The American Journal of Surgery

The American Journal of Surgery 188 (Suppl to October 2004) 2S–15S

Robotic technology in surgery: past, present, and future

David B. Camarillo, M.S.[a], Thomas M. Krummel, M.D.[b,*], J. Kenneth Salisbury, Jr., Ph.D.[b,c]

[a]Department of Mechanical Engineering, Stanford University, Stanford, California, USA
[b]Department of Surgery, Stanford University School of Medicine, 701B Welch Road, Suite 225, Stanford, California 94305-5784, USA
[c]Department of Computer Science, Stanford University, Stanford, California, USA

Abstract

It has been nearly 20 years since the first appearance of robotics in the operating room. In that time, much progress has been made in integrating robotic technologies with surgical instrumentation, as evidenced by the many thousands of successful robot-assisted cases. However, to build on past success and to fully leverage the potential of surgical robotics in the future, it is essential to maximize a shared understanding and communication among surgeons, engineers, entrepreneurs, and healthcare administrators. This article provides an introduction to medical robotic technologies, develops a possible taxonomy, reviews the evolution of a surgical robot, and discusses future prospects for innovation. Robotic surgery has demonstrated some clear benefits. It remains to be seen where these benefits will outweigh the associated costs over the long term. In the future, surgical robots should be smaller, less expensive, easier to operate, and should seamlessly integrate emerging technologies from a number of different fields. Such advances will enable continued progress in surgical instrumentation and, ultimately, surgical care. © 2004 Excerpta Medica, Inc. All rights reserved.

The playwright Karel Capek coined the term "robot" in his satirical drama *Rossum's Universal Robots* [1]. He derived the word robot from the Czech *robota* (slave labor). In the play, machines were created to do mundane work so that people would be free to pursue more creative interests. One of the characters finds a more sinister application, and soon the machines are employed for destructive rather than constructive purposes. As the fictional robotic technology improved, the machines developed an increasing amount of "intelligence." Ultimately, the robots became stronger and smarter than their masters and, believing that humankind was a nuisance, began to exterminate the population. The play caused an uproar; people became afraid that robots might replace them on the assembly line. Some interpreted Capek's play as a warning, concluding that robots, as a "cure" for human work, would be worse than the original disease.

Several famous works of science fiction have since popularized Capek's notion of robots as fully autonomous anthropomorphic machines, from the classic novels of Isaac Asimov, including *I, Robot*, to George Lucas' *Star Wars* series, and the more recent *Terminator* films [2]. Asimov's influence has left us with many probing questions as to the role robots should play in society. In his short story, "Runaround," he described "The Three Rules of Robotics" [3]:

1. A robot may not injure a human being, or, through inaction, allow one to come to harm.
2. A robot must obey all orders given to it from humans, except where such orders would contradict the First Law.
3. A robot must protect its own existence, except when to do so would contradict the First Law or the Second Law.

These rules remain a reasonable ethical framework for the development of robots as applied to surgical care.

Although the fictionalized versions have caricatured our popular conception of a robot, a less glamorous, scientific definition may be stated as follows: A robot is a reprogrammable, computer-controlled mechanical device equipped with sensors and actuators [4,5]. Moreover, very few robots in development are designed to be anthropomorphic. Under this definition there lies a range of robots from the simplest, single-axis manipulator, up through the most complicated, highly autonomous cyborg. For the moment, the state-of-the-art in artificial intelligence is such that most robots have either a limited level of autonomy, or they are relegated to perform highly structured, low-risk tasks. Thus, the current generation of robotic devices has little in common with science fiction. One is, however, reminded of the statement that there is no such thing as "science fiction"—only scientific eventuality.

---

* Corresponding author. Tel.: +1-650-498-4292; fax: +1-650-725-3918.

E-mail address: tkrummel@stanford.edu

0002-9610/04/$ – see front matter © 2004 Excerpta Medica, Inc. All rights reserved.
doi:10.1016/j.amjsurg.2004.08.025

Table 1
Advantages and disadvantages of human and robot capabilities: a balance of these elements results in the most useful technologies

	Surgeons	Robots
Advantages	Task versatility	Repeatability
	Judgment experience	Stability and accuracy
	Hand-eye coordination	Tolerant of ionizing radiation
	Dexterity at millimeter-to-centimeter scale	Diverse sensors
	Many sensors with seamless data fusion	Optimized for particular environment
	Quickly process extensive and diverse qualitative information	Spatial hand-eye transformations handled with ease
		Manage multiple simultaneous tasks
Drawbacks	Tremors	Expensive
	Fatigue	Cumbersome
	Imprecision	Large
	Variability in skill, age, state of mind	Inability to process qualitative information
	Inability to process quantitative information easily	Not versatile
	Ineffective at submillimeter scale	Technology still in infancy

The development of practical robots is a recent phenomenon, focusing on nonanthropomorphic manipulators. The first programmable industrial manipulators were developed in the 1940s. Devol, who is credited as the father of the robot, developed a magnetic process controller that could be used to manage these first robotic machines [6]. As computer technology began to develop, so did the field of robotics and, in 1954, Devol patented the first manipulator with playback memory. This event may well mark the beginning of the modern robotic age. Devol's device was capable of point-to-point motion and was the forerunner of devices used by industry today. In 1961, Engelberger formed a company called Unimation and began the commercial production of robots for industry [6].

Robotic development has been frequently motivated by the need to manipulate hazardous items, such as poisonous and radioactive materials. In the 1940s remote manipulators, or teleoperator systems, began to emerge. Faced with the need to get complex jobs done with existing technology, these devices were controlled by humans. Using visual and haptic (touch and kinesthetic) display devices to enable humans to see and feel the remote tasks they performed, these systems provided human operators with "master" input devices (glorified joysticks) to facilitate performance of complex tasks from a safe distance [7]. Since then, robots have been used in industry for everything from arc welding to assembling complex electronic devices. Applications for these devices have reached beyond the industrial arena into areas such as agriculture, space exploration, military, oceanographic exploration, education, and now surgery**.**

With the development of minimally invasive surgical techniques in the late 1980s, surgeons no longer needed to physically place their hands within the body to perform an operation. Minimally invasive surgery (MIS), or minimal access surgery, thus revolutionized the concept of surgical procedures. In MIS, instruments and viewing equipment are inserted into the body through small incisions. Long manipulators are used to perform operations under manual guidance. This minimizes the collateral surgical trauma of an access incision and results in quicker recovery. These procedures have many advantages, but with conventional endoscopic instrumentation, there are substantial difficulties. Loss of wrist articulation, poor touch feedback, the fulcrum effect, loss of 3-dimensional vision, and poor ergonomics of the tools mean that only relatively simple procedures are truly widespread [8,9]. The promise of robotic assistance is to eliminate many of these impediments, with the concurrent enhancements of motion scaling and tremor filtration. The surgeon may now remotely teleoperate a robot in a comfortable, dexterous, and intuitive manner. In fact, Satava [10] and Ballantyne and Moll [11] have suggested that, in the history of surgical evolution, laparoscopic surgery is a "transitional" technology leading to robotic surgery.

Robots have a number of advantages over humans in performing rote manipulation tasks. Their accuracy and repeatability allowed for robots to penetrate the market in the industrial sector in the 1970s with clear economic benefit [12]. However, in surgery the environment is often far less structured than in industry, highlighting some of the weaknesses in current robotic devices, such as substantial loss of force feedback (haptics) and a lack of adaptability. Using the RoboDoc Surgical System (Integrated Surgical Systems, Davis, CA) to mill a femur shaft to accept the femoral component of an artificial hip joint is an ideal implementation of a robotic tool, as is a stereotactic biopsy. However, currently it is not possible to "program" a robot to autonomously perform a splenectomy. Nevertheless, these limitations do not prevent robots from being useful in the operating room; rather considerable human input and guidance are needed. Surgical robots can then be viewed as "extending or enhancing human capabilities" rather than replacing humans, in contrast to the example of industrial automation [13]. Table 1 summarizes the strengths and weaknesses of robots compared with humans in relation to surgery [14,15].

A convincing illustration of how humans and robots can work together to improve surgery is that of retinal repair. Retinal surgery requires precise positioning of a laser, within 25 μm of a target, in order to avoid damaging retinal blood vessels. If a retinal vessel is damaged, a retinal hematoma and subsequent blindness may occur. The unaided human hand cannot reliably direct a surgical instrument to within <100 μm of its target [16]. Furthermore, as the surgeon becomes fatigued, an intention tremor develops that further decreases accuracy. Finally, the eye itself has a natural motion of 200 Hz and acts as a moving target [2]. The combination of these factors creates an operative situation that lacks the precision needed, but is well within the capabilities of current robotic technology. Robotic systems have been developed for this application to overcome human limitations. Using computer integration, the motion of the eye can be tracked and the eye made to appear stationary; moreover, the surgeon's tremor can be filtered. The end result is a system that can position a laser to within 10 μm of a target, thus making it 10 times more accurate than an unaided human hand [15]. This scenario demonstrates how the synergy between robot and surgeon can result in improved task performance.

To fully leverage this promising technology for surgical intervention, and to continue relevant innovation, it is essential that there be communication and mutual understanding among surgeons, engineers, entrepreneurs, and healthcare administrators. On the clinical side, this starts with an open mind toward resolving the unmet clinical need or the unsolved clinical problem and a willingness to evaluate promising technologies as a means for achieving resolution [2].

In this article we develop a taxonomy for surgical robots. Robot characterization is explained to provide a background as to how clinical requirements translate into technical specifications. Additionally, the historical evolution and current implementation of the da Vinci robot (Intuitive Surgical, Inc., Sunnyvale, CA) are detailed as part of a case study of innovation in the field. Finally, several research frontiers are surveyed as to current developments and we speculate on a framework for the future role of robotics in surgery.

Taxonomy

Robot-assisted surgery, as a new and emerging field, has fallen loosely under the category of computer-aided surgery [5,17]. This distinction comes from the use of a microprocessor that controls movement and processes sensory data. The landscape of computer-aided surgery is not yet concretely defined, and there are some related subfields that should be distinguished. Each field may be characterized by the devices and systems that it uses.

Medical imaging is an exceptional example of a specialty area that has been greatly augmented by the now-widespread availability of fast and cheap computing. Magnetic resonance imaging (MRI) scans generate 3-dimensional models of soft-tissue anatomy that can be integrated with various technologies for image guidance. MRI is a pillar in image-guided surgery, but MRI-based systems for computer-aided surgery are not particularly robotic and do not rely significantly on computer-controlled motions. Computed tomography (CT), however, is an imaging modality that uses a manipulator to articulate a scanner by means of actuators, sensors, and a processor. Therefore, any surgical application that uses CT is considered a robot-assisted system; many of these systems are used for image guidance. CT scans are ubiquitous in many surgical applications, but it requires detailed attention to the technology itself to realize that this is an exemplary application of robotics to surgery.

Motion tracking is another closely related field. It is used to obtain a precise quantitative measure for the spatial location of surgical instruments and/or anatomy. Optoelectronic tracking systems that use light-emitting diodes (LEDs) fastened to surgical instruments and cameras to monitor the LEDs are hybrid imaging/tracking systems. There also exist purely mechanical tracking systems in which a mechanical linkage is equipped with joint-angle sensors (encoders), so the location of the tool-end point (end-effector) of the linkage may be calculated. Because neither of these types of systems is mechanically powered, they are not considered robots. Figure 1 is a Venn diagram illustrating the areas of computer-aided surgery most relevant to robotics; it is not meant to be an exhaustive list of subfields. Robotics has found its place within the domain of computer-aided surgery.

Over the past 20 years, a wide array of surgical robots has been developed and implemented clinically on varying scales. These developments have been widespread enough to warrant an organization of the different varieties of robots into a taxonomy, and several authors have touched on this subject [5,14,18]. Taylor [14] mentions that robot classification in general can be based on technology, application, or role. A technology-based taxonomy might have categories such as autonomous and teleoperated robots, whereas an application-based taxonomy might have such categories as cardiology and urology. The problem with these 2 approaches is that, on either side, classifications may become quite esoteric and lose meaning for those outside the involved community. Furthermore, this is an artificial decoupling because the application that defines the problem is divorced from the technology that provides the solution. Role-based classifications can be more useful because they are far-reaching and speak to technology developers as well as end-users. Such a taxonomy can be a means of communication among all interested groups in describing needs, requirements, performance, and specifications.

We define our procedural role–based taxonomy as one that can be divided into 3 discrete categories:

1. Passive role: The role of the robot is limited in scope, or its involvement is largely low risk.
2. Restricted role: The robot is responsible for more invasive tasks with higher risk, but is still restricted from essential portions of the procedure.
3. Active role: The robot is intimately involved in the procedure and carries high responsibility and risk.

To better understand this classification, consider the analogy of the evolution of a surgeon's career. As a medical

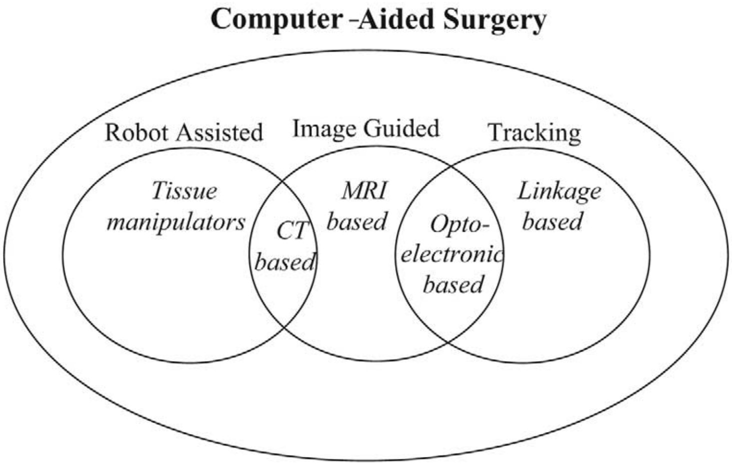

Fig. 1. Subspaces of computer-aided surgery relevant to robotics and depiction of subfields relevant to robotics. Some technologies are overlapping between subfields. Categorization as robot-assisted computer-aided surgery requires processing capabilities with sensors and actuators for controlled motion. CT = computed tomography; MRI = magnetic resonance imaging.

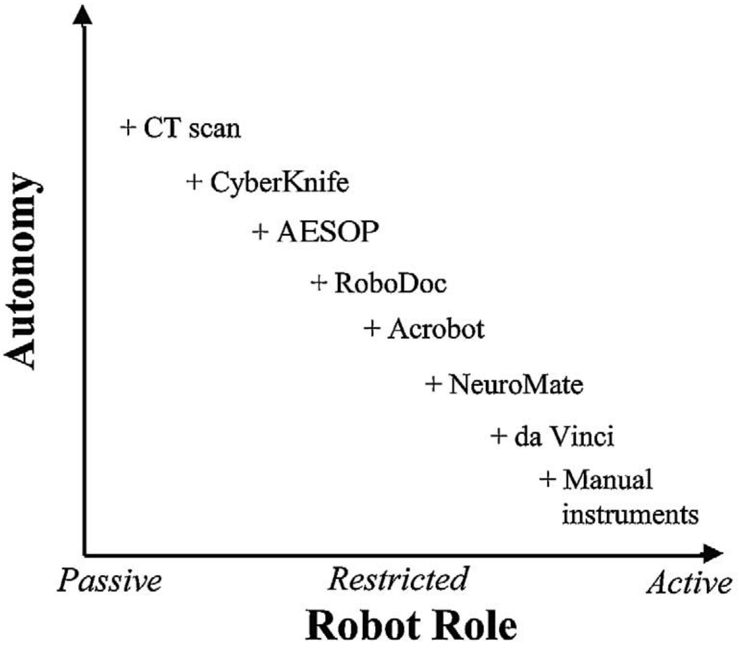

Fig. 2. Tradeoff between procedural role and autonomy. Procedural role indicates the level of responsibility and involvement the robot has with the patient during a procedure. Robot role in a procedure scales up with greater duration, scope, invasiveness, and risk, which decreases the level of autonomy in current systems, including Acrobot (Acrobot Company Limited, London, England), Automated Endoscopic System for Optimal Positioning (AESOP; formerly Computer Motions, Inc., Goleta, CA; now operated by Intuitive Surgical, Inc., Sunnyvale, CA), computed tomography (CT), CyberKnife (Accuray Inc., Sunnyvale, CA), da Vinci (Intuitive Surgical), and NeuroMate (Integrated Surgical Systems, Davis, CA).

student during clinical training, one has a relatively passive role in low-risk tasks such as camera operation or skin closure. As a surgical resident, one is progressively given broader responsibility and will often carry out higher-risk functions. There may still be other portions of the procedure that are critical or more difficult, which the attending surgeon would perform. Once the surgeon has completed residency and fellowship, responsibility is total.

This classification might seem to suggest that robots with an increasingly active role are somehow superior. However, this is not yet the case due to present limitations in artificial intelligence. For example, an active-role robot assisting in a high-risk task requires significant human interaction and supervision, resulting in increased burden on the surgeon. Similarly, a highly autonomous robot can only perform tasks that are either narrow in scope, or low risk (passive role). This is an important tradeoff to recognize in currently existing systems, and is illustrated in Figure 2. A brief description of each of these robots, and how they fit in this space is given below.

CT scan

CT is a familiar imaging modality in which a manipulator articulates a scanner to different locations to obtain various cross-sectional images. The robotic component of the CT is completely autonomous as it scans the relevant anatomy, and it has no interaction with the patient other than a very small dose of radiation.

CyberKnife

Accuray (Sunnyvale, CA) has developed the first stereotactic image-guided system that performs real-time registration (Fig. 3). CyberKnife can be used to radiate a variety of tumors, even in deformable organs such as the lungs by tracking the motion of the chest and oscillating the robot synchronously. The treatment process begins with preoperative CT images of the tumor that are input to a path-planning algorithm that generates the spatial path for the linear accelerator carried on the robot. At procedure time, it automatically registers the preoperative path by correlating real-time radiographic images with the preoperative CT images to locate and eliminate the tumor in the patient. CyberKnife is completely autonomous during the procedure while it manipulates the linear accelerator directed toward the tumor. However, before the procedure, the computer-generated path must be carefully reviewed and potentially edited by the surgeon or radiotherapist, thus diminishing autonomy. Because the level of radiation is sufficient to destroy cancerous cells, CyberKnife assumes a more active role than CT. While engaging in a highly energetic interaction, the robot does not make actual physical contact with the patient, so the scope of its involvement with the patient is still constrained.

AESOP

Computer Motion, Inc. (Goleta, CA: now operated by Intuitive Surgical) began to market Automated Endoscopic System for Optimal Positioning (AESOP) in the United States in 1994 as the first surgical robot approved by the US Food and Drug Administration (FDA). It is a voice-controlled robot that positions an endoscope [4]. AESOP is fairly autonomous in that it controls its own motion with only a few simple voice commands. Its role is not passive, because it is in constant contact with tissue throughout the entire procedure. However, it is only used for imaging, which is low risk and does not involve any invasive manipulations; therefore its role is considered restricted.

RoboDoc

Orthopedics was an early area of success in surgical robotics due to the rigid and predictable behavior of bone. RoboDoc is used for the bone-milling portion of total hip arthroplasty. It is an image-guided system that preoperatively requires the surgeon to view CT images and select the appropriate implant and its placement. The system then generates the cutting path so that it may do this portion of the procedure autonomously. The surgeon must participate in the registration of the preoperative images by locating anatomical landmarks to synchronize the CT images with the physical patient. The preoperative setup and manual registration process decrease the level of autonomy [14]. Milling is a very invasive and risky portion of the procedure, but because total hip arthroplasty is a long and complex procedure in which bone drilling is only a single step, the robot's role is still considered restricted.

Acrobot

The Acrobot Active Constraint Robotics system (Acrobot Company Limited, London, England) was developed for the technically challenging total knee arthroplasty (Fig. 4). It is a bone-drilling instrument with motors to constrain its motions to a region defined by preoperative images. This "hands-on" approach allows the surgeon to directly feel the forces of cutting, but ensures that certain regions are protected from the drill [5]. This is a lower level of autonomy for the robot, and its role is similar to RoboDoc; however, because it uses small motors, and since the surgeon is in direct control, the system is inherently safer. It is considered to have an active role [19].

NeuroMate

Stereotactic needle placement was the earliest recorded application of surgical robotics dating back to 1985. NeuroMate (Integrated Surgical Systems, Inc.) is a present-day version used in stereotactic neurosurgery. It is another image-guided system that uses anatomical landmarks for manual registration. The function of NeuroMate is to determine the location of insertion for a drill, probe, or electrode based on the preoperative images. It then positions the instrument at the correct location for insertion, locks the joints, and thereafter acts as a guide allowing the surgeon to carry out the procedure [12]. Although the robot is not powered as the instruments are introduced into the surgical field, it still passively constrains the motion of the surgeon significantly. NeuroMate therefore can be considered to have a moderate level of autonomy [20].

da Vinci

The da Vinci system (Fig. 5) is described in more detail later in this article. It is a teleoperated system in which the

Fig. 3. CyberKnife Stereotactic Radiosurgery System. (Courtesy of Accuray Inc., Sunnyvale, CA.)

Fig. 4. Acrobot Active Constraint Knee Arthroplasty System. (Courtesy of the Acrobot Company Limited, London, England.)

surgeon sits at a remote console on one side of the operating room, and directly controls the motion of instruments in the surgical field on the other side of the room. The surgeon is provided with a stereoscopic visual display that is colocated with "master" control handles (haptic interfaces) that direct movements of the "slave" instruments inside the patient's body. Because the robot closely mimics the hand motions of the surgeon, the level of autonomy is very low. The da Vinci system has been used for a number of types of minimally invasive procedures, including cardiac, abdominal, and uro-

Fig. 5. The telerobotic da Vinci Surgical System. (Courtesy of Intuitive Surgical, Inc., Sunnyvale, CA.)

logic procedures. Under human control, the robot engages in sustained physical contact with the patient's tissues using a range of instruments from simple forceps, to scissors and scalpels, to complex cautery and stapling tools. Therefore, it is considered to assume an active role.

Manual instruments

It is obvious that traditional surgical instruments have no autonomy (they are not actual robots). Because the surgeon has complete control over the instruments, they can be used for most of the necessary manipulation tasks. Manual surgical instruments are used in highly active roles in almost all surgical procedures.

Robot characterization

If one could shop for a surgical robot on the Internet, in deciding which robot to buy it would be helpful to be able to open a Web page and read about the robot's performance and specifications to ensure that it fits the desired application. We are still years away from that possibility; indeed, currently it is difficult to even get a good data sheet from a vendor. Here, we aim to provide some brief explanations of robot characteristics so that the reader will know enough to be able to ask the right questions in communicating with a robot manufacturer, or to determine meaningful requirements when participating in the process of innovation. Some of the more significant issues are detailed below.

Degrees of freedom

Degrees of freedom is an important concept in robotics in that it defines the number of independent motions of which a robot is capable. Alternatively, it can be understood as the number of "knobs" one can turn to control the tool tip, which is usually equal to the number of motors used to drive the robot. The number of degrees is significant because it describes how constrained the motion at the end-effector of the instrument will be. For example, a robot with 6 degrees of freedom should allow for motion of the end-effector in the x, y, and z directions, as well as any desired rotation in pitch, yaw, and roll (Fig. 6). A robot with only 3 degrees of freedom often does not allow for choice in rotation, and only allows choice of motion in the x, y, and z directions.

Workspace and resolution

Workspace is a simple concept, loosely defined as all of the space that the end-effector can reach. Typically, one might give a rough estimate, saying that a robot has a 1-m^3 workspace, which can be imagined as a box with 1-m sides that is centered on the robot. The robot would be able to reach all space within this box. A robot's workspace is obviously limited by the length of its links but it is also constrained by joint limits and collisions with its own links or other obstructions such as anatomy. Resolution is related to workspace in that it defines the smallest incremental movement the robot can make or measure (these can be different). It is often specified as a length; eg, cholecystec-

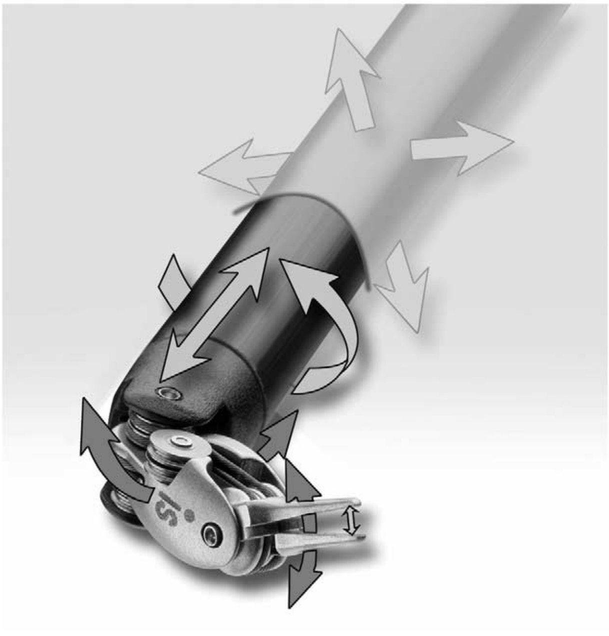

Fig. 6. Degrees of freedom. A robotic instrument with 6 degrees of freedom is shown. The first 2 degrees of freedom are the ability to pivot about the entry port in 2 planes (*hatched arrows*). The next 2 degrees are the ability to move in and out as well as the ability to roll the instrument (*light arrows*). The final 2 degrees of freedom are the ability to pitch and yaw the wrist (*dark arrows*). These 6 degrees of freedom allow for an arbitrary choice of position and orientation of the jaws, which is not possible with conventional endoscopic instruments. Final small bidirectional arrow is for grasp, which is sometimes called the seventh degree of freedom. (Courtesy of Intuitive Surgical, Inc., Sunnyvale, CA.)

tomy requires only 2-mm resolution and would never require accuracy <2 mm.

Mechanism type

There are 2 traditional broad categories of robot mechanical designs, serial and parallel. Serial linkages are the most common and are characterized by links that are serially connected, similar to the arm of a modern desk lamp. A parallel linkage has multiple links that run in parallel and meet at a common point. A simple 1-degree-of-freedom example is a scissor jack, which has 2 parallel links that allow it to lift a car in 1 direction. The major difference is that whereas serial linkages have a larger workspace, which is required to move a lamp over any region of a large desk, a parallel linkage is stiffer because it has multiple links supporting each joint, as is necessary to carry heavy weight like a car. The increased stiffness also improves accuracy.

Inertia and stiffness

Inertia and stiffness are both related to material properties. The inertia of a robot is determined by its size and the density of its material. Higher inertia leads to a more sluggish robot, because it is difficult to accelerate and decelerate a large mass (or larger, more powerful motors will be required, which inevitably drive up the cost). In addition, greater inertia makes safety a more critical concern because the robot will gain kinetic energy as it moves. Robot stiffness is determined by the stiffness of the material and its geometry. If a push is given to the end-effector of the robot as it attempts to maintain a certain position, the robot will always give somewhat according to its stiffness. The stiffer the robot is, and the less springlike give it has, the easier it is to maintain control and accuracy. However, high stiffness also increases safety concerns in case of inadvertent impact, as the robot is less compliant.

Speed, force, and backdrivability

Every robot has a transmission system to deliver force from its actuators to its end-effector. The gearing of a transmission might take 50 revolutions of the motor to result in only a tiny motion at the end-effector. This scaling down of velocity allows for forces to be scaled up. For particular applications, it is important to bear in mind the tradeoff between the force and speed, as it is expensive to achieve both. For example, in a high-force task, such as bone drilling, one should not expect the robot to move quickly. An additional effect from a high gear ratio is that it becomes more difficult for the surgeon to manually grab and backdrive the end-effector due to the force scaling. This is the same effect one would experience while trying to push a car that was still in first gear. Backdrivability is essential in case the surgeon should ever want to move the robot by hand while it is unpowered.

Dynamic range

In a particular surgical procedure, there may be some portion of the operation, such as bone drilling, that requires high force. In the same procedure, there also may be some work, such as suturing, that requires a small, fine-resolution force. The ratio between this highest and lowest force is known as the force dynamic range. This is an important specification to know early on, as it can be difficult to design a robot with high dynamic range similar to human range.

Force control versus position control

Force control and position control are commonplace terms in the robotics world and, thus, deserve some attention. In position control, the robot attempts to follow some desired trajectory in space. This type of scheme would clearly be appropriate for a robot delivering radiation therapy according to some path in free space. Force control, on the other hand, can be used when the robot is in contact with some surface, because it is often important to control the amount of force it exerts on that surface. A bone-drilling robot might use a force control scheme to ensure smooth cutting combined with position control to stay within some region. A hybrid approach such as this is most likely what the surgeon actually does. For example, a surgeon is careful to accurately position a knife and cut 3 mm deep into the tissue, which is a position control scheme. However, if the surgeon feels a significantly high force, he or she may abandon the 3-mm goal and instead modulate the force to avoid damaging some unanticipated structure.

Bandwidth

Bandwidth, an important system specification, is best understood by a simple experiment that is used to measure it. If an input signal is given to the robot to move back and forth very rapidly, the robot will attempt to execute this instruction and move at the desired rate. As the input frequency is increased, the robot eventually will not be able to keep up due to limits in stiffness and inertia (ie, the robot is too heavy and floppy, so it falls behind the command). This limiting frequency is known as bandwidth. One can easily see the importance of bandwidth in a teleoperated system. As the surgeons hands move quickly, the robot's bandwidth must be higher than the frequency with which the surgeon is moving, or the robot will not be able to keep up and on track. We can more precisely speak of bandwidth of motion (ie, how fast can we follow a commanded position with good fidelity) as well as bandwidth in force control (ie, how fast can the robot accurately exert commanded forces or adjust to disturbances).

Historical case study: da Vinci

The concept of telepresence surgery has been of interest for some time. For example, it was proposed by the National Aeronautics and Space Administration (NASA) in 1972 as a method for providing remote surgical care to orbiting astronauts [21]. At that time, the limitations of robotic and computer systems made the development of such a system impossible. Furthermore, time delay is a substantial problem. Subsequent advances in computing power and component miniaturization, coupled with the emergence of minimally invasive surgical techniques for the performance of complex operative procedures, have led to renewed interest in the application of telepresence surgery. Telepresence surgery refers to the remote operation of a robot to perform a surgical procedure [16]. This occurs by placing an electromechanical system between the surgeon and the patient to convert physical motion into electrical signals with the help of a computer. This signal is sent from the surgeon's master robot to the slave robot at the operating table on the other side of the room, or beyond.

In the late 1980s, motivated by the rapid growth of MIS and the shortcomings of existing surgical instruments, researchers at SRI International (Menlo Park, CA) began to look for ways to enhance surgeons' skills in MIS and microsurgery. Beginning with funding from the National Institutes of Health (NIH) in 1990, SRI's team developed a successful prototype system that soon became known as the "SRI system." This seminal work combined advances in remote manipulation with force feedback, stereoscopic imaging, multimodal sensory feedback, and ergonomic design, and enabled enhanced performance of MIS and remote surgical tasks.

The early success of the SRI system caught the attention of the Defense Advanced Research Projects Administration (DARPA). DARPA planners, led by Dr. Richard Satava, envisioned telesurgery being used by military surgeons to perform life-saving surgery on wounded soldiers on the battlefield to preserve life until they could be evacuated to a military hospital. It was theorized that, performing telesurgery via satellite, the military's best trauma surgeons could treat wounded soldiers at multiple locations from hundreds of miles away, removed from the hazards of the battlefield.

In 1995, the Intuitive Surgical Corporation was formed to develop the commercial technology required to bring telerobotic capabilities to MIS. Using technology developed at SRI, IBM (Yorktown Heights, NY), and the Massachusetts Institute of Technology (Cambridge, MA), Intuitive's engineers developed robotic arms and instruments with the number of degrees of freedom required for complex reconstructive surgery through 1-cm incisions. At the same time, the Intuitive team was designing a 3-dimensional video camera and stereo viewer to provide more immersive visualization. The name of the company derives from 1 of telesurgery's primary goals: creation of a surgeon-robot interface so transparent to the surgeon that his or her full set of skills can be used in a natural and instinctive manner.

When performing telesurgery, the surgeon sits at the surgeon control console, head tilted forward and eyes peering down. During the procedure, the surgeon's hands are held in a comfortable position and inserted into the system's master interfaces. A computer is used to monitor hand positioning, which is sampled at $>$1,300 times per second as the case proceeds. Using motion sensor information and kinematic models of the master and slave, the computer system issues the actuator drive commands necessary to move the robot arms and provide feedback. The position of the camera, mounted on a robotic arm, can be adjusted by the surgeon for the best view of the surgical site. Accurate visualization is critical because visual cues are used to compensate for the loss of haptic feedback. Magnification is also possible ($\times$2 to $\times$10). This visual magnification is matched by hand-motion scaling capabilities. This increases surgical precision and fine motor control by reducing the surgeon's large hand movements to the scale of the camera view. Normal hand tremors are filtered simultaneously while permitting natural hand movements, much like open surgery.

When viewing the surgical field through the console, the surgeon can see the end-effectors of the robotic arms (the instrument tips) as they move under direction. The surgeon receives some force sensation, or haptic feedback, from the instruments. This haptic feedback is currently limited to interaction with rigid structures, such as tool-on-tool collisions, and not soft tissues. This requires the surgeon to rely on visual feedback in tasks such as suturing. Careful attention must be paid to visual cues when pulling on a suture, or it will easily break before the surgeon feels the excessive tension.

From a clinical point of view, a small mechanical joint called the EndoWrist (Intuitive Surgical) is a key component of the system. The highly mobile EndoWrist gives the surgeon the ability to reach around, beyond, and behind. The motion of the EndoWrist is monitored by the computer so that the control algorithms can translate the surgeon's motions to the robot's wrist. The computer translates the surgeon's hand movements into the same movements of the instruments (Fig. 7), avoiding the reverse-fulcrum–induced movements of traditional MIS. The wrist can roll, pitch, yaw, and grip, allowing the surgeon a total of 7 degrees of freedom for each hand. Moreover, the system can apply anything from a fraction of an ounce of force for delicate suturing to the several pounds of force necessary to retract large tissue structures.

The instrument tips, or end-effectors, are a combination of standard surgical instruments and novel mechanism designs. Surgeons want to have the same interaction with the tissue they have always had. Conventional surgical instruments are the result of 150 years of surgical experience in manipulating and cutting various types of human tissue. Therefore, the very ends of the instrument tips are made to resemble conventional instruments used in open surgery, whereas the rest of the design is entirely new. The instruments can be sterilized and interchanged during surgery. Central to achieving adoption of a technology is that the instruments provide surgeons with a feeling and performance similar to their traditional instruments.

In its current configuration this surgical device is unlike most industrial telemanipulators. Recall that an important driver of industrial devices was the essential need to separate the master controller from the slave end-effector for safety reasons (toxic or radioactive environments). Current conventional surgical applications find distance separation a distinct disadvantage. The surgeon at the controller console, assisting surgeons, and nurses at the patient's side interact frequently with the slave end-effectors, removing and changing surgical instruments. This requires very safe and human-friendly engineering in the tool interface. Telerobotic surgery also requires a radically different priority. Most industrial telerobots have simple safety systems that protect themselves in the event of failure. In less complex applications, the robot is the high-value item. A telesurgical system has to protect the patient first. During a procedure, all FDA-approved systems monitor themselves continuously and will shut down and alert the surgeon if a problem arises.

Future of robotics in surgery

New applications of the technology are beginning to emerge as creative surgeons do their work; unpredicted uses in areas such as urology as well as bariatric and plastic surgery have been found. Giving the surgeon the ability to control >2 arms has proved to be unexpectedly useful, essentially allowing surgeons to become their own assistant. Nevertheless, present-day robotic surgical systems have limitations that have slowed the widespread introduction of the technology. A major barrier is cost. As an example, the da Vinci system is priced at nearly US$1 million. A second major concern is the cumbersome and unwieldy nature of robotic systems that require considerable space and additional time for setup. In the time-pressed operating room, compact functionality is highly desirable, and current robotic systems have yet to deliver in this regard.

Another area that will require optimization is the process of FDA approval of safety and regulatory issues. It has been a challenge for robot manufacturers to convince the FDA that these systems are acceptably safe, but progress has been made, and, as time passes, credibility will come with experience. Progress needs to be made, for example, in defining what it means to be safe with highly mobile electromechanical devices. This is difficult enough when real-time human judgment is still in the loop, but when progressively more autonomous capabilities are introduced, even more difficulties will arise in setting standards of acceptable risk.

Emerging technologies

We can expect that soon-to-arrive robotic surgical systems will begin to provide a centralized platform within which existing and emerging technologies can be used. It is quite easy to imagine integrated imaging, navigation, and enhanced sensory capabilities being available in the next generation of telesurgical systems. Equally plausible will be the introduction of general skill-training simulations and patient-specific rehearsal capabilities.

Another major advancement in robotic technology will be a reduction in the scale at which these systems operate. Present-day systems have augmented surgeon performance in existing procedures; however, the physical scale is largely unchanged from conventional manual procedures. Robotics has the potential to greatly scale down a surgeon's motions so that, in cooperation with the computer, surgical manipulations on a microscale would be possible. This would enable performance of procedures that are currently impossible given human force and position resolution. Advancement in the miniaturization of robotic mechanisms will most likely require entirely new materials and manufacturing processes combined with scalable designs to ensure performance and ease of assembly.

Smaller mechanisms will lead to many new applications for robotics in medicine. Catheter-based treatments could benefit substantially by integrating robotic technologies to

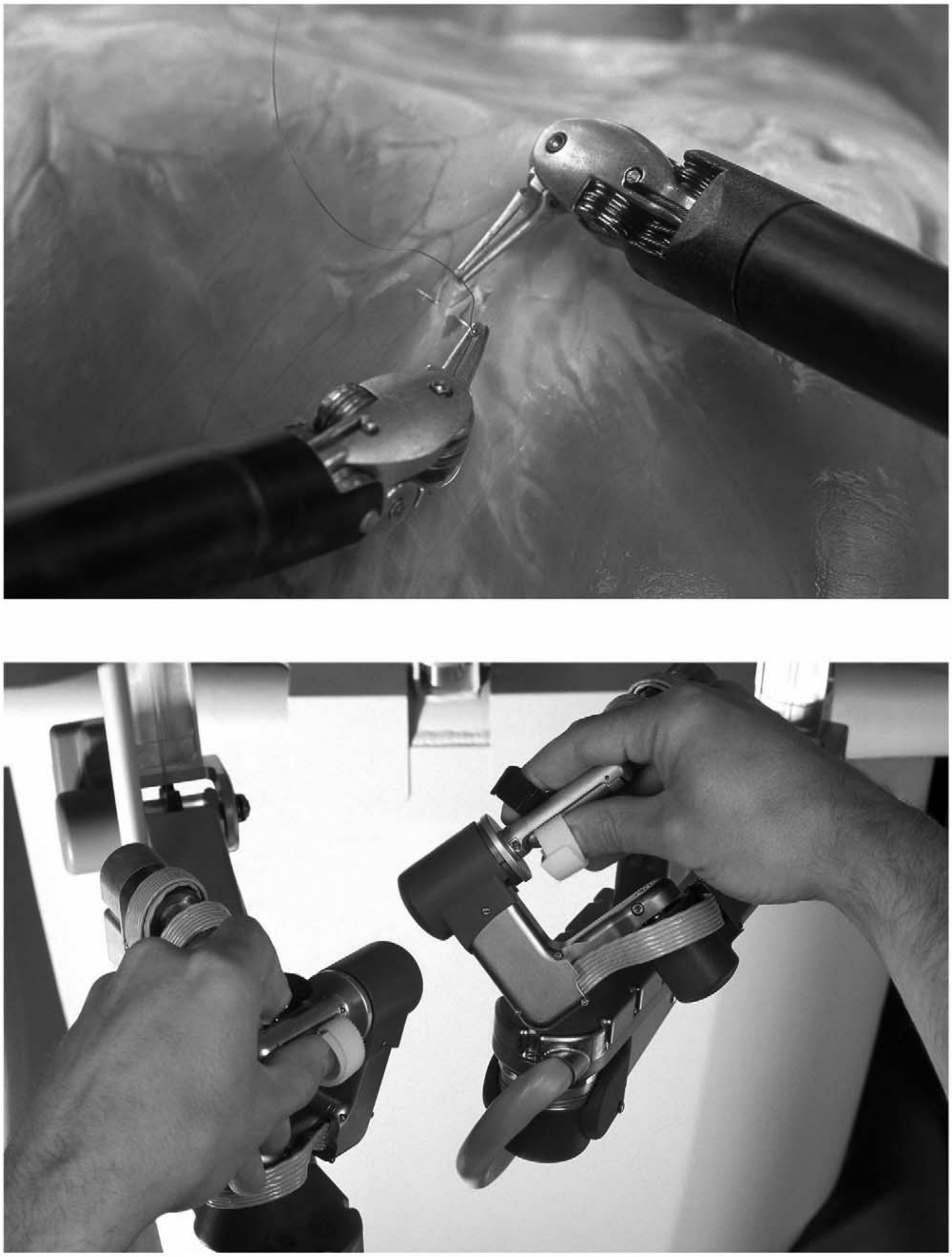

Fig. 7. The da Vinci EndoWrist (*top*) and console masters (*bottom*). The wristed slave instruments exactly track the surgeon's master controllers. (Courtesy of Intuitive Surgical, Inc., Sunnyvale, CA.)

create "active catheters" with a high degree of control. An active catheter could be steered with much greater accuracy than that of a passive, undercontrolled catheter. Such a device might be useful in minimally invasive diagnosis and/or treatment of deeply remote anatomy that would be otherwise impossible to reach. This trend toward less invasive, more specifically targeted surgical treatments has been in motion for some time. As one looks back on the "sawbones" surgeons of the US Civil War, surgical treatments have progressively become more focused, and smaller robots are just the next step in that journey.

To operate a miniature robotic device, sensors and actuators on an even smaller scale will be necessary. Recent advances in the area of microelectrical mechanical systems (MEMS) offer promise for fulfilling this need. MEMS are integrated microdevices that combine electrical and mechanical components [16,22]. These working machines have gears no bigger than a grain of pollen, and current technology permits them to be batch-fabricated, tens of thousands at a time, at a cost of only a few pennies for each device [23]. These systems can sense, control, and actuate on the microscale, and function individually or in arrays to generate effects on the macroscale [23]. This technology has been used to build devices such as microengines, microtransmissions, microlocks, and micromirrors. Current applications in industry also include accelerometers, pressure, chemical and flow sensors, micro-optics, optical scanners, and fluid pumps [22,24]. It is clear that these types of sensors could have important medical uses, from providing force feedback with a microforce sensor, to measuring biochemical data and overlaying it on a visual image to identify hidden infection.

With regard to force feedback, the inclusion of high-fidelity force sensors has the potential to improve force sensation beyond what the human hand can sense on its own. This improvement would be similar to the use of microphones and microscopes to enhance hearing and vision. For example, surgical ablation of larger tumors in the abdomen or lungs is often performed with an ultrasonic cutting instrument or radiofrequency ablation. A force-feedback type probe would be beneficial here in identifying the edge of the tumor to ensure complete ablation and to protect healthy tissue.

MEMS devices and their nanoscale counterparts may do more than just act in support of macroscopic instruments; they can be self-contained structures that function independently. Imagine robots so small that they could actually fit inside a single living cell or travel around the body in the bloodstream, navigating through the use of on-board computers. At the most microscopic level, robots could be designed to repair damaged DNA. Some researchers have suggested that robots could be designed specifically to act as antibodies against viruses and resistant strains of bacteria that defy biologists' attempts to find cures [6]. Systems for precise delivery of medication will be developed. At a slightly larger level, an implantable device, capable of functioning as a miniature laboratory, will be placed into patients with diabetes mellitus to measure glucose levels continuously and deliver insulin as needed.

The era of these microrobots is not as far off as one might think. There is at least 1 similar technology, presently in clinical use, known as the capsule colonoscopy (Given Imaging, Yoqneam, Israel). Contained in a 1-inch package are 2 silver-oxide batteries, white LEDs to illuminate the camera, and a metal-oxide detector array with 256 × 256 bits. The capsule transmits 50,000 images over the 7 hours in which it passes through the gastrointestinal tract. The images are transmitted externally via a radiofrequency communicator to a receiver belt worn by the patient. A physician then downloads the pictures for review [25,26]. This device is a revolutionary advance and truly deserves to be called a "bioMEMS" device.

An important component of any robotic system is its computational capabilities. Much research effort has been put forth in using computation to give artificial intelligence (AI) behaviors to robots. Humans learn through their experiences and, most importantly, by making mistakes. Each year, physicians learn by repeating the mistakes of those who have gone before them. Yet mistakes are costly in many currencies. One of the primary motivations for developing AI applications for medicine is to keep physicians from having to learn through making mistakes while performing critical tasks. Heuristic knowledge, or the ability of a machine to learn based on real life experiences, is the basis for AI. The rigid design of computer logic makes this very difficult to achieve.

Future directions for AI include neuromorphic engineering, genetic algorithms, and artificial evolution. The goal of neuromorphic engineering is to transform microcircuitry into an analog computing medium that resembles neural tissue [27]. The resulting structure captures the essence of neurons in hardware (ie, the transistors, capacitors, and resistors of a silicon chip), generating hardware that can reliably store analog information as an electrical charge. Current research is working to mimic the dense interconnections of the human brain. Genetic algorithms and artificial evolution attempt to apply Darwin's theory of evolution to AI. The artificial evolution approach maintains a population of viable genotypes (chromosomes), coding for control architecture [28]. The genotypes are interbred according to a selection pressure, much as in standard genetics, with a gradual emergence of the more evolutionarily favored control architecture. The combination of these 3 techniques holds promise for developing robots that learn, remember, and even evolve.

In the more near term, computer control may provide for some other interesting functionality in enhanced immersion and virtual constraints. Virtual constraints could be used to create a no-fly zone during surgery based on preoperative or intraoperative imaging data of protected structures such as arteries. This would reduce the risk of complication due to surgeon error, and would build on the related work from the Acrobot.

Virtual constraints could be a step in creating a more immersive experience for the surgeon. The goal would be to create a cockpit-like environment, where the surgeon is surrounded by all of the tools needed to "fly" or carry out the procedure. In the ideal case, the surgeon's console would contain complete data fusion in the workspace. This might include superimposed image overlay of preoperative MRI data, with real-time biochemical data, and visual images so that the surgeon sees the "whole picture." In this environment, the surgeon would never need to disengage to look at MRI images. When a virtual-limit boundary has been contacted in the surgical workspace, the surgeon would "see" the corresponding contrast in biochemical composition between the tumor being excised and the surrounding tissue. The surgical workstation may also be augmented with audio capabilities to alert the surgeon to data coming from outside of the camera field of view. Seamlessly connected via high-speed, low-latency networks to other experts in the field, a surgeon might call in special assistance or advice when a critical or unexpected situation occurs.

Table 2
Evolution of surgical procedures*

Imaging	Manipulation
• Direct visual	• 2 hands direct
• Camera/magnification	• 2 hands, long tools
• Flexible scope	• 2 hands, long tools with an enabled wrist
• 3-dimensional camera	• Electrical energy, radiofrequency energy
• Ultrasound	• Cryo- or thermal ablation
• CT, MRI, or PET scan	• Chemical energy, photodynamic therapy

CT = computed tomography; MRI = magnetic resonance imaging; PET = positron emission tomography.

* The essential elements of imaging and manipulation have evolved in parallel. Imaging is a "hot" area of development, and robotics must help to keep pace on the manipulation side.

Clinical outlook

The discovery of new opportunities requires the constant interplay between an unsolved problem and a new or emerging technology. One might characterize such solutions as the development of surgical tools that would allow the same operation to be done in a better fashion, or for the performance of a new operation with a better result (decreased mortality, decreased morbidity, more reversible).

Next-generation surgical systems should be explored that enhance either imaging or manipulation, which are the 2 fundamental components of a surgical procedure. Table 2 illustrates the parallel historical developments of imaging and manipulation technologies. The potential for new and improved imaging seems inevitable because these technologies are so widely embraced. It is important that robotic technology continues to advance in order to keep pace on the manipulation side.

Finally, looking back at Figure 2, the notion of the development of active and autonomous tools deserves exploration. Developments in this area may be far off, but they would revolutionize surgery by using a robot to autonomously perform intricate but widely varying tasks with a high level of responsibility. This will require considerable algorithm development and expansion of computing power, but given the progress in the past 50 years, this does not seem unreasonable. As Asimov predicted, new issues in terms of ethics and standards would then become even more relevant.

Many of these emerging technologies have dedicated research and development groups working feverishly on the next stage of evolution. For these developments to be truly relevant in surgery, however, they will require input and guidance from the clinical community. The surgeons' role in this technology is thus 2-fold: (1) to educate and collaborate with technical developers, and (2) to find and refine areas in their own specialties where these technologies will be useful. There are even some institutional programs that are currently being built on this premise such as the Surgical Innovation Program at Stanford University [29]. We believe it is possible to provide an orderly framework for clinical needs assessment, technology evaluation, and the blurring of the interface between clinical medicine and engineering to create the next generation of surgical innovations and innovators, following in the footsteps of Dr. Thomas Fogarty, Dr. William New, Dr. Rodney Perkins, Dr. John Simpson, Dr. Paul Yock, and others.

On the other end of the spectrum, there are now a group of engineers coming to be known as "clinical engineers," who have a technical background but are also educated in clinical applications. They may serve as the intermediary between surgeons and other engineers. This educational cross-pollination must continue, preferably at an increased rate and in a more structured manner. Only then will each community be able to respond to one another's needs, requirements, constraints, and philosophies sufficiently to pave the path toward advancing the state-of-the-art of surgical intervention and, ultimately, enhancing patient care.

In some sense, we probably should think of medical robotic technology much like the Wright brothers' first aircraft. Today's medical robots already do work in surprisingly useful ways and yet comprise a technology only in its infancy. We have every reason to believe that the future of robotics in medicine will be full of surprises, and we should be prepared to recognize them and capitalize on the opportunities they provide. Much as airplanes now perform tasks never imagined by the Wright brothers, it is likely that tomorrow's medical robots will deliver functionality and breadth of utility beyond our current dreams.

References

[1] Capek K. Rossum's Universal Robots. Playfair N, Selver P, trans. Landes WA, ed. New York: Doubleday, 1923.
[2] Satava RM. Surgical robotics: the early chronicles: a personal historical perspective. Surg Laparosc Endosc Percutan Techn 2002;12:6–16.
[3] Asimov I. The Complete Robot. Garden City, NY: Doubleday, 1982.
[4] Stoianovici D. Robotic surgery. World J Urol 2000;18:289–95.
[5] Davies B. A review of robotics in surgery. Proc Inst Mech Eng[H] 2000;214:129–40.
[6] Gibilisco S. The McGraw-Hill Illustrated Encyclopedia of Robotics & Artificial Intelligence. New York: McGraw-Hill, 1994.
[7] Vertut J, Coiffet P. Teleoperation and Robotics: Evolution and Development, Volume 3A. London: Hermes Publishing, 1985.
[8] Diodato MD, Damiano RJ Jr. Robotic Cardiac Surgery: Overview. Surg Clin North Am 2003;83:1351–67.

[9] Falk V, Diegler A, Walther T, Autschbach R, Mohr FW. Developments in robotic cardiac surgery. Curr Opin Cardiol 2000;15:378–87.

[10] Satava RM. Emerging technologies for surgery in the 21st century. Arch Surg 1999;134:1197–202.

[11] Ballantyne GH, Moll F. The da Vinci telerobotic surgical system: the virtual operative field and telepresence surgery. Surg Clin North Am 2003;83:1293–304.

[12] Cleary K, Nguyen C. State of the art in surgical robotics: clinical applications and technology challenges. Comput Aided Surg 2001;6:312–28.

[13] Howe RD, Matsuoka Y. Robotics for surgery. Annu Rev Biomed Eng 1999;1:211–40.

[14] Taylor RH. Robots as surgical assistants: where we are, wither we are tending, and how to get there. Lecture Notes in Artificial Intelligence. 1997;1211:3–11

[15] Lanfranco AR, Castellanos AE, Desai JP, Meyers WC. Robotic surgery—a current perspective. Ann Surg 2004;239:14–21.

[16] Satava RM. Cybersurgery: Advanced Technologies for Surgical Practice, 1st Ed. New York: Wiley-Liss, 1998.

[17] Langenburg SE, Knight CG, Klein MD. Robotic surgery: an update. J Long Term Eff Med Implants 2003;13:429–36.

[18] Guyton SW. Robotic surgery: the computer-enhanced control of surgical instruments. Otolaryngol Clin North Am 2002;35:1303–16.

[19] Jakopec M, Harris SJ, Rodriguez y Baena F, Gomes P, Cobb J, Davies BL. The first clinical application of a "hands-on" robotic knee surgery system. Comput Aided Surg 2001;6:829–39.

[20] Varma TRK, Eldridge PR, Forster A, et al. Use of the NeuroMate stereotactic robot in a frameless mode for movement disorder surgery. Stereotact Funct Neurosurg 2003;80:132–5.

[21] Alexander AD. Impacts of telemation on modern society. Proceedings of the First CISM-ITOMM Symposium. New York: Springer Wein, 1972;121–36.

[22] Gertner ME, Krummel TM. Micro- and nanoelectromechanical systems in medicine and surgery. In: Greco R, ed. Nanobiology: Nano Scale Fabrication of New Generation of Biomedical Devices. New York: Taylor & Francis Books, 2004: In press.

[23] Sniegowski J, Miller S, LaVigne G, Rodgers M, McWhorter P. Monolithic-geared mechanisms driven by a polysilicon surface-micromachined on-chip electrostatic microengine. Proceedings of the Solid-State Sensor and Actuator Workshop. Piscataway, NJ: IEEE, 1996;178–82.

[24] Howe R. Polysilicon integrated microsystems: technologies and applications. Proceedings of Transducers'95. Piscataway, NJ: IEEE, 1995;43–6.

[25] Mylonaki M, Fritscher-Ravens A, Swain P. Wireless capsule endoscopy: a comparison with push enteroscopy in patients with gastroscopy and colonoscopy negative gastrointestinal bleeding. Gut 2003;52:1122–6.

[26] Lewis B, Goldfarb N. Review article: the advent of capsule endoscopy—a not-so-futuristic approach to obscure gastrointestinal bleeding. Aliment Pharmacol Ther 2003;17:1085–96.

[27] Watson A. Why can't a computer be more like a brain? Science 1997;277:1934–6.

[28] Husbands P, Harvey I, Cliff D, Miller G. Artificial evolution: a new path for artificial intelligence? Brain Cogn 1997;34:130–59.

[29] Surgical Innovation Program at Stanford. Stanford University Website. Available at: http://surgery.stanford.edu/innovation/. Accessed September 14, 2004.