulability, vision, pre- and intra-operative planning, and tissue damage to the surrounding tissues.

An open procedure, in which a large incision is made to fully expose the anatomical structure(s), is still the common practice for many surgical procedures. A minimally invasive surgery (MIS), also known as minimal access surgery (MAS), aims to minimize the impact on the tissue surrounding the surgical site. In this approach, holes 5 mm or smaller are made in the skin and three or more ports—including one camera and two endoscopic tools are inserted. Usually additional holes are created to accommodate additional tools used for tissue retraction, and to provide alternate approaches to the surgical site. The cavity under the skin (typically in the abdomen) is inflated with $CO_2$ in order to create a space for the surgeon to interact with the tissue under the skin. If the incision diameters are reduced to 2 mm, the skin will tend to seal by itself without stitches, and the scar tissue will be kept to a minimum. During this type of procedure, an endoscopic camera provides a view of the internal anatomy, which is projected onto a screen. It was the MIS approach that enabled the important and relatively widespread introduction of robotic systems into the operating room.

MIS as it is practiced today represents an important first step in the effort to deliver effective tools to the surgical site, while minimizing trauma to the surrounding tissue. There are three evolving approaches that further minimize the impact on surrounding tissues: natural orifice transluminal endoscopic surgery (NOTES), needles, and catheters.

***NOTES***- NOTES is a relatively new approach to surgery, still in an experimental phase, without fully developed surgical tools and robotic systems. As part of this surgical approach, an assembly of tools and one or more endoscopic camera(s) are incorporated into a flexible snake-like tool that is inserted into the body through natural orifices (e.g. the mouth, urethra, anus, eye socket or nose) and provides access to internal organs while avoiding an external incision and potentially scar tissue.

***Needles*** -Needles are commonly inserted into the body either to inject medicine, to deposit radioactive seeds or to collect a biopsy. Steering a long and narrow needle through a non-homogeneous tissue is a challenging task, previously explored via an image-guided robotic device [26]. Based on principles of soft tissue biomechanics and structural beam theory, it is possible to steer the tip of a needle by manipulating its base [27]. Spinning the needle may provide another mode of stabilizing the needle, thus improving its steering capability [28].

***Catheters*** - Catheters are typically introduced into the body on a guide wire through the vascular system. Catheters are capable of carrying a variety of end effectors such as balloons for mechanically widening narrowed or obstructed blood vessels. They may also carry stents that are deposited as part of an angioplasty procedure. As another example, catheters with steerable tips are used to treat atrial fibrillation, the most common cardiac arrhythmia. Tissue ablation is conducted by the settable catheter-controlled teleoperation system so that the surgeon is not exposed to the X-ray radiation associated with fluoroscopy used for imaging [29-31].

***Radiosurgery*** - Radiosurgery is a medical procedure that allows non-invasive treatment of tumors. As part of this surgical technique, ionizing radiation is used to ablate the tumor via radiation generated by an external source. The CyberKnife reviewed in this chapter, is a commercial system that utilizes this approach [32].

### 2.3 Tissue Biomechanics

Tissues are the target medium of surgery, and their biomechanical properties play an important role in both the preoperative planning and the execution of the surgical procedure itself. Tissues may be classified into two categories (a) hard tissue, which is primarily bone; and (b) soft tissue, such as tendons, muscles, nerves and blood vessels, which accounts for all of the remaining tissue in the human body. During surgery, hard tissue does not experience large deformations, unlike soft tissue, which undergoes large deformations in response to internal and external loads. Soft tissues are non-homogeneous, non-isotropic, non-linear, and viscoelastic materials – properties that make them difficult to model and that make their response to loads or displacements difficult to predictable. Furthermore, soft tissues are attached to each other in ways that generate internal stresses that are again difficult to assess or predict. Once the tissue is cut, or the connective tissues are dissected, the internal stresses are removed and the soft tissue may change its geometry significantly.

There are several aspects of experimental tissue biomechanics methodologies that are unique to surgery and to surgical robotic applications in particular. First, during surgery, tissues are exposed to loads resulting from tool-tissue interactions. These interactions generate loads that are significantly different from normal physiological loads. For example, internal organs are subjected to localized compression, tension and shear loads applied by endoscopic tools, loads that they would never experience otherwise, under normal circumstances. Figure 4 shows stress-strain relationships of various internal organs. These data were acquired by utilizing an endoscopic tool that applied loads similar to those applied during surgery [33]. Second, biomechanical properties change significantly, depending on the conditions under which they were collected: in vivo, in vitro or ex-corpus. To the extent possible, in vivo data is preferred, since they can provide the most accurate tissue characterization. Several experimental robotic devices with in vivo data collection capabilities have been developed. Among these are the Motorized Endoscopic Grasper (MEG) [34], ROSA and TeMPeST I-D [35,36]. Third, *preconditioning* is a process used for testing soft tissue biomechanics, in which the tissue is subjected to multiple loading cycles prior to the data acquisition cycle. This process "stabilizes" the mechanical properties of the tissue, and is known as "tissue conditioning." Despite positive effects on the consistency of the data collected following tissue conditioning, this approach cannot be applied in the context of surgery. The surgeon who palpates the tissue may experience different stress-strain relationships for each palpitation, and these cycle- and time-dependent changes must be accounted for during data collection in order to fully characterize the tissue. Figure 4 a, b shows the difference in the stress-strain relationship between the first and the fifth palpations. Fourth is the issue of tissue damage generated as a result of loads or energy transmission by the surgical tools. *Dissection* is a form of controlled tissue damage that results from the application of mechanical shear stresses or the application of electrical or other energy sources to generate a cut in the tissue while controlling potential bleeding. In this case, the damage is intentional, a derivative of the surgical requirements. However, unintentional tissue damage may also occur as a result of the mechanical interaction between the tissue and the tool during tissue manipulation or retraction. This unintentional tissue damage may have short-term effects that lead to recoverable tissue function with or without scar tissue. Or it may result in uncontrolled bleeding that must be resolved through the surgical procedure itself. In the worst case, tissue damage may have long-term effects that lead to necrosis and tissue death. The extent of tissue damage caused during surgery as a result of loads applied by the surgical tools depends in part on the distribution of stress, which itself is based on the design of the contact surfaces, the level of the applied loads, and the time duration that these loads are applied to the tissue. Sensor-based surgical tools—along with a knowledge of biomechanics of tissue damage—can be used to monitor these parameters and mitigate tissue damage. Figure 4 c,d shows the correlation between histological analysis of tissue damage (identified by marking dead cells) and the stress distributions predicted by a finite element analysis.

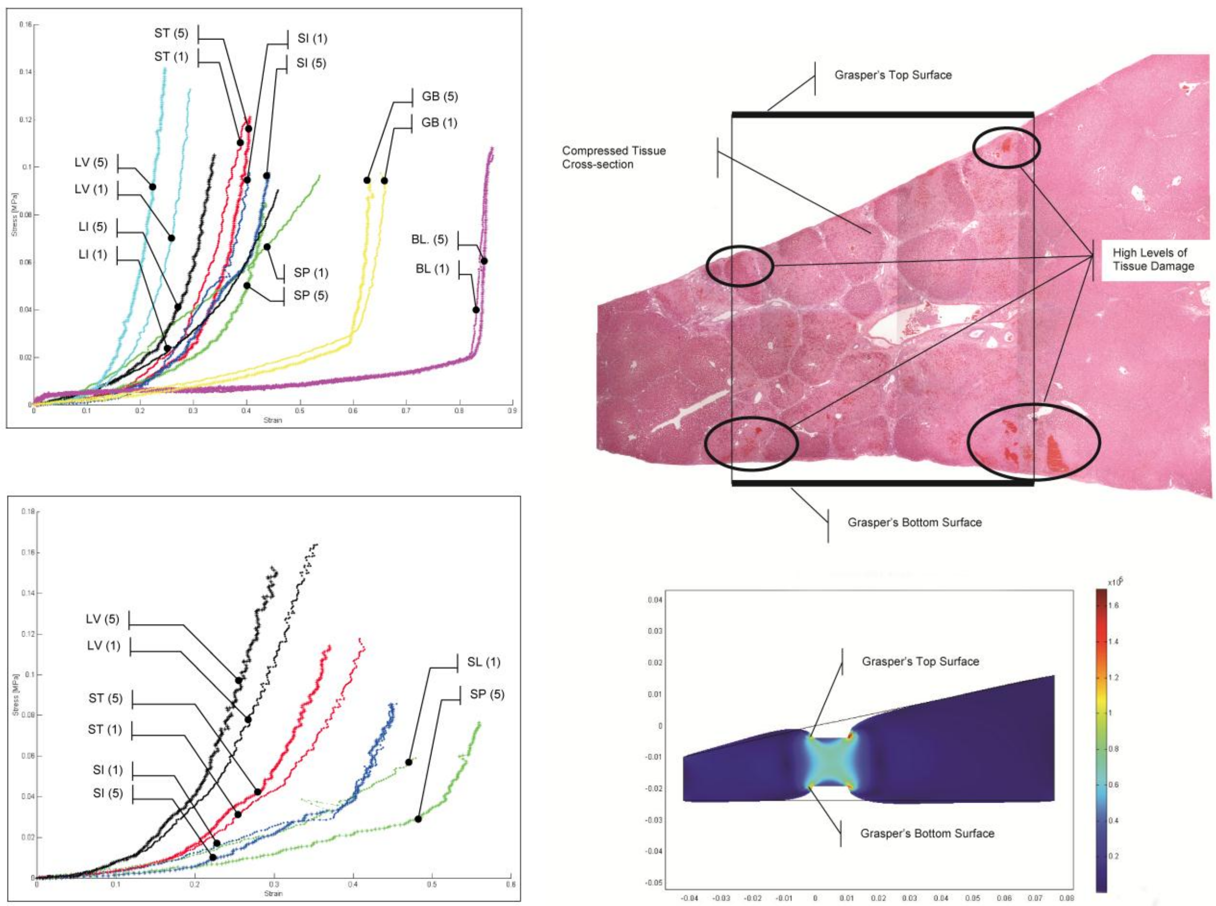


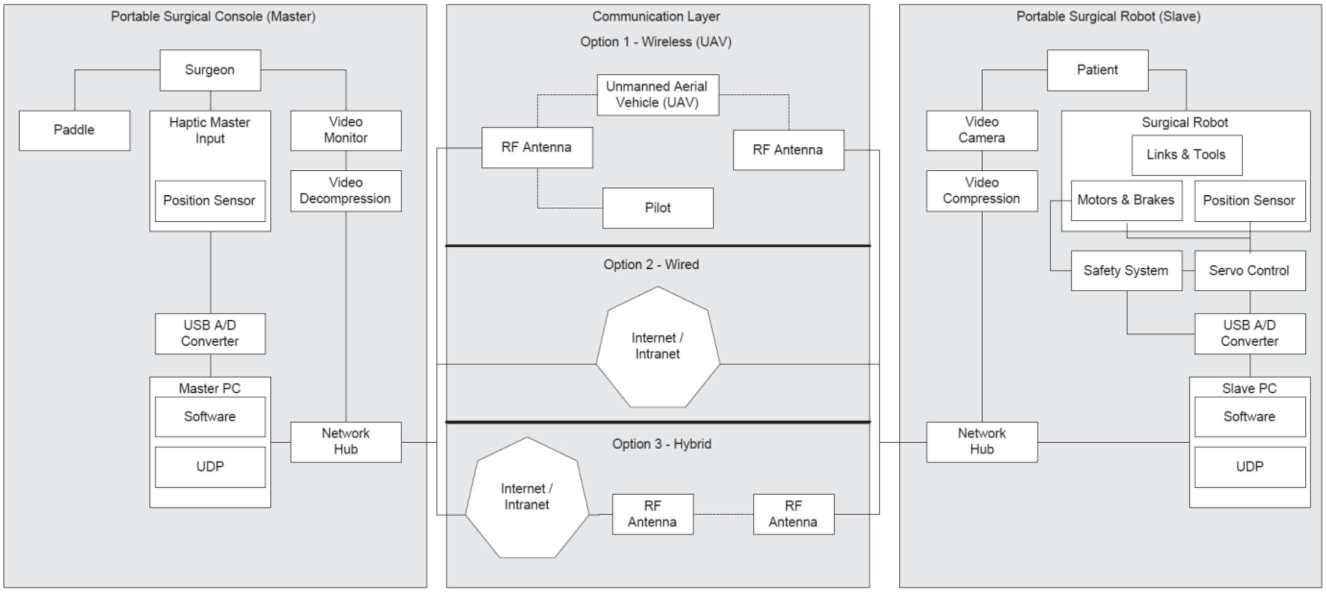

***Figure 4:*** *Biomechanics properties of soft tissue (swine internal organs) and tissue damage. Examples of stress-strain curves for all organs under study, as measured with the motorized endoscopic grasper at 5.4 mm/s loading velocity. First and fifth cycles show (a) in vivo and (b) ex corpus (organs legends: BL-bladder, GB-gallbladder, LI-large intestine, LV-liver, SI-small intestine, SP-spleen, and ST-stomach). The loading cycle number (1 or 5) is defined in the brackets. Liver response to compression loads of 40% strain. (c) A cross-section of a liver generated as an assembly of multiple tissue slices using standard pathological techniques following an application of compression strain by a Babcock grasper attached to the MEG. Vascular tissue damage is indicated by dark red areas across the tissue slices. The horizontal arrow indicates the approximate span of the grasper jaws. (d) Von Mises stress distribution and the displaced cross section of liver as predicted by a linear FEM. The geometrical dimensions are expressed in meters and stresses are expressed in Pascal [33,34].*

## 2.4 Teleoperation

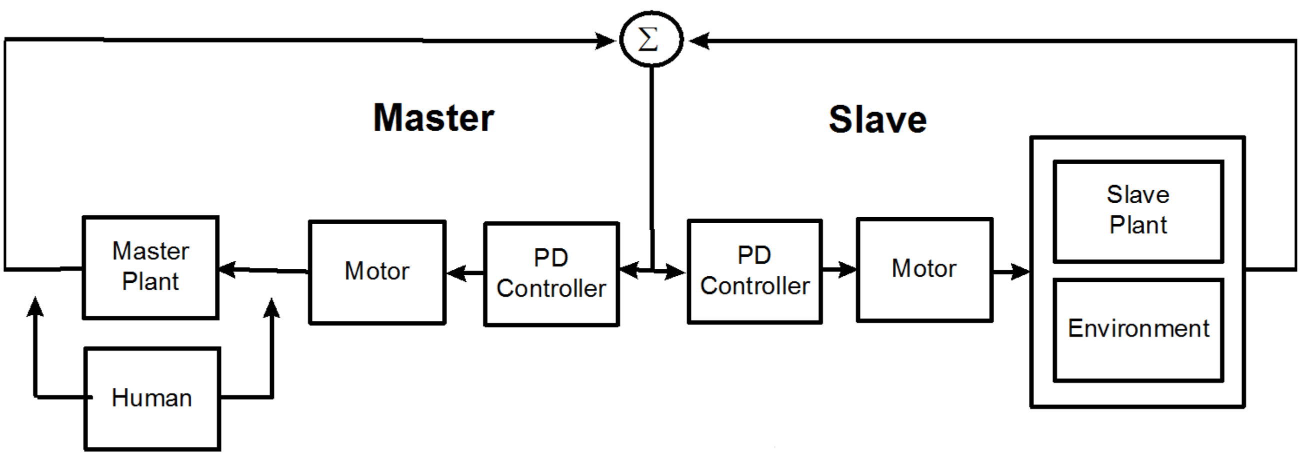
Surgical robotic systems that rely heavily on the surgeon's control of the system are based on a classical master/slave teleoperation architecture. This architecture consists of two modules: the surgeon console (master) and the robot (slave). The surgeon console includes a set of input devices for the hands and feet, a display system, and in some cases voice command components. The device that interacts with the surgeon's hands and fingers acts as an input device that generates position commands to the surgical robot. It also serves as a haptic device which, along with its embedded actuators, can render forces and torques that are reflected back to the surgeon, providing information about the interacting forces between the surgical robot tool tip and the tissues.

The robotic system interacting with the patient (slave) includes a minimum of three robotic arms: two are used to manipulate the surgical instruments and a third is used to control the endoscopic camera. Additional arms may include other surgical tools for operation or tissue retraction. The surgeon controls the position of the robotic arms by manipulating the two input devices at the console. The endoscopic camera arm is controlled by one of the input devices or by voice commands from the surgeon, and the view of the internal anatomy acquired by the endoscopic camera is transmitted back to the surgeon console. If two endoscopic cameras are embedded into the endoscope, a three-dimensional view of the anatomy can be displayed to the surgeon.

A surgical robotic system using a teleoperation architecture enables two modes of operation: a bilateral control mode and a unilateral control mode (Figure 5a). In both modes of operation, in the feed-forward flow of information, the surgeon generates position commands to the robot by moving the input devices located at the surgeon's console. The position commands are transferred through a controller to the surgical robotic arms (slave), and the actuators move the arms and the surgical tools to the proper positions. This flow of information is common to both the bilateral and the unilateral control modes. Force feedback is the flow of information that is included in the bilateral control mode and eliminated in the unilateral control mode.




(a)



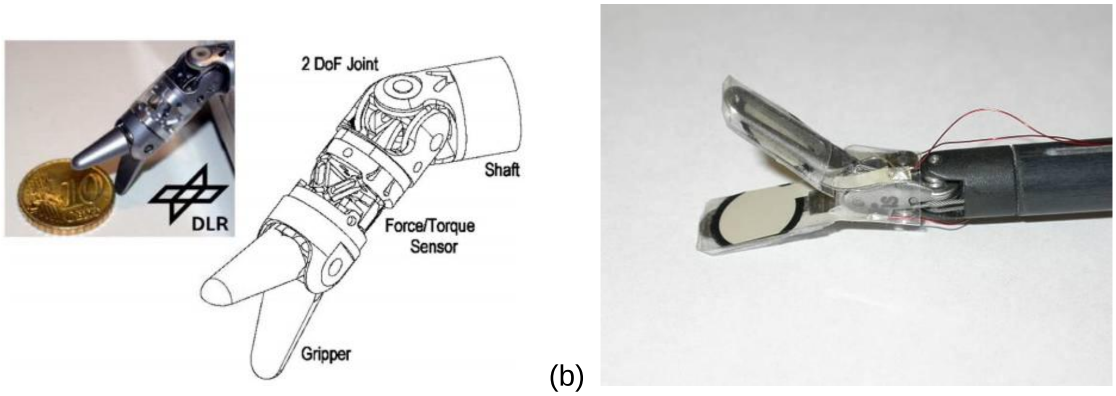

(b)

*Figure 5: A block diagram of a typical bilateral teleoperation system used in surgical robotic systems. (a) A simplified block diagram of the teleoperation scheme. Note that the actuators and controllers on the master console are eliminated if force feedback is not incorporated into the system. (b) A detailed overview of the system architecture including the surgical console (master) and surgical robot (slave) connected through a communication layer with three options. A wired communication (option 2) is the common practice and FDA-approved for clinical use. Other alternative communication layers (options 1 and 3) were studied as part of the experimental evolution research systems [37,38]. The surgeon*

*initiates the movement of the robot by moving the stylus of a haptic master input device. The position of the stylus is sensed by position sensors embedded in the master joints and acquired by the A/D converter that is connected to the Master PC via USB. Using a UDP protocol the position command is transmitted through the network layer to the remote site and received by the slave PC. Using inverse kinematics, the position command is translated into joint command and sent via the D/A to the servo controllers. The servo controllers generate voltage commands to the DC actuators of the surgical robot which in turn move the robot to the commanded position. A video stream of the surgical site is first compressed in the remote site by either software or hardware and then streamed through the network layer to the surgical console. In the surgical console, the video following its decompression is presented to the surgeon on a monitor. A foot paddle controlled by the surgeon allows him or her to engage and disengage the master and the slave. by activating the brakes.*

There are two primary methods of generating source signals for the force feedback in a bilateral master/slave teleoperation architecture, thus allowing the system to reflect haptic sensation to the surgeon as the tool tip interacts with the tissue. The primary method used in surgical telerobotic systems and approved for clinical use, is based on the difference between the position command generated by the surgeon using the input devices at the console (master) and the actual position achieved by the robot. This error is usually scaled by a constant and reflected as a force rendered by the master's actuators. As the difference between the position command and the actual position increases, the force feedback to the operator increases proportionally and vice versa. In spite of the fact that the bilateral mode of operation does not require additional sensors for generating force feedback, the high level of friction caused by non-direct-drive actuators and the high inertia due to large robotic arms may degrade the quality of the force feedback signal using this algorithm. An alternative approach for incorporating force feedback requires the use of force/torque sensors located as close as possible to the end-effector in order to diminish the mechanical and dynamic interferences. Force and torque acquired by the sensors are sent back to the surgical console to be rendered by the haptic device and delivered to the surgeon's hands.

Given the harsh environments associated with tool sterilization (high temperature steam) and operation, attaching force/torque sensor wires and connectors to the tool and protecting them from this environment remains a technological challenge, but research efforts have shown promising results in this area (Figure 6) [39,40]. Alternative sterilization methods such as gas sterilization may relax these requirements. For MIS tools in particular, placing force sensors at the distal end of the tool is further limited by the 5-10 mm diameter of the port.




(a) (b)

***Figure 6:*** *Force sensor mounted on the proximal end of a surgical tool (a) DLR endoscopic tool instrumented with a six axis force-toque sensor (b) UCLA Tactile sensor mounted on the faces of a robotic endoscopic grasper.*

### 2.4.1Haptics

Haptics (from the Greek word for "touch") in the context of surgery refers to surgeon perception and the technology associated with conveying this perception. Surgeons rely heavily on haptic perception to assess soft tissue. This assessment is conducted in part by palpating the tissue with the fingers in an open surgical procedure. The stiffness of a tissue is either increased or decreased as a result of damage or disease. Variation in stiffness of a specific organ may also help to target a localized tumor. As surgical approaches become less invasive, the surgeon is gradually removed from the surgical site and the interaction with the tissue is facilitated by mediating surgical tools and surgical robotic systems. Surgeons have regained some of the haptic capabilities by visually assessing the deformation of the tissues in response to the interaction with the surgical tools. Although this technique may be useful for soft tissue stiffness assessment, it cannot be used to assess suture tension, given the relatively high stiffness of sutures. As a result, a suture may break during knot tying due to lack of haptic sensation.

Surgical robotic systems have the capability of regaining the haptic sensation through a force feedback control algorithm embedded in the surgeon's console. Experimental results using the hand, a regular MIS grasper, and a robotic device with force feedback for ranking the stiffness of materials with similar stress-strain characteristics as soft tissue of internal organs indicated that the performance with the robotic device was closer to the performance of the human hand in rating material stiffness than to the performance obtained by MIS grasper [41]. Even in the hand-in-glove conditions, the test operators were able to rank the material stiffness correctly in all cases. This fact emphasizes the need for advanced instruments for increasing the haptic sensation beyond the capability of an unaided hand.

### 2.4.2 Time Delay

During actual teleoperation, physical distance and a network separate the patient site from the surgeon sites with time varying delays. When a surgeon makes a gesture using the master device, motion information is sent through the network to the patient site with a network time delay (Tn). The manipulator moves, and the audio/video device observes the motion. Digital a/v is compressed (Tc), sent from the patient site to the surgeon site through the network (Tn), then decompressed (Td) and observed by the surgeon. The surgeon has experienced a total delay of T= 2Tn + Tc +Td, from the time the gesture was made to the time the action was observed.

Lab experiments showed that the completion time of the task as well as the length of the tool tip trajectory significantly increased in correlation to the time delay. For teleoperation with a time delay of 0.25s and 0.5s the task completion time increased by a factor of 1.45 and 2.04, and the length of the tools' trajectory increased by a factor of 1.28 and 1.53. There were no statistical differences in the number of errors or in the completion time and tool-tip path length between experienced surgeons and non-surgeons (Figure 7) [42].

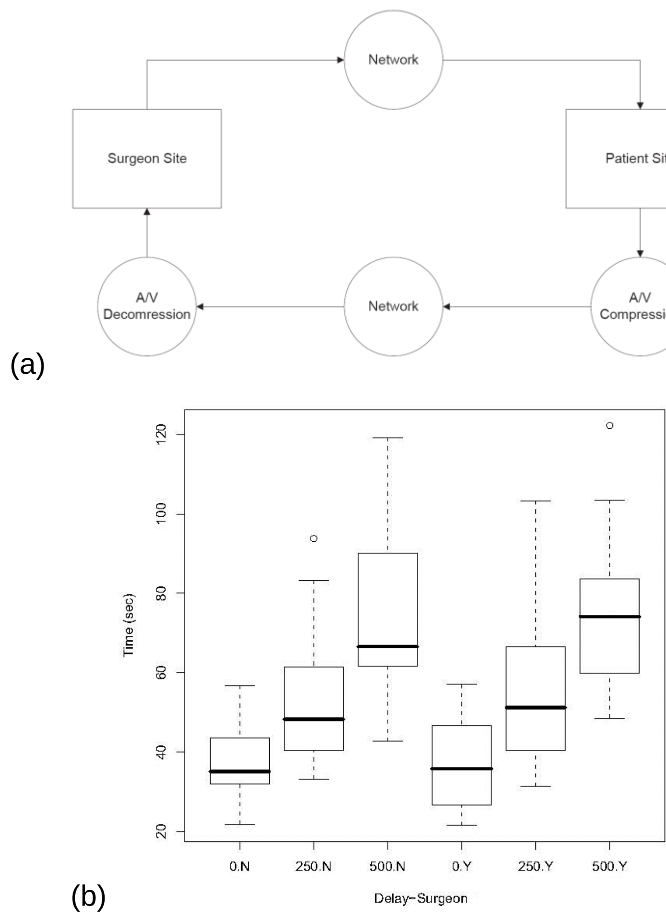



***Figure 7:*** *Time delay and its effects on surgical performance in telesurgery. (a) Schematic block diagram representing all time delay sources. (b) Completion time of an FLS block transfer as a function of time delay (0, 0.25. 0.5 sec) for surgeons (Y) and non-surgeons (N) using the Raven surgical robotics system in a teleportation mode.*

### 2.4.3 Indexing, Motion Compensation and Scaling

***Indexing*** -Indexing is the process whereby the surgeon disengages the master from the slave, repositions the input devices, and reengages the master and slave to continue the operation. Indexing is enabled by brakes mounted on the motors of the robot, which fix the position and orientation of the robot in space while the robot is disengaged from the surgical console. Indexing allows the surgeon to keep the robot’s hands and arms within the optimal workspace and to maximize manipulability and personal comfort. Indexing is limited to positioning only, and not to orientation. As a result, the orientation of both the master and the slave must be locked during position indexing. If locking the orientation is for some reason not possible, for example during a tool change, the master orientation may have to adjust itself to match the orientation of the slave prior to the reengagement.

***Motion Compensation -*** A tremor is an involuntary muscle contraction and relaxation generating movements of one or more body parts that may occur at rest or while the body is in motion. For a surgeon holding a surgical tool, a tremor may affect his or her ability to effectively interact with the tissue. It is particularly critical in microsurgery and ophthalmology, where the accuracy and repeatability required to perform the surgical procedure may exceed human performance capabilities. Surgeons are trained to lock body parts in order to reduce tremors. For example, in open and MIS surgery, surgeons will hold the upper arm close to their body, essentially eliminating movements of the shoulder and upper arm and allowing only elbow, wrist and finger movements. In microsurgery, the palms are usually at rest against a stationary surface so that movements of the entire arm are eliminated, and only hand and finger movements are enabled. Surgical robotics may provide two forms of motion compensation depending on the system architecture.

In a master/slave teleoperation architecture the surgeon controlling the master is physically removed from the surgical tool. Because of this physical separation between the surgeon hand/fingers and the surgical tool, motion compensation is sometimes introduced in the control algorithm to eliminate the tremor. There are two types of architectures in which the surgical tool is held by the robot and the surgeon simultaneously. When the base of the robot is grounded—such as in the Freehand/JHU [26] or the Rio/Mako [43]—the control system may attenuate a specific bandwidth associated with the human tremor. If the entire system is hand-held and the base is not grounded, as in Micro CMU [44], the actuators connected between the base of the tool and the portion held by the hand are actuated in such a way that the tool tip remains stationary, and thus the tremor from the human hand is reduced.

***Scaling -*** In a master/slave teleoperation architecture the movements provided to the system by the surgeon through the master input device can be amplified (*scaled up*) by a scale factor greater than one or attenuated (*scaled down*) by a scale factor smaller than one. In actual surgery scenarios, scaling down is more often utilized than scaling up, since scaling down increases precision (but also increases duration). Scale factors are task-specific.

## 2.5 Image-Guided Surgery

In image-guided surgery, imaging modalities track surgical tools, using images acquired prior to or during the operation in order to guide the intervention. This surgical approach, sometimes called *computer assisted surgery* (CAS), includes the following critical steps:

1) image acquisition, which can be accomplished by a variety of imaging modalities, including X-ray, PET, CT, MRI, ultrasound and tomography
2) image analysis
3) diagnostics
4) preoperative planning with or without surgical simulation
5) the surgical procedure, which includes registration and navigation and
6) post-operative verification

These steps, with some variation, are described in Section 3 for a number of robotic systems that rely on imaging modality to perform surgery. In the context of surgery, the various imaging modalities can be classified into two categories: (1) on-line or real-time imaging systems, which provide immediate visual feedback to the surgeon during the surgery; (e.g. Ultrasound, Fluoroscopy) and (2) off-line imaging systems that require image-acquisition time and/or post-processing time, and therefore cannot be used intra-operatively (e.g. CT). Imaging modalities such as MRI require significant post-processing calculations in order to produce the image; however, this process occurs quickly enough to provide feedback to the surgeon intra-operatively. As a result, several robotic systems were developed with MRI computability with non-magnetic materials that allow the surgeon to conduct the surgery within the MRI bore [45].

### 2.6 Objective Assessment of Skill

Conducting a surgical procedure involves high-level cognitive decision making in conjunction with low-level manual control of the surgical tools. Basic and advanced surgical training must produce surgeons who can be trusted to conduct unsupervised surgical intervention in a clinical setting.

Methods for evaluating surgical proficiency remain mostly subjective. While surgical simulators and surgical robotic systems can capture the physical parameters associated with surgery, capturing the cognitive parameters is more challenging. Data on physical parameters such as surgical tool type, tool kinematics—which includes position and orientation of the tools in space, as well as their forces and torques—and the camera view of the surgical site [46-48] can serve multiple purposes: it can facilitate objective assessments of technical skills, can be used for mentoring during and after the operation, and can help form a clinical record of the surgical procedure.

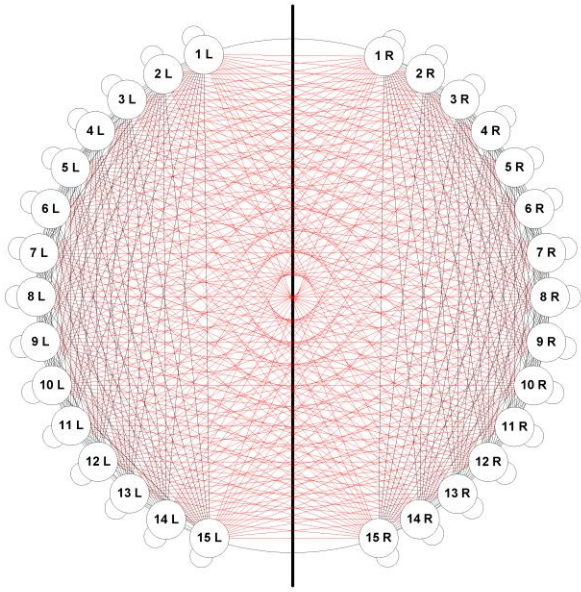
On the other hand, capturing the high-level decision-making processes that occur during surgery is difficult. One technique is to simply ask the surgeon to verbalize the mental decision-making processes as they occur. Given the difficulty in capturing the many cognitive processes associated with surgery, there are no quantitative data that documents how the surgeon's mental load is distributed between high-level decision-making and low-level tool manipulation, both of which are needed to complete the surgery. It is assumed that the decision-making load is higher than the motor-skill load for a proficient surgeon, and that the attention required for these two tasks may vary based on the level of training.

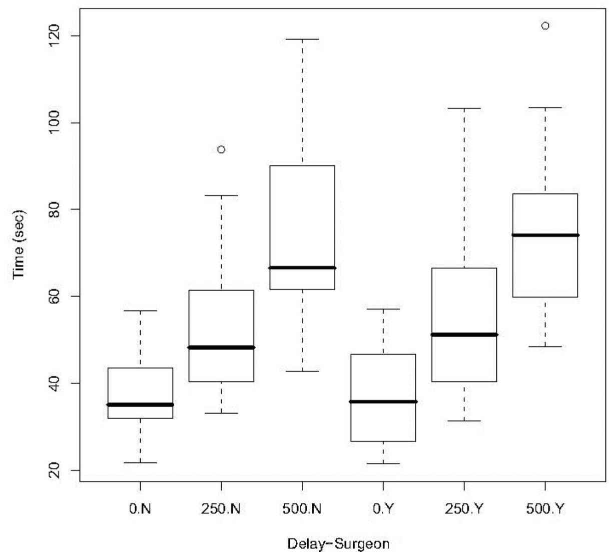
The decision-making and motor skills of a surgeon are assessed through his or her training period as well as during the professional certification exam. This assessment is fundamentally subjective, and as the medical profession faces greater demands for accountability and patient safety, there is a critical need for the development of consistent and reliable methods for objective evaluation of clinician performance during procedures. The methodology for assessing surgical skill as a subset of surgical ability is gradually shifting from subjective scoring by an expert—which may constitute a biased opinion based on vague criteria—toward a more objective, quantitative analysis.

Developing an objective analysis of surgical skill based on task deconstruction or decomposition is an essential component of a rigorous objective skills-assessment methodology. A broader understanding of procedures is achieved by exposing and analyzing the internal hierarchy of tasks while providing objective means for quantifying training and skills acquisition [49, 50]. There are three primary approaches or models for task decomposition and its associated skills assessment and training applications: (1) black box (2) gray box and (3) white box. In the *black box approach*, the models and their states are abstract and do not correlate with specific events in reality; for example, surgical suturing is represented by a single model with abstract states and model architecture. In a *white box model*, every state of the model represents a specific and well-defined event in reality; for example, each tool tissue interaction (grasping pushing etc.) is represented by a unique state with a specific signature of forces, torques and velocities [49]. An intermediate approach decomposes a step of an operation into more fundamental tasks, and each task is represented by a single black box model. The level of granularity in this so called *gray box approach* is higher than the black box approach but lower than the white box approach.

A useful analogy that may explain the white box approach for decomposing the surgical task is the human spoken language. Based on this analogy, the basic states, which are made up of tool/tissue interactions, are equivalent to “words” of the minimally invasive surgery (MIS) “language,” and the states form the MIS “dictionary” or set of all available words. In the same way that a single word can be pronounced differently by different people, the same tool/tissue or tool/object interaction can be performed differently by different surgeons. Differences in force/torques (F/T) magnitudes account for this different “pronunciation,” yet different pronunciations of a “word” have the same meaning, or outcome, as in the realm of surgery.

A cluster analysis was used to identify the typical F/T and velocities associated with each tool/tissue and tool/object interaction in a surgery’s “dictionary” or, using the language analogy, to characterize different pronunciations of a “word.” Utilizing the “dictionary” of surgery, the Markov model (MM) was then used to define the process of each task or step of the surgical procedure, thus “dictating chapters” of the surgical “story.”




(a) (b)

Figure 8: Objective assessment of skill in MIS. (a) A multi states Markov model representing a generic MIS procedure conducted with two endoscopic tools. (b) The learning curve of minimally invasive suturing. Normalized statistical distances between surgical residences, R. (R1 first year, R5 fifth year) and experienced surgeons, E. The statistical distance between surgeons in training compared to experienced surgeons decreases as the surgeons progress through their five years of training (for details see [49]).

## 3. Commercial Systems

### 3.1 ROBODOC (CUREXO Technology Corporation)

#### Clinical Procedure – Problem and Needs

Hip joint replacement is a relatively common orthopedic procedure normally conducted to relieve chronic arthritis pain, or in cases where the joint has been fractured or otherwise severely damaged as a result of trauma. In a total hip replacement procedure, or “total hip arthroplasty” (THA), both the head of the femur and the acetabulum are replaced. A hemiarthroplasty replaces only half of the anatomical joint, typically the femur head. In both cases, the anatomical joint is replaced by a metal or ceramic prosthetic implant. The femoral component consists of a stem and head and is inserted into the femur. The acetabular cup is implanted into the hip socket of the pelvis. During the procedure, cartilage and bone are removed, and the bone is reshaped to accepted the prosthesis. The acetabular cup is screwed into the pelvis, and the stem of the femoral component is either cemented or, more recently, pressed fit (cementless) into the femur.

### System Architecture

The ROBODOC® system by CUREXO Technology Corporation includes two major sub systems: ORTHODOC® Preoperative Planning Workstation and ROBODOC® Surgical Assistant. ORTHODOC converts the CT scan of the patient's joint into a three-dimensional bone image, which can be manipulated by the surgeon to view bone and joint characteristics, thus allowing for optimal prosthetic selection and accurate alignment. Using ORTHODOC's digital library of prosthetic images, the surgeon selects the best size, type (anatomical or straight stem) and brand of femoral stem prosthesis. This virtual surgery creates a precise pre-operative plan customized for each patient. The pre-operative plan is then transferred to ROBODOC, which executes the plan by milling the bone with sub-millimeter accuracy, thus preparing the bone to receive the prosthetic implant with a precise fit. ROBODOC is also capable of removing bone cement for revision surgeries [18-21].


*Figure 9: The ROBODOC system by CUREXO*

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### 3.2 daVinci (Intuitive Surgical)

### Clinical Procedure – Problem and Needs

In a classical minimally invasive (MIS) surgery, surgical tools are inserted through ports, along with an endoscopic camera, into the human body. A cavity in the human body is inflated with $CO_2$, and the operation is conducted under the patient's skin. This revolutionary surgical technique minimizes the trauma and maximizes the recovery of the patient. However, it requires tools that reduce the quality and number of degrees of freedom (DOF) for tissue manipulation: from seven DOF down to five DOF. The tools also reduce haptic sensation, since long endoscopic instruments do not convey sensation in the same way that fingers do. The technique also limits the view of the surgical site, since endoscopic cameras display the site in two dimensions, whereas the human eye can view the site in three dimensions. Despite these drawbacks and difficulties, MIS is becoming common practice for an ever increasing number of procedures, due to patient benefits and positive clinical outcomes. The challenge is therefore to retain the benefits of MIS while reducing as possible the deficiencies of this approach with respect to open surgery.

### System Architecture

The da Vinci® system by Intuitive Surgical Inc. is a surgical robotic system that utilizes an MIS approach. The system follows the classical master/slave teleoperation architecture, which includes a surgical console (master) that controls the patient-side subsystem (slave). The system was originally based on technologies developed by SRI, MIT and IBM [22,23] and evolved through two prototypes (Lenny and Mona) into three FDA-approved versions of the same product named da Vinci (1999) da Vinci S (2006) and da Vinci Si (2009).

The most recent version of the system, da Vinci Si, includes a patient-side subsystem with four arms mounted to a post next to the operating room table. Three of the four arms carry MIS surgical tools (5-8 mm in diameter) and the fourth arm is equipped with two endoscopic cameras with a single shaft (12 mm in diameter) that can reproduce a three-dimensional view of the surgical scene. There are approximately 50 different tools that can be mounted on the robotic arms through a surgical sterile barrier. Like the rest of the system, the tools are cable-driven. The four DOF of the tool along with the three DOF of the slave they form a seven-DOF mechanism. The tools may be divided into two groups including double-wrist-joint 8 mm tools and snake-like 5 mm tools. The double-joint internal wrist of the MIS tools set the da Vinci system apart from the manually controlled MIS tools and provide a superior manipulability. Although snake-like manual tools do exist, they are more difficult to manipulate manually through their proximal end outside of the patient.

The patient- and master-side arms are structured as extended four-link parallelograms with a pivotal point (also known as *remote center of rotation*) located outside of the mechanism. At the patient side, this center is located at the port where the tool is inserted into the patient through the skin, and at the surgeon side, this point is the center of the gimbal mechanism attached to the surgeon's hand. By locating the remote center of the mechanism at the port, the system eliminates site to side translation of the tool, which can damage the skin, but still maintains permissible in/out translation and rotation along any direction. Both of these mechanisms are actuated through mechanical cables, and in some DOF through single stage gears connecting each joint to the corresponding actuator located at the moving base of mechanism. The actuators also serve as a counter balance for the entire arm. On the patient side, the four robotic arms are connected to a single post through passive linkages. Counter balance mechanisms along with electromechanical clutches allow positioning and orientation of the base of each arm with respect to the patient.

The surgical console includes two robotic arms that are used as the primary input devices to the system. By manipulating these two devices the surgeon provides position and orientation commands to the arms on the patient side. The console also includes two screens that are fed by the two endoscopic cameras to recreate a three-dimensional view of the surgical scene. A series of foot paddlers allows the surgeon to index the system as well as to control other surgical functions. The surgeon supports his/her arm on a horizontal bar and uses the index finger and thumb inserted through finger loops to interact with the input devices. A surgeon looking down towards his or her hands through an eyepiece can view the 3D display positioned between the surgeon's eyes and hands. Using this unique setup along with a precise mapping from the surgeon's wrist joint to the surgical tool's wrist joint, the surgeon perceives the surgical instruments as a natural extension of his or her own hands. This console configuration along with the system technical capabilities is the major contributor to the "intuitive" sensation of operating the system.

Two surgical consoles are electronically linked, allowing two surgeons to control the tools and endoscopic cameras. Although the system is based on a teleoperation architecture, in which the master and slave can be separated by a large distance, the approved mode of operation is limited to a scenario in which the patient-side and the surgeon-side are co-located, keeping the surgeon and the patient in the same room [22].

Figure 10: The da Vinci Si by Intuitive Surgical Inc. (a) Surgeon-side two surgical console (b) Patient-side subsystem

## 3.3 Sensei X (Hansen Medical)

### Clinical Procedure – Problem and Needs

Cardiac arrhythmia (abnormal heart rhythm) is used to describe a large number of conditions associated with abnormal electrical activity in the heart. The effects of cardiac arrhythmia may vary between non-life-threatening abnormal heart beat to life-threatening predisposition to stroke, embolism and cardiac arrest leading to sudden death. Atrial fibrillation (AF) is the most common cardiac arrhythmia, and involves the two upper chambers (atria) of the heart. Its name comes from the fibrillating (i.e., quivering) of the heart muscles of the atria, rather than a normal coordinated contraction.

If rhythm control cannot be maintained by medication or cardioversion, than catheter ablation may be used. Catheter ablation is an invasive procedure which involves a flexible catheter inserted into the heart through the veins. The catheter delivers high-frequency electrical impulses that ablate the heart tissue responsible for the abnormal conduction of the electrical signal pathways.

### System Architecture

Sensei® X by Hansen Medical is configured as a master/slave robotic teleoperator. The surgical console includes a single parallel robotic haptic device, along with an array of switches and knobs operated by the left hand. With these two input devices, the surgeon steers and navigates the catheter. The display includes visualization of fluoroscopy, intra-cardiac ultrasound images, three-dimensional mapping system images and real-time electrograms.

The surgical robotic arm (slave) is attached to the surgical table. It can be manipulated with respect to the patient but remains fixed during the operation. It carries a set of actuators that manipulate the various degrees of freedom of the two sheaths and catheter. The Artisan Catheter includes two steerable elements, an outer sheath and an inner sheath. The outer sheath allows deflection in a single plane, and the inner sheath is steerable and maneuverable in all directions. An ablation catheter is placed within the lumen of the Artisan Catheter allowing the surgeon to ablate the tissue once the tip of the catheter is navigated to the targeted anatomical structure [29-31].

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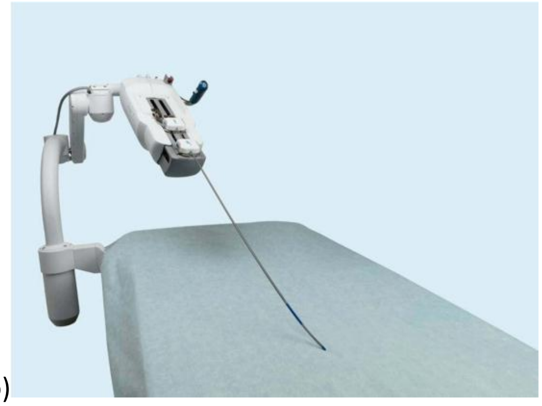
(a)



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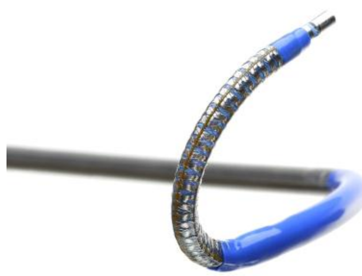


(c)

**Figure 11:** Sensei X by Hansen Medical: (a) surgical console; (b) surgical robotic arm (3) Artisan Catheter

### 3.4 Rio MAKOplasty (MAKO Surgical Corporation)

#### Clinical Procedure – Problem and Needs

Total knee arthroplasty (THA) or “knee replacement” and unicompartmental arthroplasty (UKA) or “partial knee replacement” are surgical procedures aimed to replace the entire or part of the knee joint to treat disability or relieve pain arising from either trauma or various joint disorders due to infection or age, usually involving arthritis or other inflammatory condition. The knee is generally divided into three elements: the inside (medial), the outside (lateral), and the joint between the kneecap and the femur (patellofemoral). Between ten and thirty percent of patients experience wear limited to a single element, typically the medial element, making them candidates for UKA.

Modern total knee replacement implants include a femoral head, tibial plate and a patellar plate (usually not introduced with a robotic procedure). The diseased or damaged weight-bearing joint surfaces of the knee are replaced with either a cementless or cemented implants including metal and plastic components shaped to maintain the kinematics of the knee. The soft tissues are removed and the bones are cut by a *reamer* (a hand-held drill) and *broaches* (serrated cutting tools) to create specific planes and cavities in the cortical bones which accommodate the implant. The bone preparation for this procedure is challenging, and is the primary motivation for a robotically assisted solution. Large gaps created between the bone and the implant may result when large bone elements are removed by the broach. These gaps may generate a suboptimal stress distribution and stress transfer between the implant and the bone. Undersizing or oversizing the implant may cause a variety of problems, including unstable joint fractures and pain. Accurate fit, placement and prosthesis selection are facilitated by the abilities of robotic and robotic assisted systems to execute a preoperative plan [51].

### System Architecture

The MAKO Robotic Arm Interactive Orthopedic System (RIO®) comprises three major hardware components (Figure 12). The Robotic Arm supports the cutting system that allows the surgeon to create the desired resections of bone. The Camera Stand supports both the computer monitor used by the surgeon to view the bone resections as well as the localizing camera system for tracking the patient anatomy though the use of tracking arrays mounted to the bone. The Guidance Module is used by the physician's assistant or a surgical technician to assist the surgeon navigating through the implant planning and surgical application. The surgical tool is held by the surgeon and the robot simultaneously. The surgeon guides the tool using virtual fixtures so that the robotic arm is passive as long as the motions are within the boundaries of the pre-planned space. The robotic arm applies haptic force feedback only if the surgeon attempts to move the cutting burr outside the pre-defined surgical plan. The robotic arm is a six-DOF serial manipulator attached to a mobile cart that is fixed during the operation. The total range of motion of each joint is designed to accommodate both right-handed and left-handed surgeons, as well as to provide sufficient workspace to perform the worst case surgery envisioned. The accuracy of positioning the tip of the tool is less than 1 mm.

The cutting burr spins at up to 80,000 RPM, removing the bone volume to be replaced by the implant. A variety of cutting burrs can be used and exchanged in the system during a surgery. Irrigation is provided to the area of the resection using irrigation tubing attached to the End Effector assembly (not shown) to cool the bone during cutting, preventing thermal necrosis which can lead to loosening of the prosthetic implant over time.

Figure 12c is a screenshot of the RIO system software, showing the model of the patient's femur bone with the planned resection volume in green as well as a portion of the bone already removed. This is the interface the surgeon uses to guide the bone resections. The surgeon is expected to cut the green colored bone away up to the planned boundaries shown as white. If the surgeon attempts to move the cutting burr outside of the planned green resection areas, the RIO robotic arm applies a force on surgeon's hand preventing any cutting outside the planned boundaries. The ability to passively move with the pre-defined space with minimal resistance due to friction, backlash and internal effects is enabled by the back drivability of the system. This operational requirement is met by using a cable-driven transmission, a tungsten wire rope, implemented in each DOF [43].

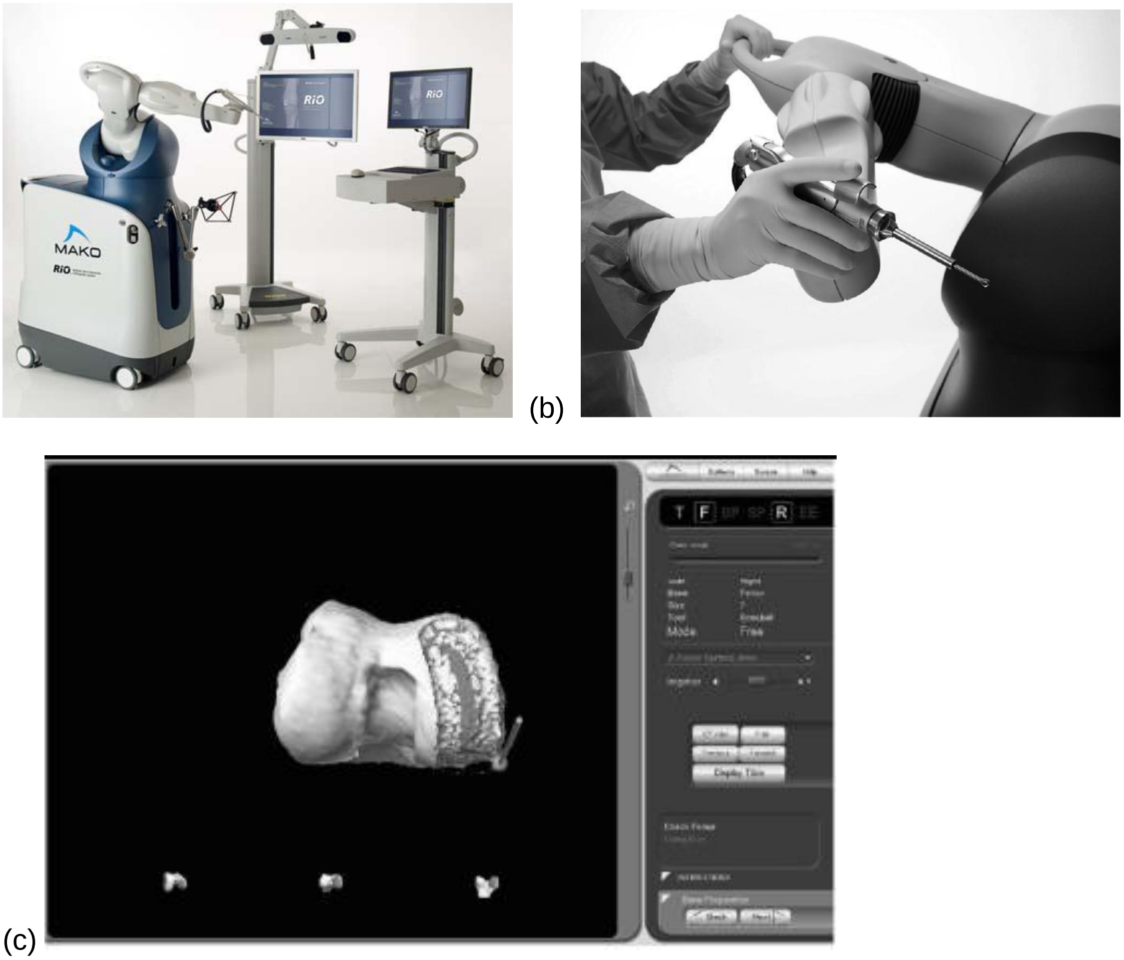
The RIO system is currently used for implantation of medial and lateral UKA components as well as patellofemoral arthroplasty. These procedures follow four steps:

1) *Pre-operative Imaging:* Pre-operative CT scans are obtained, consisting of 1 mm slices for the knee joint and 5 mm slices for the hip and ankle. The scans are then reconstructed to obtain a three-dimensional view of the anatomy. Initial pre-operative planning is conducted using 3D CAD models of the implants.

2) *Pre-operative Planning:* The pre-operative plan is based on four main parameters: metrics of component alignment; 3-D virtual visualization of implant position; intraoperative gap kinematics; and dynamic lower limb alignment assessment. Pre-operative planning based on CT scans is limited since the CT scan is not capable of imaging soft tissues. As a result, the plan must be modified intra-operatively to achieve precise gap balancing and long-leg alignment. Bone resection volumes are defined automatically by the system, and boundaries for the cutting instrument are set to prevent inadvertent surgery to areas outside these predefined zones.

3) *Operation and Intra-operative Soft-Tissue Balancing:* Following the setup and initialization of the robotic system, a standard orthopedic leg holder is used to restrain the leg. Anatomical surface landmarks are registered before the skin is incised. After skin incision, small articular accuracy checkpoint pins are inserted on the tibia and femur, and the two bone surfaces are registered at these points to match them to the CT models. Virtual kinematic modeling of the knee and intraoperative tracking allow real-time adjustments to be made to obtain correct knee kinematics and soft-tissue balancing. The surgeon moves the arm by guiding its tip within the predefined boundaries. The robot gives the surgeon active tactile, visual and auditory feedback during burring. Following the preparation of the bone, the implant is attached.

4) *Post-Operation Follow-Up:* A 24-hour overnight hospital stay for pain control, antibiotics and anticoagulation is often used. The patient is mobilized the same day with PT and a continuous passive motion (CPM) system that flexes and extends the knee overnight to begin motion and determine comfort level.




(a) (b) (c)

**Figure 12:** Robotic Arm Interactive Orthopedic System (RIO) by MAKO: (a) Overview of the entire system; (b) Shared control of the surgical tool – the surgical robotic arm and the surgeon holding the surgical tool together; (c) Screenshot of the RIO system software showing the model of the patient's femur bone with the planned resection volume

### 3.5 CyberKnife (Accuray)

#### Clinical Procedure – Problem and Needs

Radiosurgery allows non-invasive treatment of both benign and malignant tumors. It is also known as stereotactic radiotherapy (SRT) when used to target lesions in the brain, and stereotactic body radiotherapy (SBRT) when used to target lesions in the body. Radiosurgery operates by directing highly focused beams of ionizing radiation. The ionizing radiation is used to ablate, by means of a precise dosage of radiation, tumors and other lesions that could be otherwise inaccessible or inadequate for open surgery due to potential damage to nearby anatomical structures such as arteries, nerves and other vital organs. As part of the selective ionizing radiation ions and free radicals are formed from the water in the cell and the surrounding tissue which produce damage to DNA, proteins and lipids, resulting in the cell's death. The technological and clinical challenges are to deliver the correct dose of radiation to a specific location in space is order to ablate the target tissues while minimizing the damage to the surrounding tissue under dynamic conditions such as breathing or unexpected patient movements.

The CyberKnife by Accuary can deliver a therapy anywhere in the body where radiosurgery is clinically indicated (with FDA 510(k) regulatory clearance). Common treatment sites include intracranial, head & neck, spine & paraspinal, lung, prostate, liver, and pancreas.

**System Architecture**

Procedures that use the CyberKnife system include the following steps, which are described below: scanning, planning, treatment and follow-up.

1) *Scanning:* Prior to treatment with the CyberKnife system, the patient undergoes imaging procedures using CT, MRI, angiography or PET to determine the size, shape and location of the tumor.
2) *Planning:* The image data is then digitally transferred to the CyberKnife system's treatment planning workstation, where the treating physician identifies the exact size, shape and location of the tumor to be targeted and the surrounding vital structures to be avoided. A physician then uses the CyberKnife software to generate a treatment plan to provide the desired radiation dose to the identified tumor location while avoiding damage to the surrounding healthy tissue. As part of the treatment plan, the CyberKnife system's planning software automatically determines the number, duration and angles of delivery of the radiation beams.
3) *Treatment:* During a CyberKnife procedure, a patient lies on the treatment table, which automatically positions the patient. Anesthesia is not required, as the procedure is painless and non-invasive. The treatment, which generally lasts between 30 and 90 minutes, typically involves the administration of between 100 and 200 radiation beams delivered from different directions, each lasting from 10 to 15 seconds. Prior to the delivery of each beam of radiation, the CyberKnife system simultaneously takes a pair of X-ray images and compares them to the original CT scan. The radiation is generated by 1000 MU/min 6MV X-band linear accelerator that is carried by a robotic arm. During treatment, the six-DOF robot, a KR240-2 Kuka, with manufacturer specification for position repeatability of better than 0.12 mm, moves in sequence through the nodes selected during treatment planning. An optimized path traversal algorithm allows the manipulator to travel only between nodes at which one or more treatment beams are to be delivered, or through the minimum number of additional zero-dose nodes required to prevent the robot trajectory intersecting fixed room obstacles or a ‘safety zone’ surrounding the couch and patient. At each node, the manipulator is used to re-orient the linear accelerators such that each beam originating at the node can be delivered [add ref]. Using an image guided approach along with three stereo CCD cameras mounted on a boom that is attached to the ceiling continually tracks, detects and corrects for any

movement of the patient and tumor throughout the treatment to ensure precise targeting without the clinician intervention. The patient typically leaves the facility immediately upon completion of the procedure.

4) *Follow-up:* Follow-up imaging, generally with either CT or MRI, is usually performed in the weeks and months following the treatment to confirm the destruction and eventual elimination of the treated tumor.

In 2010 Accuray released a new product called CyberKnife VSI. The basic concept remains unchanged, but significant improvements and additions to the system technology implemented in the last decade have made the early technical publications obsolete. For a recent review see [32]

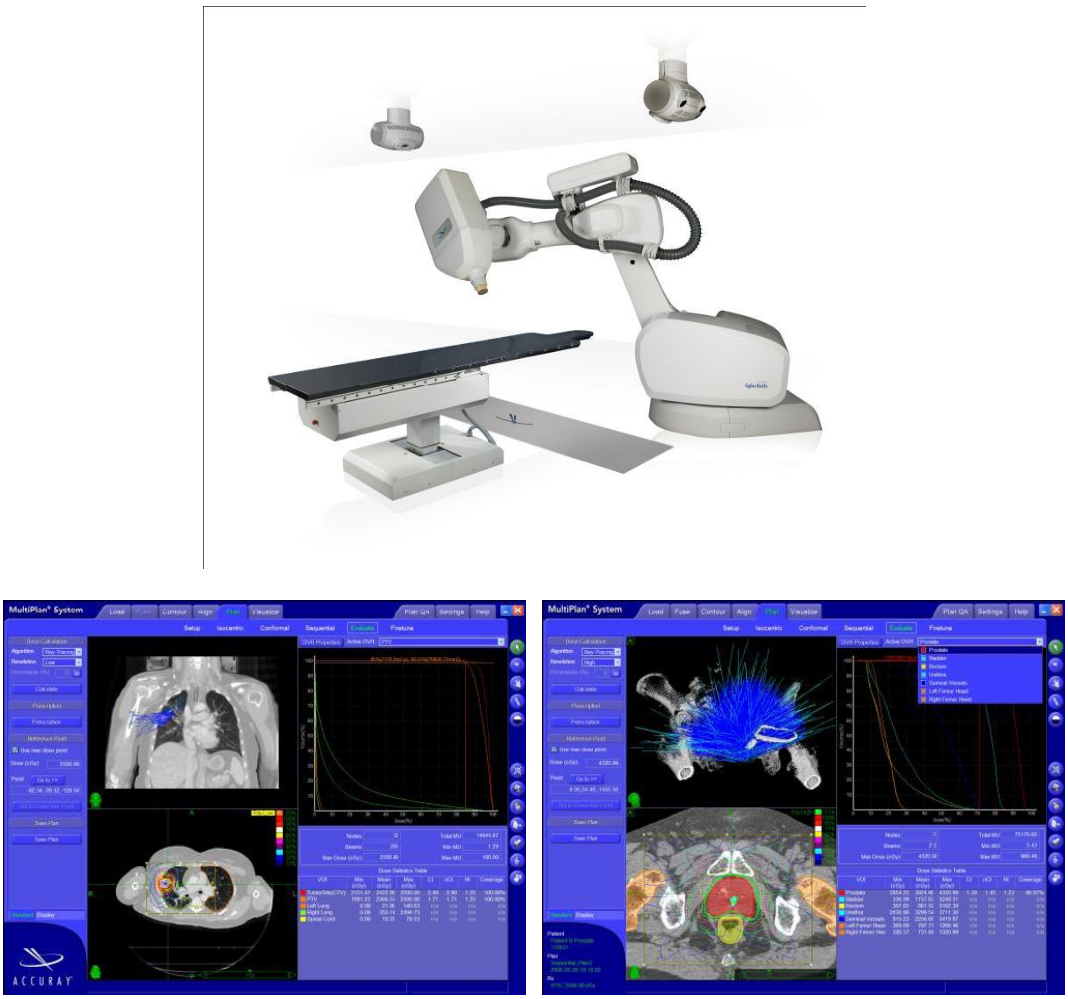



**Figure 13:** CyberKnife System: (a) along with the treatment delivery graphical user interface (GUI); (b) Lung Treatment Plan Image; (c) Prostate Treatment Plan Image

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### 3.6 Renaissance (Mazor Robotics)

#### Clinical Procedure – Problem and Needs

Spinal fusion, i.e. fixing the relative motion between two or more adjacent vertebrae by joining them through an implant made out of screws, rod, plates and cages as well as bone graft, is an orthopedic surgical procedure that is performed in cases of fracture of vertebral body, degenerative disc disease (disc herniation, instability of facet joint, compressive radiculopathy), spine tumors and scoliosis. As part of the procedure two screws per fused vertebra are inserted on the left and right pedicles, which are the segments that connect the body to the arch of the vertebra. A rod is fixed to the head of the pedicle screws of two vertebra to achieve the fusion. The introduction of the implant's screw into the pedicle is conducted under fluoroscopic imaging and requires exposing the pedicles, drilling a pilot hole for each screw and inserting the screw. The introduction of the pedicle screw is complicated since the fluoroscopic imaging provides anterior-posterior and lateral images of the anatomy that is not aligned with screw insertion plane. As a result, the screw is misplaced in 10 to 40% of cases by more than 2 mm from its ideal position [add ref] and in about 3% of cases, that screw misalignment reaches 5 mm, resulting in damage to the nerves. The difficulty and the risk of nerve damage increase as the procedure is performed in the thoracic and cervical spine since the size of the vertebrae decreases in these regions.

#### System Architecture

Renaissance™ (formally SpineAssist®) by Mazor is a miniature bone-mounted robotic system. The base of parallel architecture robotic device is directly attached to the spine and its end effector includes a metal tube guide for surgical instruments such as a needle or drill that can be positioned and oriented to a desired location near the mounting site of the base [55-57].

The surgical procedure incorporating the robot includes the following steps:

1) *Preoperative planning:* The surgeon plans the desired orientation, entry point, and depth of one or more drill or needle procedures based on Computer Tomography (CT), or magnetic resonance imaging (MRI) images;

2) *Intraoperative robot attachment:* The sterilized robot with the targeting guide is rigidly attached with a minimally invasive attachment jig to the bony structure close to the surgical site;

3) *Robot registration:* A precise geometric relation between the coordinate systems of the robot, the target anatomy, and the plan is established;

4) *Robot positioning:* The robot controller moves the targeting guide to its planned position and locks the robot in place; and

5) *Manual execution:* The surgeon executes drilling or needle insertion through the positioned guide.

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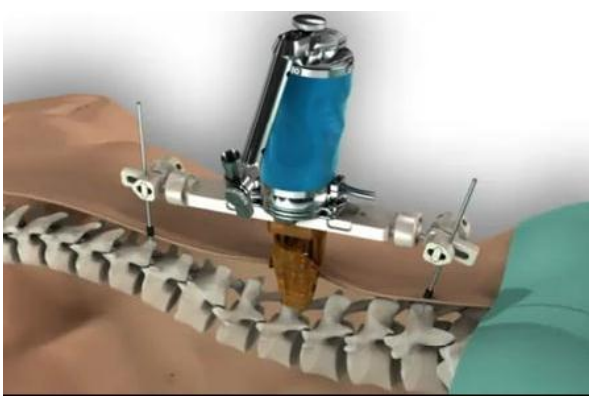
Steps 4) and 5) are repeated for each planned location.


(a)

(b)



(c)


**Figure 14:** (a) Overview of the Renaissance; (b) Mounting Renaissance to the spine; (c) 3D planning of pedicle screws to be introduced into L3 vertebra.

### 3.7 ARTAS (Restoration Robotics)

#### Clinical Procedure – Problem and Needs

The total number of hair follicles for an adult human is estimated at 5 million, with 1 million on the head of which 100,000 alone cover the scalp. Most cases of hair loss are due to androgenic alopecia (AGA). Fifty percent of men by age 50 and 40% of women by menopause have some degree of AGA. The treatment options are either medical or surgical. Hair transplantation is one among several surgical procedures and is considered as a permanent solution to baldness. Restoration is possible because the hair follicles on the sides and back of the scalp are insensitive to the hormones that cause androgenic alopecia, so there is less chance of fallout. During surgical hair transplantation, hair follicles are redistributed in bald areas, where they grow hairs for the rest of the individual's life.

#### System Architecture

ARTAS™ by Restoration Robotics is an interactive, computer assisted system utilizing image-guided robotics to enhance the quality of hair follicle harvesting. The ARTAS System includes an interactive, image-guided robotic arm, special imaging technologies, small dermal punches and a computer interface. The System is positioned over the patient's donor area of the scalp. The robotic arm is equipped with two cameras that serve as a stereo-vision sensor that can identify and detect follicular units on the patient's scalp. The physician chooses which follicular units are to be harvested and inputs this patient-specific information into the system. The system is capable of adjusting itself and compensating for the patient's head movements using visual servoing, as well as calculating the angle, ordination and position of each follicular unit on the scalp surface. The type and number of follicular units as well as the pattern of harvesting can be selected. Using this information, the imaging system semi autonomously guides the robotic arm and it's tool to extract the follicular units one at the time. Each follicular extraction made by the robotic system tool involves 1 mm incision that does not require sutures or other wound-closure treatments that are needed following other harvesting techniques. The follicular units are stored until they are implanted into the patient's recipient area using current manual techniques [58].

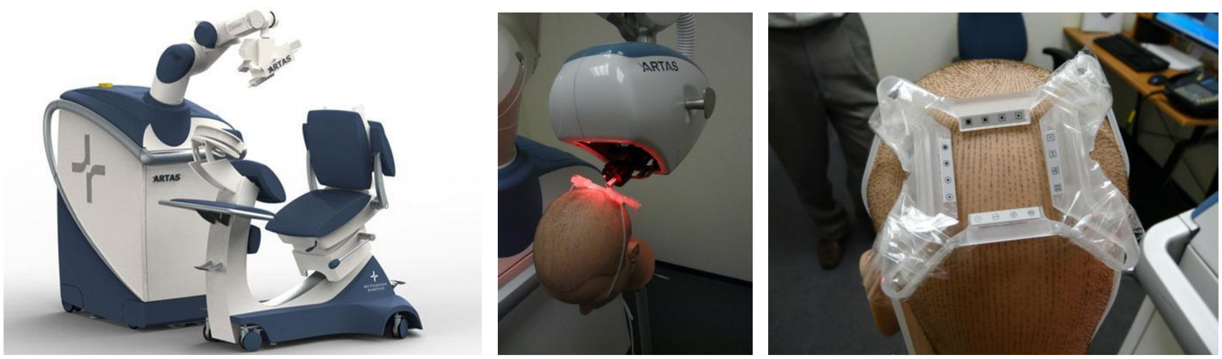



Figure 15: ARTAS Restoration Robotics

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## 4. Trends & Future Directions

Progress in science and engineering typically follows one of two paths: a common step-by-step evolutionary process or a rare leap-forward revolutionary process due to a breakthrough idea concept or principle. Predicting the first pattern may be based on extrapolation of existing trends whereas the second pattern is almost impossible to predict. In the context of surgery, events such as the introduction of minimally invasive surgery, NOTES and robots into the operating room may be considered as breakthroughs that changed the common practice in surgery. In addition to the evolutionary/revolutionary patterns there are also synergetic and symbiotic relationships between innovation in surgical practice and the technology and sciences associated with it. In the case of surgical robotics, the technology was made available in many cases ahead of its time followed by an evolutionary process of developing new surgical approaches to utilize it to improve the outcome of surgery. In contrast, the surgical concept of NOTES was ahead of the technology that would enable it to fully explore its limits.

We can identify three current evolutionary processes, which may at some point also experience a revolutionary breakthrough. The first relates to the level of invasiveness of the surgical procedure. There is an effort to reduce the level of invasiveness which leads to minimizing the impact and trauma to the surrounding tissue, reducing the risk for infection, quicker recovery, and shorter hospitalization periods. This trend faces the challenge that a reduction in the level of invasiveness is associated with smaller tools with fewer degrees of freedom and therefore limited manipulability. Moreover, in the vast majority of the surgical robotic systems, the actuators are left outside of the human body and the actuation is transmitted through cables and rods. The ability to reduce the tool tip and still maintain an external actuation source is limited by the material and mechanical properties of the transmitted mechanisms. In many respects current designs have exhausted these capabilities. The alternative approach is to transmit energy for an external source and in that way prevent the need to invade the body or alternately to introduce the entire robotic system into the body without any electrical or mechanical physical connections. Packing the energy source into a small form factor capsule along with actuation, sensing, manipulation capability and computational power remains a significant challenge [52]. From the actuation perspective it is possible to use external electromagnetic fields to guide and navigate an internal robotic system through the body.

The second trend is associated with an ongoing effort to improve visualization capabilities. Endoscopic cameras along with imaging modalities provide a view and representation of the anatomical structures. However, the physiology and function are not visually represented in conjunction with the anatomy. For example, if neural activity and blood flow can be merged with the anatomical representations of the brain, heart and prostate, the outcome of procedures such as brain surgery for treating epilepsy, cardiac procedures to treat cardiac arrhythmia, and prostatectomy along with many other procedures in which both nerves and blood vessels must be spared would be significantly improved.

The third trend is related to the level of automation and control of the surgeon over the execution of the surgical procedure. Automation can be addressed at two interfaces: (1) the interface between the surgeon and the peripheral activity in the operating room (i.e., sterile and circulation nurses) and (2) the interface between the surgeon the surgical site. *Trauma Pod,* a research program funded by the Defense Advanced Research Projects Agency (DARPA), demonstrated in 2007 that the entire operating room can be fully automated without the need for human presence [53]. The functions of the sterile nurse were replaced by a tools changer, an equipment dispenser, along with a robotic arm that the replaces tools for the surgical robot and provides disposable equipment to the surgical site. The surgeon who teleoperated the robotic system, in this case the da Vinci system, issued verbal commands which triggered a fully automated tool changing and equipment dispensing. The functions of a circulating nurse were replaced by an IT system that tracked the tools and supplies throughout the procedure. Automating the surgical procedure itself using a surgical robot is currently demonstrated for hard tissues whereas operating on soft tissue is conducted under full human control. It is anticipated that the wide spectrum between these two extremes will continue to be explored by automating sub tasks of the operations while developing operational modes in which the surgeon and the robot share surgical robotic tools.

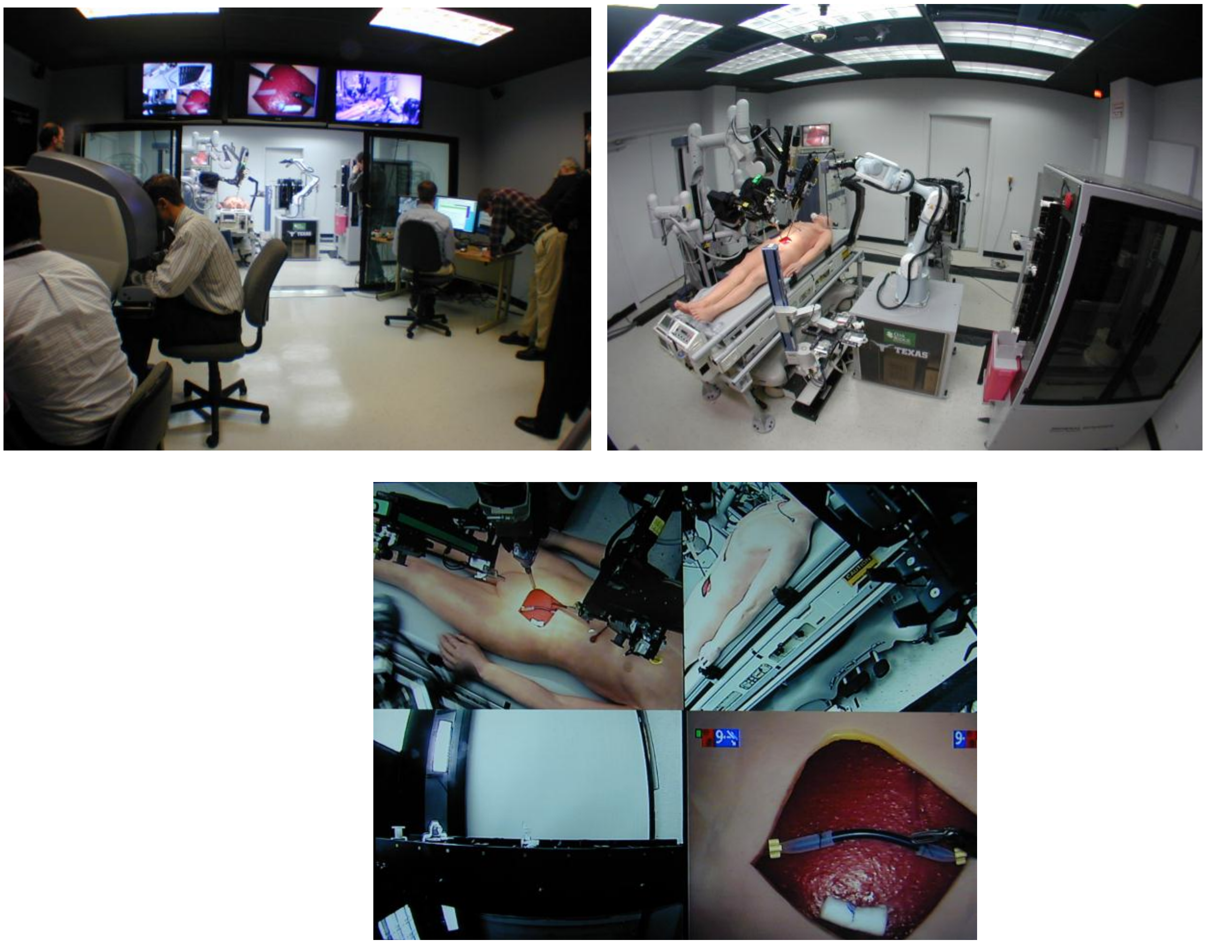

Figure 16: Operating room of the future. Trauma Pod – Phase 1, a fully automated operating room.

Surgical robotic systems are primarily close architecture systems. This approach to system design prevents any change or modification to the system by any entity other the company who developed that system and in that way avoid any liability issues. However, these circumstances present a major difficulty to research community for using such a system as research platform in which change is the order of the day. In order to accommodate the needs of the research community a surgical robotic platform named Raven was developed in the past decade at the University of Washington and the University of California – Santa Cruz. As a research platform Raven is a completely open architecture system from both the software and the hardware perspectives. Its two generations were extensively tested in different modes of operation and the final version provides a technologically mature platform for research purposes [59-62].

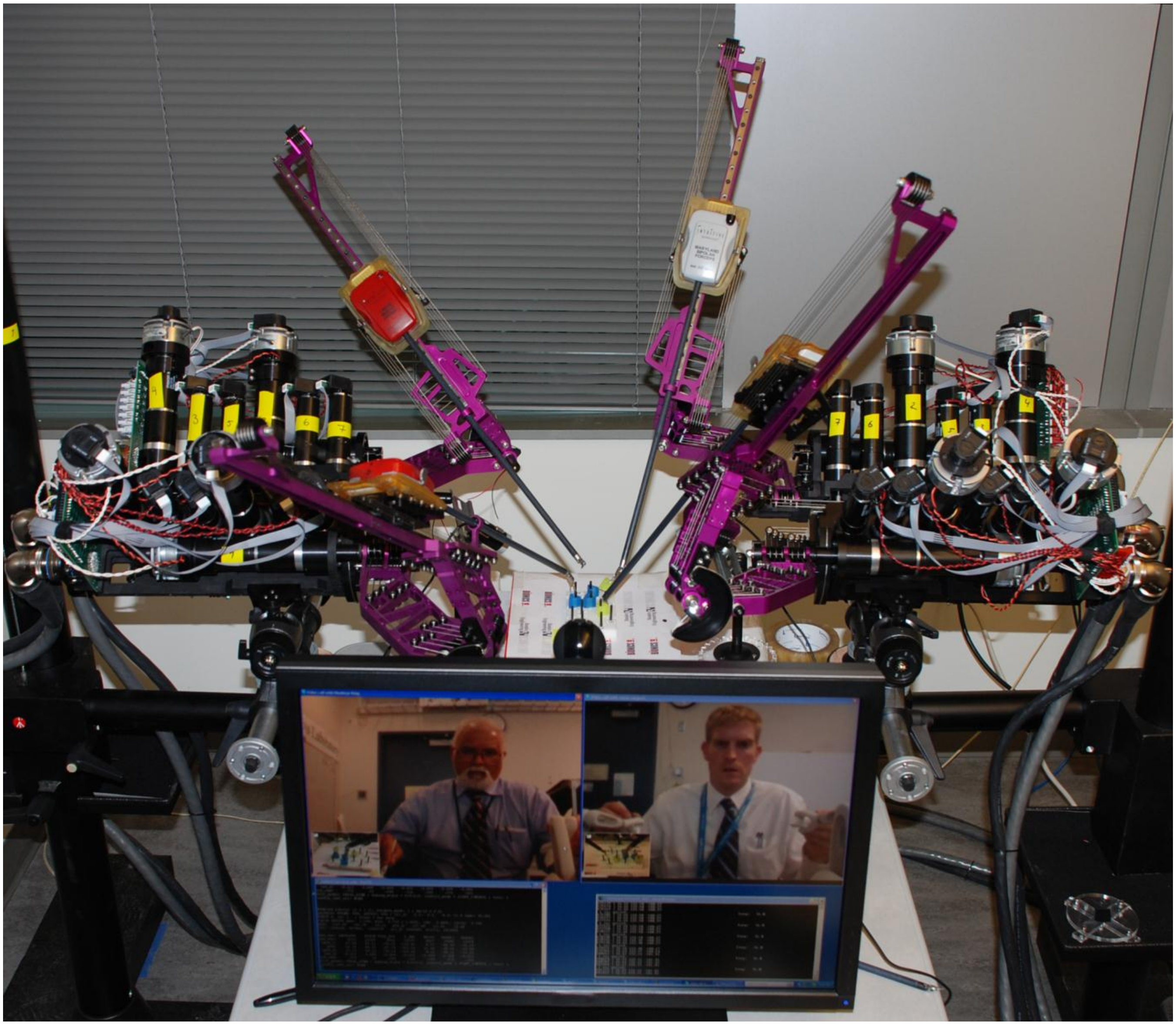

Figure 17: Raven II – A research platform for studying surgical robotics. The image depicts a teleportation experiment in which two surgeons located at the University of Washington collaboratively teleoperated Raven II located at the University of California – Santa Cruz such that each surgeon control one pair of robotic arms.

The revolutionary process involved with the introduction of surgical robotics system into the operating room is still in its infancy. It is anticipated that the number of operations conducted with surgical robotics will continue to grow and eventually become common practice. As innovation in surgery science and technology will continue to evolve in their unique and unexpected fashion, it is likely that surgical robotic systems will have significant impacts on surgical outcomes and human health.

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**System Reference – Listed in Alphabetic Order (See Figure 2)**

- **Acrobot (Imperial Collage, UK ) – [63]**
- **Acubot (JHU) – [64-65]**
- **ARTAS (Restoration Robotics) – [58]**
  URL - http://www.restorationrobotics.com/
- **BRIGIT (MedTech, France) – [66]**

- **CASPAR (Medicalrobotics) – [67]**
- **CARDIOARM (CMU) – [68]**
- **Compact Teleoperated Robotic System (UH) – [69]**
- **Concentric Tube (BU) – [70]**
- **CyberKnife (Accury) -** [32]
  URL -
- **Da Vinci (Intuitive Surgical Inc.) -**[22]
  URL -
- **LARS (Vanderbilt) – [71]**
- **M7 (SRI) – [22]**
- **MicoSurge (DLR) – [72]**
- **Miniature Robot (U. Nebraska) – [73]**
- **MrBot (JHU) – [74]**
- **Multi Capsular Surgical Robot (U. Pisa) – [52]**
- **NeuroARM (U. Calgery) – [74-75]**
- **Raven (UW/UCSC) – [59-62]**
- **Renaissance (Mazor) – [55-57]**
  Renaissance / Mazor - http://www.mazorrobotics.com/
- **Rio (Mako) – [43]**
  URL - http://www.makosurgical.com
- **RoboDoc (Curexo) – [18-21]**
  **URL** - http://www.robodoc.com/
- **Steady Hand (JHU)**
- **SenseX (Hansens Medical) – [29-31]**
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