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## Review Article

# State of the Art in Surgical Robotics: Clinical Applications and Technology Challenges

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**ABSTRACT** Although it has been over 15 years since the first recorded use of a robot for a surgical procedure, the field of medical robotics is still an emerging one that has not yet reached a critical mass. Although robots have the potential to improve the precision and capabilities of physicians, the number of robots in clinical use is still very small. In this review article, we begin with a short historical review of medical robotics, followed by an overview of clinical applications where robots have been applied. The clinical applications are then discussed; they include neurosurgery, orthopedics, urology, maxillofacial surgery, radiosurgery, ophthalmology, and cardiac surgery. We conclude with a listing of technology challenges and research areas, including system architecture, software design, mechanical design, imaging compatible systems, user interface, and safety issues. Comp Aid Surg 6:312-328 (2001). ©2002 Wiley-Liss, Inc.

**Key words:** medical robotics, technology challenges, neurosurgery, orthopedics, urology, maxillofacial surgery, radiosurgery, ophthalmology, cardiac surgery

## INTRODUCTION

Medical robotics has tremendous potential for improving the precision and capabilities of physicians when performing surgical procedures. However, we are just at the beginning of the application of robotics to medicine, and many questions remain open regarding their effectiveness, safety, and cost. Although there are several commercial companies selling medical robots, the total number installed is extremely small, and the market will most likely continue to grow slowly. Unlike the area of factory robotics, which grew rapidly during the 1970s and 1980s, medical robotics has not yet reached a critical mass. However, it is believed the benefits of medical robotics will become increasingly clear,

and this will lead to a continued rise in their use in medicine.

According to the Robotic Institute of America, a robot is "a reprogrammable, multifunctional manipulator designed to move materials, parts, tools, or other specialized devices through various programmed motions for the performance of a variety of tasks." While the term "robot" may conjure up images of R2D2 from the movie *Star Wars*, in this paper we will stay with the definition above. These robots consist of nearly rigid links that are connected with joints that allow relative motion from one link to another.<sup>1</sup> Attached to the end of the links is the robot hand, usually referred to as the

end-effector. The robot is controlled by a computer system that is used to move the end-effector to any desired point and orientation within its workspace.

This article highlights the state of the art of medical robotics across several clinical areas. In this review, we will focus on robots that play an active role during a surgical intervention. These systems are not meant to replace the physician, but rather to augment the capabilities of the physician. There are other categories of medical robotics, such as robotics for rehabilitation or miniature robots that might be placed inside the body, but these will not be discussed here. This review is not intended to be comprehensive, but rather to give an overview of the field, with a focus on key historical developments and current work.

Several other medical robotics review articles with a focus on surgical procedures have also been written. Davies<sup>2</sup> describes the history of surgical robotics and gives one classification for the types of robot systems studied by researchers. Taylor<sup>3</sup> discusses several taxonomies for surgical robotics and presents a different classification. Troccaz and Delnondedieu<sup>4</sup> give a historical review and describe passive, semiactive, and active robotic systems. Howe and Matsuoka<sup>5</sup> provide an overview of applications in image-based procedures, orthopedic surgery, and neurosurgery, among others. Specialized reviews also exist, such as the article by Caddeu et al. on urology robotics.<sup>6</sup>

The paper is organized as follows. The next section gives a brief historical review, which is followed by a table of clinical applications. Each of these clinical applications is then described. The penultimate section presents technology challenges and research areas, with conclusions appearing at the end of the article.

## HISTORICAL REVIEW

Medical robotics is a relatively young field, with the first recorded medical application of a robot occurring in 1985.<sup>7</sup> In this case, the robot was a simple positioning device to orient a needle for biopsy of the brain. A 52-year-old man was put on a CT scanner table, the target was identified on the CT images, and the robot was used to orient a guide tube through which a needle was inserted. Unfortunately, the robot used was a PUMA 560 industrial robot, and safety issues concerning the operation of the robot in close proximity to people prevented this work from continuing.<sup>2</sup>

Shortly thereafter, research groups in Europe, Asia, and the United States began investigating medical applications of robotics: In Europe, a

group at Imperial College in London under the direction of Davies began developing a robot for prostate applications;<sup>8</sup> at Grenoble University Hospital in France, Benabid, Lavallée, and colleagues started work on neurosurgical applications such as biopsy;<sup>9</sup> in Asia, Dohi and colleagues at Tokyo University developed a prototype of a CT-guided needle insertion manipulator;<sup>10</sup> and in the United States, Taylor and associates at IBM began developing the system later known as ROBODOC.<sup>11</sup>

Currently, there are several commercial ventures and a handful of research laboratories active in the field of medical robotics. These early research efforts have led to some commercial products. For example, the work at Grenoble University Hospital led to the NeuroMate robot of Integrated Surgical Systems, as described later.

## CLINICAL APPLICATIONS

There are several ways to classify the use of robots in medicine. One scheme, as developed by Taylor,<sup>3</sup> is to classify robots by the role they play in medical applications. Taylor stresses the role of robots as tools that can work cooperatively with physicians to carry out surgical interventions, and identifies five classes of systems: (1) intern replacements, (2) telesurgical systems, (3) navigational aids, (4) precise positioning systems, and (5) precise path systems.

Although this classification is technology oriented, we have chosen to divide the field by clinical application in this paper. Clinical applications are more interesting to the end-user, and a list of seven clinical areas where robotics have been applied appears in Table 1. This table is not meant to be exhaustive, but representative research groups and commercial vendors in several areas have been selected to give the reader an overview of the field. The column labeled "Studies" indicates whether human trials, animal studies, cadaver studies, or other studies have been done.

### Neurosurgery

As mentioned in the historical review, neurosurgery saw the first clinical application of robotics, and continues to be a topic of current interest. Neurosurgical stereotactic applications require spatial accuracy and precision targeting to reach the anatomy of interest while minimizing collateral damage. This section presents three neurosurgical robotic systems: (1) Minerva from the University of Lausanne in Switzerland, (2) NeuroMate from Integrated Surgical Systems in the United States,

**Table 1. Clinical Application Areas and Representative Robotic Developments**

Clinical area	Country	Institution/company	System	Studies	Reference
Neurosurgery	Switzerland	Univ. of Lausanne	Minerva	human	12, 13
Neurosurgery	USA	Integrated Surgical/ Grenoble Univ. Hospital	NeuroMate	human	14
Neurosurgery	Japan	Univ. of Tokyo	MRI compatible	tissue samples	15
Orthopedic	USA	Integrated Surgical	ROBODOC	human	11
Orthopedic	USA	Georgetown/Hopkins	PAKY/RCM	cadaver	16, 17
Orthopedic	USA	Univ. of Tokyo/Hopkins	PAKY/RCM	phantom	This issue
Orthopedic	USA	Marconi	Kawasaki	pig	This issue
Orthopedic	UK	Imperial College	Acrobot	human	This issue
Urology	UK	Imperial College	Probot	human	18
Urology	USA	Hopkins	PAKY/RCM	human	This issue
Maxillofacial	Germany	Charité	SurgiScope	pig	19
Maxillofacial	Germany	Karlsruhe/Heidelberg	RX 90	pig	20
Radiosurgery	USA	Accuray	CyberKnife	human	21
Ophthalmology	USA	Hopkins	Steady-Hand	in development	22
Cardiac	USA	Intuitive Surgical	da Vinci	human	23
Cardiac	USA	Computer Motion	Zeus	human	24
Cardiac	France	Grenoble	PADyC	in development	This issue

and (3) an MRI-compatible robot developed by Dohi and colleagues in Japan.

### Minerva

One of the earliest robotic systems developed for precise needle placement was the neurosurgical robot Minerva,<sup>13</sup> designed for stereotactic brain biopsy. A special-purpose robot was constructed that was designed to work within the CT scanner so that the surgeon could follow the position of the instruments on successive CT scans. This constraint ensured that CT images would be available throughout a procedure, keeping all procedures under the surgeon's supervision and control. A diagram of the system and associated components is shown in Figure 1.

The mechanical design of this system was presented by Glauser et al.<sup>12</sup> The system consists of a five-degree-of-freedom structure with two linear axes (vertical and lateral), two rotary axes (moving in a horizontal and vertical plane), and a linear axis (to move the tool to and from the patient's head). The robot is mounted on a horizontal carrier which moves on rails. A stereotactic frame, the Brown-Roberts-Wells (BRW) reference frame, is attached to the robot gantry and coupled to the motorized CT table by two ball-and-socket joints arranged in series. The system was used for two operations on patients in September 1993 at the CHUV Hospital in Switzerland, but the project has since been discontinued.

### NeuroMate

The NeuroMate is a six-axis robot for neurosurgical applications that evolved from work done by

Benabid, Lavallée, and colleagues at Grenoble University Hospital in France.<sup>9,14,25</sup> The original system was subsequently redesigned to fulfill specific stereotactic requirements and particular attention was paid to safety issues.<sup>26</sup> The current version (Fig. 2) is a commercial product that has been licensed by Integrated Surgical Systems (Davis, CA), and is FDA approved.

The system has been used in over 1600 procedures since 1989, covering a range of neurosurgical procedures. The major clinical applications include: (a) tumor biopsies (1100 cases), (b) stereoelectroencephalographic investigations of patients with epilepsy (200 cases), and (c) midline

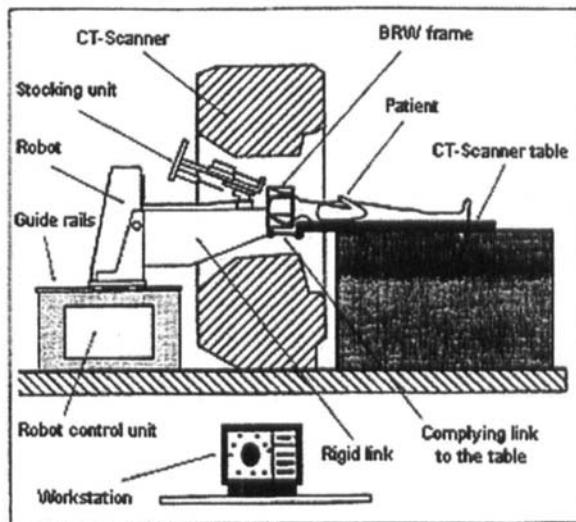
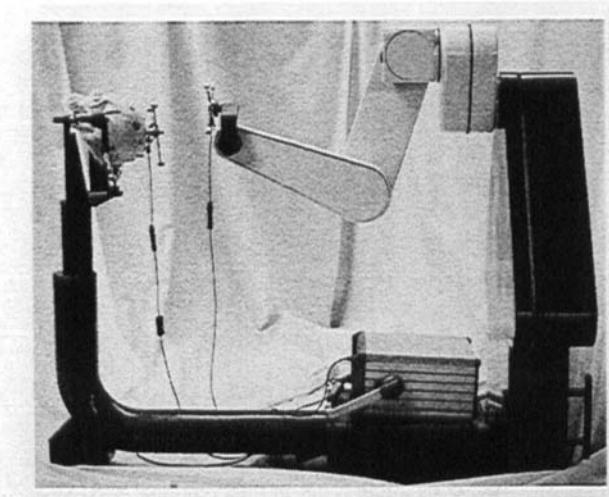


Fig. 1. Minerva components and system overview (© 1995 IEEE, from ref. 13).

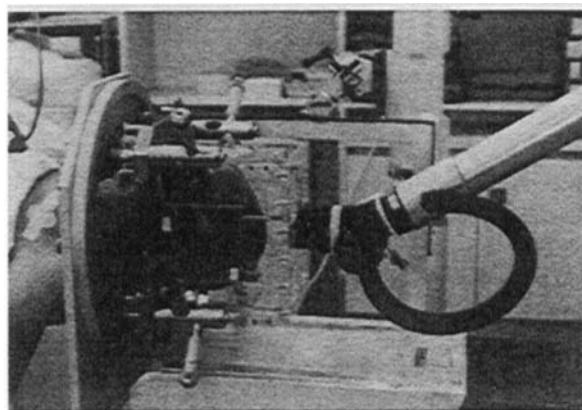
stereotactic neurosurgery and functional neurosurgery of the basal ganglia (200 cases).

A typical clinical procedure consists of an initial data acquisition step, followed by data transfer to the control computer, and then the procedure itself. Data acquisition involves obtaining images of the brain from which path planning from the skin entry point to the target point can be done using a specially developed software program. The images can be in digital form (DSA, CT, or MRI images) or can be digitized (radiographs, for example) using a digitizing table or scanner. Once the path is planned, the images are transferred directly from the planning workstation to the control workstation in the operating room over an Ethernet link.

To carry out the procedure, the robot must know where it is located relative to the patient's anatomy. This is typically done using a calibration cage, which is placed on the end-effector of the robot around the patient's head (Fig. 3). This cage looks like an open cubic box, and the four sides are each implanted with nine X-ray-opaque beads, the positions of which have been precisely measured. Two X-rays are taken which show the position of these beads along with the fiducial markers of the patient's frame. This information is used to determine the transformation matrix between the robot and the patient. The defined trajectory is used to command the robot to position a mechanical guide, which is aligned with this trajectory. The robot is then fixed in this position and the physician uses this guide to introduce a surgical tool such as a drill, probe, or electrode.



**Fig. 2.** NeuroMate neurosurgical robot (courtesy of Integrated Surgical Systems, Davis, CA).



**Fig. 3.** Calibration cage held by the robot (from ref. 14, used by permission of MIT Press).

#### ***MRI-Compatible Robot***

While several robots have been developed for stereotactic neurosurgery, including those mentioned above, almost all of these systems used CT images for guidance. However, many structures in the brain are best visualized using magnetic resonance imaging (MRI). The robotic systems described so far are not suitable for use in an MRI scanner because the strong magnetic fields generated dictate that only nonmagnetic materials can be used. In Japan, in the Mechatronics Laboratory at the University of Tokyo, Dohi, Masamune and colleagues developed an MRI-compatible needle insertion manipulator intended for use in stereotactic neurosurgery.<sup>15</sup> The manipulator frame was manufactured using polyethylene terephthalate (PET), and ultrasonic motors were used for the actuators. Other parts such as bearings, feed screws, and gears that must be strong and precisely fabricated are made of nonmagnetic materials including brass, aluminum, delrin, and ceramics. In phantom tests using watermelons, the robot performed satisfactorily with a positioning error of less than 3.3 mm from the desired target. The unit was small enough at 491 mm in maximum height to fit inside the MRI gantry of 600 mm diameter.

Rather than retrofitting an industrial robot, Masamune developed a completely new design based on the clinical requirements for safety, MRI compatibility, and compactness. As shown in Figure 4, the system includes an X-Y-Z base stage. An arch mechanism is mounted on the base stage along with a linear needle carriage. This isocentric design was adopted for its mechanical safety and simplicity. The system was controlled by a personal computer. The control computer and motor driver

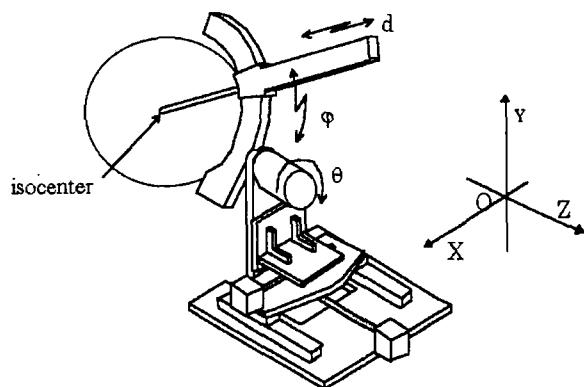


Fig. 4. MRI-compatible robot design (courtesy of Ken Masamune, Tokyo Denki University, Japan).

boards were remotely located in the MRI control room and connected by shielded cables to the robot.

In a related development, a new MRI-compatible robot has been developed to work within the interventional MRI unit at the Brigham and Women's Hospital in Boston, MA.<sup>27</sup> The interventional MRI has a pair of parallel facing donut-shaped magnets, with an air gap of 560 mm. The robot sits between the magnets and is mounted on top of the unit as shown in Figure 5. The system is currently undergoing testing, and one potential clinical application is needle placement for prostate brachytherapy.

Finally, researchers in Germany have developed an MRI-compatible robotic biopsy system, focusing on breast cancer as an initial application. In vitro experiments using pig livers in a 1.5-Tesla magnet and 4-mm targets resulted in all eight targets being successfully hit.<sup>28</sup>

### Orthopedic

Orthopedics is well suited for robotic assistance due to the rigid nature of bone. Because bone does not deform significantly when it is drilled or cut, it is possible to intraoperatively apply preoperative imaging and planning information more easily than for soft tissues such as the brain or abdominal organs.<sup>29</sup> Orthopedics was also an early adopter of robotics, as the ROBODOC system described next was used to assist surgeons in performing part of a total hip replacement in 1992. This marked the first use of an active robot for hip surgery, as the robot was used to mill out the hole for the hip implant.

### ROBODOC

The ROBODOC system was developed clinically by Integrated Surgical Systems (Davis, CA) for

total hip-replacement procedures from a prototype created at IBM Research. The system was used in over 1,000 cases at a Frankfurt, Germany, hospital from 1994 until 1998.<sup>30</sup> The system consists of three major components: a planning workstation, the robot itself that does the cutting, and the workstation that guides and controls the robot.

A typical hip-replacement procedure using ROBODOC is carried out as follows.<sup>31</sup> The procedure starts with the surgeon implanting three locator pins in the hip. These pins are later used as fiducial points for registering the patient anatomy with the robot. A CT scan is then obtained and the CT data is transferred to the planning workstation (ORTHODOC). The surgeon can then choose a suitable implant from a library of possible implants. The surgeon can virtually position the implant on the planning workstation, check different positions, and assess the impact on anteversion, neck length, and stress loading (Fig. 6). When the planning session is finished, the data is transferred to the computer that controls ROBODOC.

In the operating room, the hip joint is exposed and the robotic system is moved into position to mill out the femoral cavity. The locator pins are used to register the hip joint with the robot. Cutting time is 20–35 minutes, and the surgeon monitors this process by watching a computer screen that shows the progress of the cutting operation. The robot can also be stopped at any time. When the milling is complete, the robot is removed and the rest of the operation is completed by hand in the conventional manner. A photograph of ROBODOC milling the cavity for the implant is shown in Figure 7.

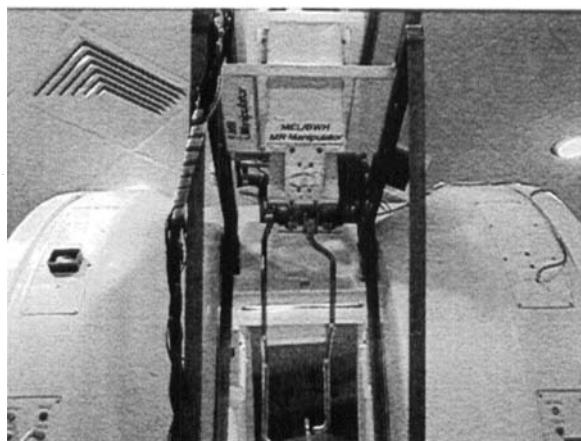


Fig. 5. MRI-compatible robot in interventional MRI system (courtesy of Kiyoyuki Chinzei, AIST, Japan, and Ron Kikinis, Brigham and Women's Hospital, Boston, MA).

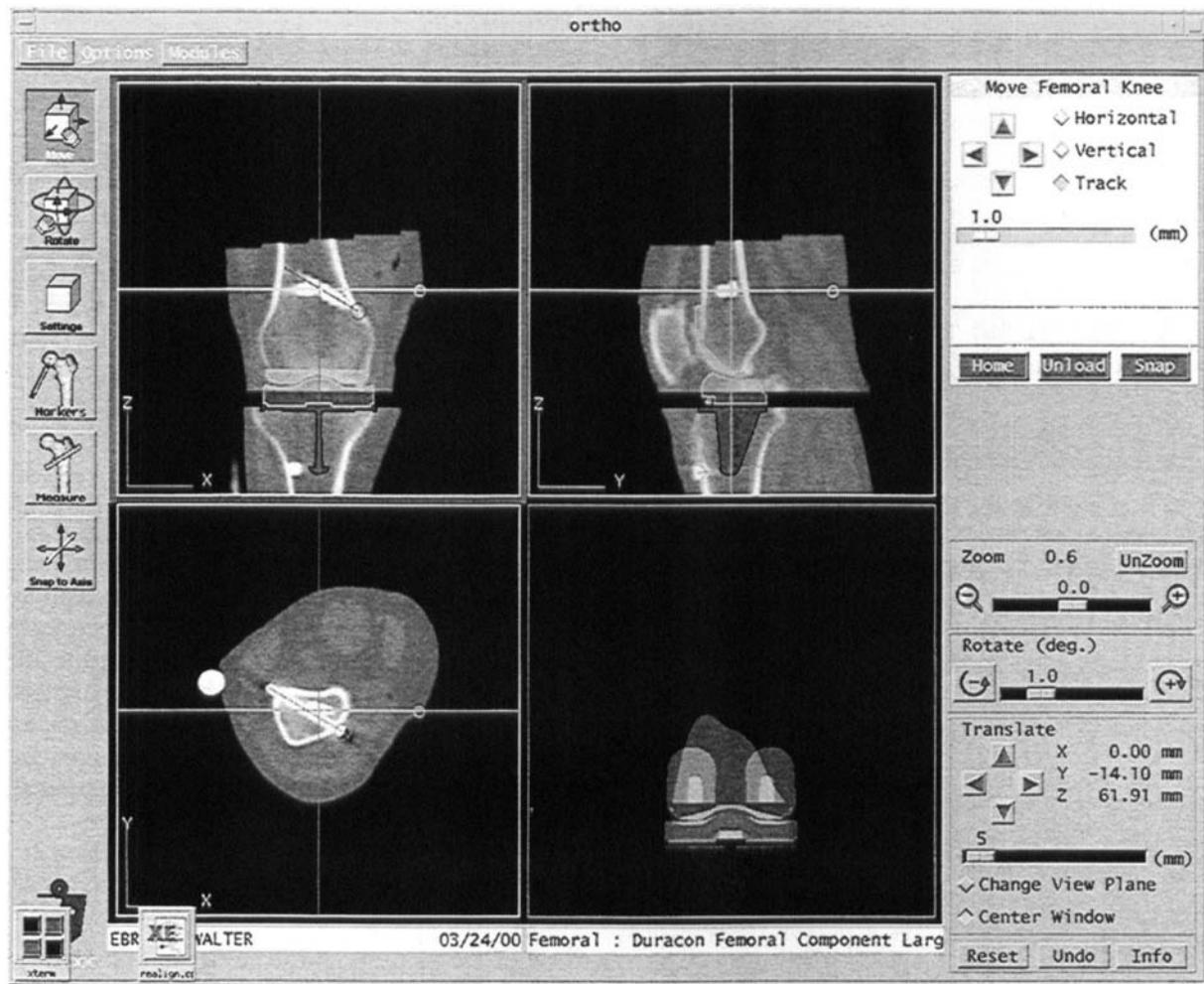


Fig. 6. ORTHODOC planning workstation (courtesy of Integrated Surgical Systems, Davis, CA).

### *Georgetown University/Johns Hopkins Collaboration*

At Georgetown University Medical Center, our research group has been focusing on the use of robots for precision placement of instruments in minimally invasive spine procedures.<sup>16,17</sup> This work is a collaboration with the Urology Robotics Laboratory of the Johns Hopkins Medical Institutions and the Computer Integrated Surgical Systems and Technology (CISST) Engineering Research Center at Johns Hopkins University.

Low back pain is a common medical problem, and minimally invasive procedures such as nerve blocks are rapidly growing in popularity as a potential method of treatment. To assist the physician in needle placement during these procedures, we have begun to use a newly developed version of the PAKY/RCM needle-driver robot developed at



Fig. 7. ROBODOC milling implant cavity for hip replacement surgery (courtesy of Integrated Surgical Systems, Davis, CA).



**Fig. 8.** Needle-driver robot cadaver study. Physician uses touch-screen/joystick interface to control the robot and monitors the intervention on the fluoroscopy screens.

the Urology Robotics Laboratory. Robotic systems such as these have great potential as physician-assist devices for improving the precision of needle placement and enabling the development of the next generation of precision guidance systems for interventional techniques.

The newly developed needle-driver robot consists of a translation stage with 3 degrees of freedom (DOF), a 7DOF passive positioning stage, and a 3DOF orientation/driving stage. The robot is mounted on the interventional table and the physician controls the system through a touch screen/joystick interface, as shown in Figure 8. A cadaver study has been done (Fig. 9), and institutional approvals for human studies are nearly complete. Clinical trials using the robot to place a 22-gauge needle for nerve and facet blocks in the spine are expected to begin by early 2002.

#### **University of Tokyo/Johns Hopkins Collaboration**

An integrated robotic system for percutaneous placement of needles under CT guidance was developed by Masamune at the University of Tokyo in collaboration with Johns Hopkins. Single image-based coregistration of the PAKY/RCM robot and image space was achieved by stereotactic localization using a miniature version of the BRW head-frame built into the radiolucent needle driver. A phantom study was done with an orientation accuracy of 0.6 degrees and a needle-tip-to-target distance of 1.04 mm. The system is applicable to orthopedic (spine) and many other percutaneous

procedures. For further details, see the article by Masamune et al. in this issue.<sup>32</sup>

#### **Marconi Medical Systems**

An active robot has been integrated with a CT scanner for interventional procedures by Yanof and colleagues at Marconi Medical Systems (Highland Heights, OH). Animal experiments using pigs were completed to investigate needle placement in the abdomen. The path was planned based on the CT scans, and this information was sent to the robot, which automatically moved to the skin entry point and then oriented and drove the needle. For further details, see the article by Yanof et al. in this issue.<sup>33</sup>

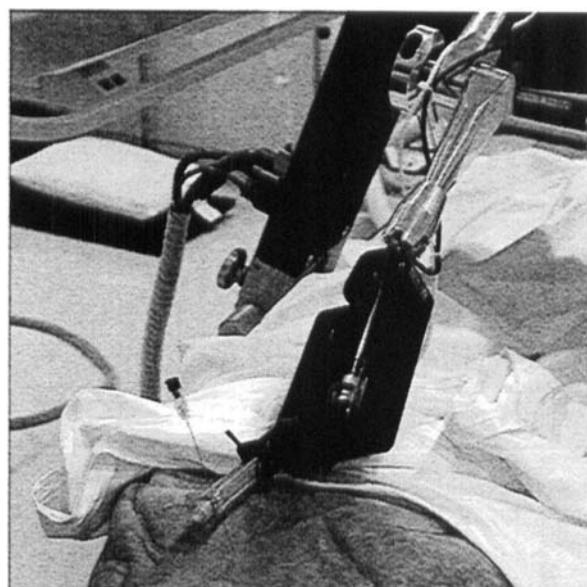
#### **Imperial College, London**

A special-purpose robot called Acrobot (from Active Constraint Robot) has been developed for safe use in the operating room for total knee replacement surgery. The surgeon guides the robot using a handle attached to a force sensor attached to the robot tip. Following two preliminary clinical trials, the first clinical trial was conducted in which Acrobot was used to register and cut the knee bones. For further details, see the article by Jakopec et al. in this issue.<sup>34</sup>

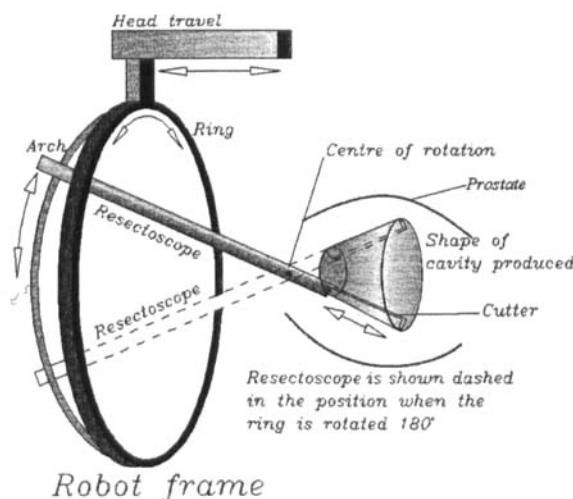
#### **Urology**

##### **Prostate Resection**

One of the pioneering research groups in Medical Robotics is the Mechantronics in Medicine Labo-



**Fig. 9.** Close-up of cadaver study showing needle driver and passive positioning arm.



**Fig. 10.** Prostate robot frame (courtesy of Brian Davies, Imperial College, London, UK).

ratory at Imperial College in London. Starting in 1988, the group began developing a robotic system named Probot to aid in transurethral resection of the prostate.<sup>18</sup> While an initial feasibility study was carried out using a standard six-axis PUMA industrial robot, such a system was determined to be impractical for medical purposes, as these robots are not designed to work in close proximity to humans. Therefore, a special-purpose robotic frame was designed to hold the surgical instrument. The first patient was treated in April 1991, and this was the first use of a robot to remove substantial quantities of tissue from a human patient.<sup>2</sup>

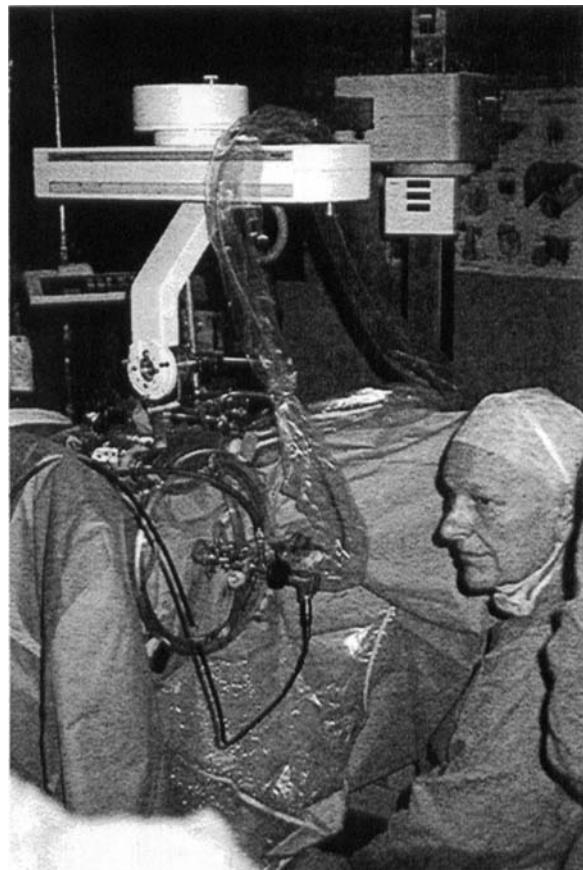
The robotic frame shown in Figure 10 consists of three axes of movement. An additional axis is provided by the resectoscope, which is the surgical instrument used to remove the tissue. The geometry of the system is designed to allow a cavity to be hollowed out from within the prostate and restrict movements outside an allowable range. This restriction provides an additional margin of safety.

The clinical application consists of four stages: (1) measurement; (2) imaging; (3) cavity design; and (4) cutting. To begin the procedure, the patient is positioned on the operating table and the Probot is positioned at the bladder neck. The user interface allows the surgeon to view the internal anatomy from a video camera within the resectoscope. An ultrasound probe is then passed down the resectoscope and the robot is set to acquire a series of scans at 5-mm intervals to build up a 3D image of the prostate. The surgeon can then outline the cavity to cut on each slice of the ultrasound image

using a light pen. The final step is the actual cutting operation. A picture of the operating room and Probot in clinical use is shown in Figure 11. The surgeon is sitting to the left, and can observe the progress of the cutting on a video monitor (Fig. 12). The real-time image of the prostate is displayed at the top left of the monitor, and an overlay of the cuts on an ultrasound image is shown at the bottom right.

#### ***Urology Robotics Laboratory***

The Urology Robotics (URobotics) Laboratory is a part of the Urology Department at Johns Hopkins Medical Institutions, and is dedicated to the development of new technology for urologic surgery. The program combines engineering and medical personnel in close cooperation and is the only academic engineering program devoted exclusively to urology. This group and colleagues at the Engineering Research Center at Johns Hopkins University have developed the PAKY (percutaneous access of the kidney) needle driver<sup>35</sup> and RCM



**Fig. 11.** Probot in clinical use (courtesy of Brian Davies, Imperial College, London, UK).



**Fig. 12.** Video monitor display during procedure (courtesy of Brian Davies, Imperial College, London, UK).

(remote center of motion) robot,<sup>36</sup> which has been applied to minimally invasive kidney procedures. Further details about this project and other work at the Urology Robotics Laboratory can be found in the article by the laboratory director, Dan Stoianovici, in this issue.<sup>37</sup>

### Maxillofacial

Maxillofacial surgery is a branch of surgery that is concerned primarily with operations on the jaws and surrounding soft tissues. In many maxillofacial surgery cases, it is necessary to manipulate the skull bone by drilling, cutting, shaping, and repositioning operations. Accuracy is at a premium, because the shape of the bone and the esthetic appearance of the skull and face are extremely important to patients. The current procedures are done manually using tools such as pliers, chisels, electric saws, and drills. As primarily bony structures are involved and accuracy is so important, maxillofacial surgery may be a good application

area for robotics.<sup>19</sup> Examples of robot-supported clinical tasks in this field include the following:<sup>38</sup>

1. Guidance for nonflexible catheter implantation (brachytherapy).
2. Handling of electric drills, taps, and screwdrivers for fixing bones and implants (anaplastology).
3. Handling of electric saws and retractor hooks.

### Experimental Operating Room

For developing an interactive robot system for maxillofacial surgery, an experimental operating room has been set up at the Charité Hospital of Humboldt University in Berlin, Germany,<sup>19</sup> as shown in Figure 13. This operating room includes a unique robotic system, the SurgiScope. While most robotic systems described in this review are based on a serial kinematic structure in which the links are attached one after the other as in the



**Fig. 13.** Surgical robotics laboratory showing parallel robot (ceiling mounted), mobile CT (back of photo), and serial robotics arm (foreground) (courtesy of Tim Lueth, Charité, Berlin, Germany).

human arm, at least one company has developed a medical robot based on a parallel kinematic structure. The SurgiScope is a general-purpose 6DOF robotic device consisting of a fixed base, three parallel links, and a movable end-effector. The system is designed to be fixed on the ceiling, and provides a large workspace while not cluttering the operating room floor. The parallel kinematic structure also provides a very stable structure for precision operations. The robot was originally sold by Elekta, but is now being marketed by Jojumarie Intelligente Instrumente in Berlin. The use of this system for placement of the radiation source in brachytherapy in animal studies is described by Heissler et al.<sup>39</sup>

#### Craniofacial Osteotomy

Another system for maxillofacial surgery has been developed at the Institute of Process Control and Robotics in Karlsruhe, Germany, in cooperation with the Clinic of Craniofacial Surgery at the University of Heidelberg. Animal studies were carried out to perform osteotomies where an RX 90 surgical robot (ortoMaquet, Staubli) was used to guide a surgical cutting saw.<sup>20</sup> The studies were carried out as follows. Twelve titanium screws were implanted into the head of a pig to be used as landmarks. A CT scan with 1.5-mm slice spacing was done, and the resulting images were used to create a surface model for surgical planning. A haptic interface was used to trace the cutting lines on the surface of the skull (Fig. 14). Once the planning was completed, the robot was registered with the pig in the operating room (Fig. 15), and the surgeon manually

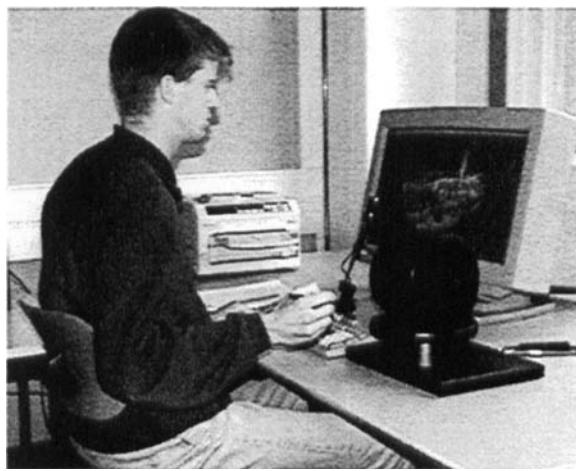
guided the robot arm along the trajectory where his movements perpendicular to the cutting line were restricted. This system has also been evaluated, using sheep, for the autonomous milling of a cavity in the skull needed for a customized titanium implant.

#### Radiosurgery

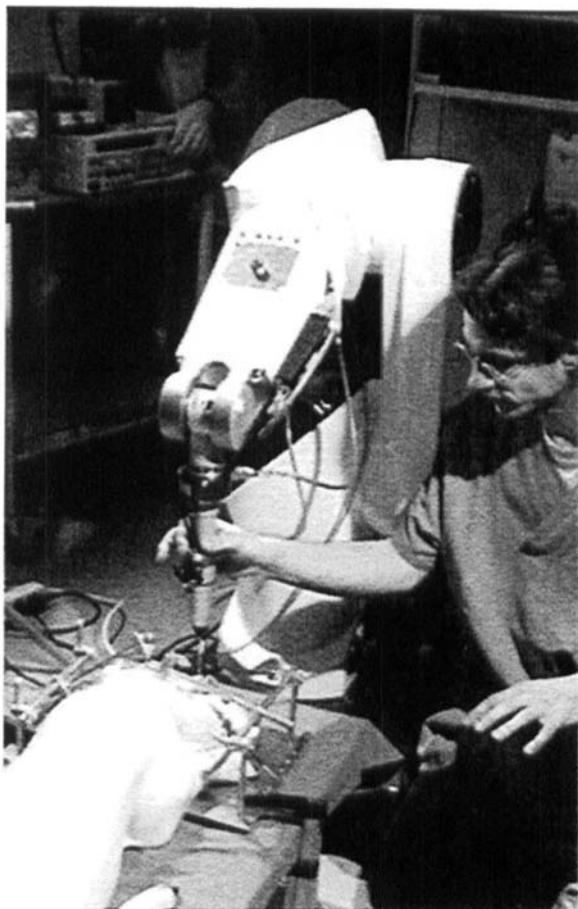
Radiation is a common means of treatment for tumors. Radiosurgery is the delivery of radiation to a tumor while attempting to spare adjacent normal tissue. In the brain, radiosurgery has typically been carried out using stereotactic frames that are rigidly fixed to the patient's skull. A novel method for precision irradiation called image-guided radiosurgery has been developed by Adler and associates at Stanford University in California.<sup>21</sup> The system consists of a lightweight linear accelerator, a Kuka robot, paired orthogonal X-ray imagers, and a treatment couch (Fig. 16). During a radiosurgery treatment session, the X-ray imaging system determines the location of the lesion. These coordinates are sent to the robot, which adjusts the pointing of the accelerator beam towards the lesion. The robot arm moves the beam through a series of preset positions to maximize the dose to the lesion while minimizing the dose to the surrounding normal tissue.

#### Ophthalmology

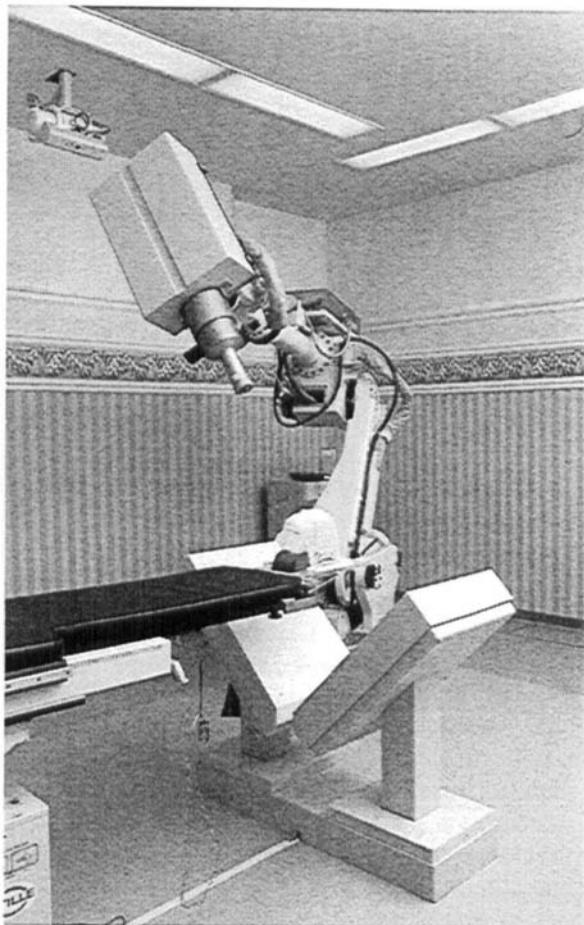
There are many surgical operations on the eye, ear, brain, nerves, and blood vessels that require extremely precise positioning and manipulation of surgical instruments. It is not uncommon for a microsurgeon to perform 150–200- $\mu\text{m}$  movements



**Fig. 14.** Planning of the bone cuts using a haptic interface (courtesy of Catherina Burghart, University of Karlsruhe, Germany).



**Fig. 15.** Registration by force-controlled manual guiding of the robot arm (courtesy of Catherina Burghart, University of Karlsruhe, Germany).



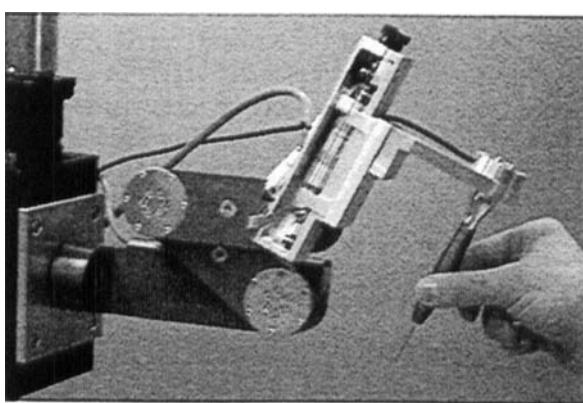
**Fig. 16.** CyberKnife robotic radiosurgery system (courtesy of Accuray, Sunnyvale, CA).

during an operation, and smaller movements would be desirable.<sup>40</sup> One representative microsurgical application is eye surgery, and prototype systems for this purpose have been developed by Das et al.<sup>41</sup> and Hunter et al.<sup>42</sup>

Taylor and colleagues at Johns Hopkins University recently developed a "Steady-Hand" robot for microsurgical augmentation<sup>22</sup> (Fig. 17). While the initial target application is eye surgery, the system is applicable to numerous clinical specialties. The system consists of four modular subassemblies: (1) an off-the-shelf XYZ translation assembly (only the Z-axis can be seen here), (2) an orientation assembly, (3) an end-of-arm motion and guiding assembly including a force/torque sensor, and (4) specialized instruments.

The major difference between this robotic device and the other robotic systems described in this review is that the Steady-Hand robot is designed to work cooperatively with the physician. In

operation, the physician will grasp the tool held by the robot and manipulate the tool with the aid of the robot. The control system of the robot senses the



**Fig. 17.** Steady-hand robot for microsurgical augmentation (courtesy of Russell Taylor, Johns Hopkins University, Baltimore, MD).

forces exerted by the physician on the tool, and by the tool on the environment, and responds accordingly. The robot can thus provide smooth, tremor-free, precise positioning and force scaling.

The Steady-Hand robot was employed in a series of experiments to test the ability of a human to position a 10-0 microsurgical needle to 250-, 200-, and 150- $\mu\text{m}$  accuracy.<sup>43</sup> A datum surface was fabricated consisting of two metallic sheets separated by an insulating surface. Three different versions of the experiments were performed: (1) unassisted series (human only); (2) hand-held (human plus Steady-Hand); and (3) autonomous (in which Steady-Hand was registered to the plates). The use of the Steady-Hand robot was found to significantly improve the ability of the human to position the needle, as success rates improved from 43% (unassisted) to 79% (hand-held) for the 150- $\mu\text{m}$  holes (autonomous performance was even better at 96.5%).

### **Cardiac**

Two companies have recently developed master-slave systems for minimally invasive surgery that are aimed at restoring the dexterity that is lost when using traditional laproscopic instruments. The introduction of these systems is a paradigm shift for surgical applications, in that the physician is no longer directly manipulating the surgical tool, but rather controlling the device from a remote interface. While these systems might be used for remote telesurgery in the future, in current practice the master and slave devices are in the same operating room. The initial clinical applications of these systems have been in cardiac surgery, although other applications are beginning to appear as well.

### **Intuitive Surgical: da Vinci**

The da Vinci system (Fig. 18), developed by Intuitive Surgical (Mountain View, CA), consists of the surgeon's viewing and control console, a control unit, and a three-arm surgical manipulator.<sup>23</sup> The system is designed to combine the freehand movements used in open surgery with the less traumatic methods of minimally invasive surgery. The surgeon sits at the console and sees a high-resolution 3D image of the surgical field. The surgeon's hands grasp the instrument handles that control the remote endoscopic manipulators and end-effectors. The surgeon's console is shown in Figure 18, and a view of the instrument handles, along with the remote manipulators, is shown in Figure 19. The manipulators provide three degrees of freedom (pitch, yaw, and insertion), and the end-effector



**Fig. 18.** da Vinci surgeon's console (courtesy of Intuitive Surgical, Mountain View, CA).

consists of a miniature wrist that adds three more degrees of freedom (pitch, yaw, and roll) and one motion for tool actuation (such as grip). The system allows increased precision by providing motion scaling, whereby large motions of the input devices can be scaled down proportionally to produce small motions at the end-effector. Finally, unintended movements caused by tremor, which typically occur with a frequency of 6–10 Hz, are filtered by applying a 6-Hz motion filter.<sup>44</sup> Design issues associated with these types of systems are described by Madhani et al.<sup>45</sup>

The da Vinci system has been used to perform over 500 procedures as of October 1999.<sup>23</sup> The system has not only been used for cardiac procedures such as fully endoscopic coronary artery bypass grafts (CABG), but has also been used for a wide variety of other procedures including Nissen fundoplication, cholecystectomy, and lumbar sympathectomy.

### **Computer Motion: Zeus**

A similar telesurgical system, called Zeus, has been developed by Computer Motion (Santa Barbara, CA). A picture of the surgeon's console is shown in Figure 20. The Zeus slave system consists of three

interactive robotic arms (two endoscopic instrument arms and one endoscopic camera arm), which are mounted on the operating room table. However, while the Intuitive Surgical system is a 6DOF system (plus grip motion), the Computer Motion system only has four degrees of freedom, and is therefore not as dexterous. Still, the performance of these systems in clinical applications is just beginning to be investigated, and it is difficult to draw conclusions about their efficacy at this point.

The clinical use of the system for endoscopic coronary artery bypass on 25 patients has been described by Boehm et al.<sup>24</sup> This study showed that endoscopic coronary artery bypass on the beating heart is possible, but further development of the technology and techniques is required to minimize the procedure time.

#### **Grenoble: Pericardial Puncture**

A prototype robot for pericardial puncture has been developed by Troccaz and colleagues at the TIMC/IMAG laboratory of Grenoble University Hospital. The robot is a 6DOF SCARA design consisting of a vertical translational axis, three vertical rotational axes, a rotation about a horizontal axis, and a last modular joint that can be a rotational or translational axis. The robot is designed as a "synergistic" device that is to be used in cooperation with a human operator. For further details, see the article by Schneider and Troccaz in this issue.<sup>46</sup>

#### **TECHNOLOGY CHALLENGES/ RESEARCH AREAS**

While a number of different clinical areas are being explored, as noted earlier, the field of medical robotics is still in its infancy, and we are just at the beginning of this era. Only a handful of commercial companies exist, and the number of medical robots sold each year is very small. Part of the reason for this is that the medical environment is a very complex one, and the introduction of new technology is difficult. In addition, the completion of a medical robotics project requires a partnership between engineers and clinicians that is not easy to establish. Technology challenges and research areas for medical robotics include both the development of system components and the development of systems as a whole. In terms of system components, research is needed in: (1) system architecture, (2) software design, (3) mechanical design, (4) imaging-compatible designs, (5) user interface, and (6) safety.

For medical robotics systems, the development of application testbeds is critical to move the field forward. These testbeds can also serve to

improve the dialog between engineers and clinicians. However, at least in the United States, it is difficult to get funding to develop these testbeds. Governmental funding agencies such as NIH or NSF will usually not fund such efforts, as they are geared more towards basic research than applied research and development, while manufacturers are usually not interested because the environment and investment payback for medical robotics is uncertain. The regulatory issues for medical robotics have not been fully explored, although several systems have received FDA approval. These factors remain obstacles to advancing the field.

In the following sections, each of the six system components listed above are briefly discussed.

1. *System Architecture.* For medical robotics to evolve as its own field, and for the cost and difficulty of developing prototype systems to decrease, the establishment of a system architecture would be an enabling step. The systems architecture should emphasize modularity (as noted by Taylor in the design of the Steady-Hand robot, which emphasizes modularity in mechanical design), control system electronics, and software.<sup>22</sup> A modular approach has also been emphasized in the Urology Robotics laboratory of Stoianovici,<sup>37</sup> where a number of mechanical modules have been developed for precision interventional procedures.
2. *Software Design.* The development of a software environment for medical robotics, possibly including an appropriate real-time operating system, is a significant challenge. Many researchers developing medical robotics systems base their software development on commercially available software packages that may not be suitable for the surgical environment. However, the low cost and widespread availability of these software packages makes their use attractive, and there are steps that can be taken (such as watchdog timers, backup systems, and error-recovery procedures) to make these systems more reliable. Still, it is believed that, along with the system architecture mentioned above, a robust software environment geared to the medical environment would be a substantial contribution. Although this software environment would still need to be customized for different surgical procedures, researchers would at least



**Fig. 19.** da Vinci instrument handles and remote manipulators (courtesy of Intuitive Surgical, Mountain View, CA).

have a starting point for their development work.

3. *Mechanical Design.* In addition to better software design, novel mechanical designs are needed to improve the utility of robotics in medical procedures. As noted in the historical review in this paper, the first recorded medical application of a robot was for biopsy of the brain, using a standard PUMA industrial robot. Although some other researchers have described the use of industrial robots for medical tasks, it is the belief of these authors and others (see ref. 2, for example) that special-purpose mechanical designs are more appropriate for most applications. In particular, these designs should be safer, as they can be designed specifically for the medical environment and customized for different medical procedures. Novel mechanical designs presented in this review include the Probot<sup>18</sup> and the Steady-Hand robot.<sup>22</sup> However, it should be noted that special-purpose designs will not enjoy the same economies of scale as more general designs, and another solution may be to develop more general-purpose medical robots with specialized end-effectors.
4. *Imaging-Compatible Systems.* With the increasing popularity of image-guided inter-

ventions, robotic systems are required that can work within the constraints of various imaging modalities such as CT and MRI. While these systems are, for the most part, still under the direct control of the physician, in the future they will be increasingly linked to these imaging modalities. In this review, some systems were noted that fall within this category, such as the MRI-compatible manipulator of Masamune et al.<sup>15</sup> and the CT-integrated robot Minerva.<sup>13</sup>

5. *User Interface.* One question that arises in the development of all medical robotics systems concerns the user interface. What is a suitable user interface for a medical robot? Should the robot be given a commanded path or volume and then autonomously carry out the task? Is a joystick or pushbutton interface appropriate, or would the physician rather manipulate the tool directly with the assistance of the robot? Is force feedback required for a high-fidelity user interface? These are all questions that require further investigation by the medical robotics community. The answer certainly will vary, depending on the medical task for which the robot is designed. It seems that medical robots will, at least initially, be more accepted by physicians if the physicians feel that they are still in control of the entire procedure.



**Fig. 20.** Zeus surgeon's console (©2001 Computer Motion, Santa Barbara, CA. Photograph by Bobbi Bennett).

**6. Safety Issues.** Safety is a paramount concern in the application of these systems. This is an area that must be addressed to move the field forward. Safety issues have been discussed by Davies<sup>47</sup> and Elder and Knight.<sup>48</sup> According to Davies, medical robotics is a completely different application from industrial robotics in that medical robots must operate in cooperation with people to be fully effective. Therefore, appropriate safety levels should be defined and discussed by the community at large. Safety measures that can be taken include the use of redundant sensors, the design of special-purpose robots whose capabilities are tailored to the task at hand, and the use of fail-safe techniques so that if the robot does fail it can be removed and the procedure completed by hand. One other safety issue for medical robotics is the need for sterilization and infection control in the operating room and interventional suite.

Davies also presents a hierarchical scheme for the host of tools available to surgeons, ranging from hand-held tools to a fully powered autonomous robot. As the hierarchy moves towards autonomous robots, the surgeon is less and less in control, and more dependent on the mechanical and software systems of the robot. Davies contends that until a consensus is developed on what level of safety is acceptable for what level of autonomy, the medical manufacturers will be slow to develop robotic systems.

Although mechanical constraints are one means of assuring safety, programmable constraints, while inherently not as safe, are more flexible. The idea is to dynamically constrain the range of possible motions.<sup>4,46</sup> Four programming modes can be envisioned: free mode, position mode, trajectory mode, and region mode. As an example, region mode is particularly suited to resection operations such as total knee replacement, in that the surgical tool is constrained to remain within a predefined region. This mode could also be valuable in the training of residents and fellows.

## CONCLUSIONS

This paper has reviewed the state of the art in surgical robotics. Several prototype and commercial medical robotics systems were described. Technology challenges and areas for future re-

search were discussed. The use of robots in medicine clearly offers great promise.

We are just in the initial stages of the application of robotics to medicine, and much more work remains to be done. In particular, the development of more testbeds is required for different medical procedures so that more experience with the technology and its integration into clinical practice can be gained. The issues of cost, safety, and patient outcomes also need to be considered. Although there have been some modestly successful commercial medical robots, such as ROBODOC and da Vinci, they still are not completely accepted by the medical community.

It may be that the full benefits of robots in medicine will not appear until more integrated systems are developed, in which the robots are linked to the imaging modalities or to the patient anatomy directly. This link will highlight the potential advantages of robots, such as the ability to follow respiratory motion, and enable physicians to successfully complete procedures that can only be imagined today.

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