The heart of microsurgery

Shrinking robots and growing processors are taking minimally invasive techniques where they have never gone before.

An important milestone in medical history was achieved in May this year when surgeons performed a delicate operation to repair a valve in a patient's heart. During the procedure, the patient's defective valve was trimmed and reconstructed. The operation was remarkable not because of what it accomplished—many thousands of patients have undergone heart-valve repair—but because of how it was done. During much of the complex procedure, the surgeon's hands never entered or touched the patient's body. In fact, the doctor wasn't even at the operating table.

The delicate steps of the operation were performed with the aid of a highly sophisticated surgical system that controlled instruments inserted through small incisions, or "ports," in the patient's skin. The movements of the tools were remotely controlled by an experienced cardiac surgeon seated at a console 20 feet away. He manipulated telerobotic arms in the patient's body and watched the operation through a three-dimensional video-imaging system, also inserted through a port in the skin. The surgeon was able to complete each step of the complex operation with a deftness and precision that were previously impossible.

This valve repair was part of a landmark series of human cardiac surgical trials performed in Paris and in Leipzig, Germany, in recent months by doctors using a telerobotic
system developed by Intuitive Surgical Inc. of Mountain View, Calif. In June, a surgical team used the system in completing the first "closed chest" videoscopic coronary artery bypass graft. This is a significant accomplishment because of the large number of patients who can benefit from such procedures. The traditional open procedure requires an extraordinarily high level of mechanical skill that now, with the marriage of new telerobotic and surgical technologies, can be performed through tiny ports less than one centimeter (0.4 inch) long. The result is that for the first time heart surgery patients will receive the benefits of true minimally invasive surgery.

The benefits of less-invasive surgical procedures are well-known. Traditionally, much of the hospital stay and postoperative pain and discomfort have resulted from the large wound left from conventional open surgery. Open-heart surgery, moreover, usually involves a sternotomy—splitting the breastbone from neck to abdomen and prying it open. A less invasive minithoracotomy was used to gain access to the heart of the patient who underwent the first computer-enhanced heart-valve repair. The procedure required one surgical wound eight centimeters (3.2 inches) long and two wounds only eight millimeters (0.32 inch) long. As surgeons become more familiar with the system, all the incision sizes could shrink to less than one centimeter.

### Extending the Human Reach

Robots in one form or another have been around for decades. Master-slave manipulators and telerobots are a special breed of robot—one in which the human is directly in the control loop commanding the robot's actions. Telerobots are a modern version of master-slave manipulator technology, which has been used successfully in critical applications for more than four decades. The early mechanically connected master-slave systems have evolved into today's sophisticated electromechanical telerobotic systems and, in doing so, have opened the way for enhanced operation via computer mediation.
New telerobotic surgery enables complex procedures to be performed through tiny ports, less than one centimeter long, in a patient's body.

Television news and the movies have awed viewers with the feats of telerobots—docile machines that do the exact bidding of a remote operator, often performing tasks beyond the capability of human beings. Many viewers have witnessed the majestic movements of the space shuttle arm against a panoply of stars. Others have held their breath as the undersea rover in the movie Titanic glides into the barnacled stateroom and pries open the safe, in search of the elusive necklace. A key attribute of this technology is that the remote robot responds precisely to the commands of a human operator—no more and no less.

In contrast, today's autonomous robots can be programmed to move with great precision and speed, performing such tasks as spray painting, welding, and simple assembly. Even so, autonomous robots can't do tasks requiring complex physical interaction and response to unplanned events. However, telerobotics, by placing a human in the control loop, takes advantage of human cognitive and sensorimotor skills and, in combination with a robot's mechanical ability, bridges gaps in scale and distance to perform tasks that are impossible by any other means.

Telerobots have been used for many years to defuse bombs, handle hazardous wastes and radioactive materials, and explore the ocean and outer space. Designed to work on human-scale tasks, these devices are typically capable of large forces and coarse motions. To create telerobots that can work at the scale and precision demanded by minimally invasive surgery has required a careful understanding of the task and its environment, and the fundamental development of new telerobotic technology.

Robots in the Operating Room

Computer-controlled diagnostic instruments have been used in the operating room for years to help provide vital...
information through ultrasound, computer-aided-
tomography (CAT), and other imaging technologies.
More recently, robotic systems have been developed to
aid in positioning cameras used in minimally invasive
surgery (the automatic endoscopic system for optional
positioning, or AESOP), placing neurosurgical tools
(NeuroMate), and guiding bone-cutting tools (RoboDoc).
However, until the recent developments by Intuitive
Surgical, placing dexterity-enhancing robotic systems in
the operating room has remained an elusive goal. The
introduction of the Intuitive system places telerobots as a
direct link between the surgeon's hands and the patient to
enhance surgical technique during delicate procedures.

The Intuitive system grew out of the need to overcome
the limitations of minimally invasive surgery, a surgical
technique developed in the 1980s. Using minimally
invasive techniques, surgeons make small incisions in the
patient's skin and insert an endoscope—a narrow
cylindrical scope attached to a camera—into the patient's
body. The surgical instruments tend to be simple,
consisting of long, straight tools that also enter the
patient through additional short incisions. Although the
surgeon cannot view the surgical site directly, he can
follow movement of the instrument tips on a video
monitor.

Telerobots are becoming a vital link
between a surgeon's hands and a
patient's health.

Surgeons quickly ran into problems when they tried to
apply minimally invasive surgery to more complicated
procedures. The first problem was the counterintuitive
motion of the instruments. Those used in minimally
invasive surgery are straight, metal tools, sometimes
more than a foot long. Because the tool shaft passes
through a small port in the skin, as the surgeon moves the
handle of the instrument in one direction (outside the
body), the tip of the instrument (inside the body) moves
in the opposite direction in a reverse motion. Although
the surgeon can watch the motion of the tools on a video
monitor, learning to manipulate them in a
counterintuitive manner involves mastering a new set of
surgical skills. Surgeons have compared minimally
invasive surgery to "tying one's shoelaces with golf
clubs."
Secondly, because the tools lack sufficient mobility inside the body, such instruments have fewer degrees of freedom of motion at the surgical site than a surgeon's hand in open surgery. Consequently, traditional minimally invasive surgery, or MIS, has been limited to procedures far simpler than heart-valve repair. Additionally, traditional techniques impose an ergonomic disadvantage: The surgeon's visual and mechanical frames of reference are widely separated and misoriented. This lack of registration of sensory information causes a severe mental burden during operation and contributes to a long learning curve in acquiring skills.

Despite these limitations, minimally invasive gall bladder removal became widespread, mostly because it is an extraction rather than reconstruction, which had not been possible with minimally invasive techniques. Economical when compared with open gall bladder removal, minimally invasive surgery significantly reduced patient discomfort and hospital stays. Today, approximately 1.2 million gall bladder removals are performed each year using minimally invasive techniques. While the success of such techniques had been limited to simpler surgical interventions, they demonstrated the potential of surgery through small holes. This drove the search for new methods of minimally invasive surgery for use in more complex procedures, and to make the operation more natural for the surgeon. Engineers sought to overcome the limitations of minimally invasive surgery by looking toward the development of more sophisticated surgical systems that would take advantage of the lessons learned in telerobotics.

**A Plan for Battle**

In the late 1980s, motivated by the rapid growth of minimally invasive surgery and the shortcomings of existing surgical tools, researchers at SRI International in Menlo Park, Calif., began to look for ways to enhance surgeons' skills in MIS and microsurgery. Beginning with funding from the National Institutes of Health 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 minimally invasive surgery and remote surgical tasks.
The early success of the SRI system caught the attention of the Defense Advanced Research Projects Administration, or DARPA, in Arlington, Va., the same agency that funded the original development of the Internet, then known as the DARPA-net. DARPA planners envisioned telesurgery being used by military surgeons to perform life-saving surgery on wounded soldiers on the battlefield—to keep them alive until they could be evacuated to a critical-care hospital. Using 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.

An experienced cardiac surgeon is able to remotely control movements of the tools while seated at a console 20 feet away from the patient.

In 1995, Intuitive Surgical was formed to develop the commercial medical technology needed to bring telerobotic capabilities to the minimally invasive environment. Using technology developed at SRI, IBM, and the Massachusetts Institute of Technology, Intuitive's engineers developed robotic arms and instruments with the number of degrees of freedom required for complex reconstructive surgery through one-centimeter incisions. At the same time, the Intuitive team was designing a proprietary 3-D video camera and stereo viewer to provide unprecedented visualization of the patient's interior. The name of the company derives from one of telesurgery's primary goals—creation of a surgeon-robot interface so transparent to the surgeon that he can use his full set of surgical training skills in a natural and instinctive manner.

Progress was accelerated by the explosion in processing power from newly available computer processors; current versions of the Intuitive system use four digital signal processors to provide 250 megaflops of processing power. Almost a decade of telesurgical development culminated with the first telesurgeries being performed on human patients by a team of vascular and digestive surgeons in Belgium last year.

Using concepts derived from virtual reality, the Intuitive system immerses the surgeon in a visual and tactile
environment that, as much as possible, resembles the one he experiences in conventional open surgery. The three main elements of creating immersion are superior visualization, sufficient force feedback, and accurate remote manipulation of surgical tools.

When performing telesurgery, the surgeon sits comfortably at the Intuitive console, head tilted forward and eyes peering down, like a child viewing a stereoscopic movie in a penny arcade. However, in this case, the surgeon is viewing one of the most sophisticated 3-D video images available today. During the procedure, 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 surgeons perform procedures and make decisions based on visual cues, and because many of the most important surgical procedures are performed under magnification. With a magnified surgical site, the operation can actually seem easier; a coronary artery a few millimeters in diameter may look as large as a garden hose.

Nevertheless, the fact remains that the surgeon is still manipulating a tiny coronary artery, which requires the translation of the surgeon's hand movements into very small movements at the operating site. This is accomplished by the motion scaling capability of the Intuitive system. This increases surgical precision and fine motor control by reducing the surgeon's large hand movements and the effect of normal hand tremors, while permitting him to use natural hand movements much like open surgery.

During the procedure, the surgeon's hands are held in a comfortable position in front of his body and his fingers are inserted into the system's master interfaces that monitor, in minute detail (over 1,300 times a second), the position of his hands as he performs the surgery. Every move the surgeon makes is precisely and simultaneously replicated by tiny, electromechanically driven surgical instruments inside the patient's body. Using motion sensor information and kinematic models of the master and slave, the computer system computes, at 1.5 kilohertz, the actuator drive commands necessary to move the robot arms and provide feedback.
This drawing shows the relationship among the various components of the minimally invasive Intuitive surgical system, including the surgical cart, the operative console, and the interchangeable instruments themselves.

When viewing the surgical field through the console, the surgeon can see the ends of the robotic arms—the instrument tips—as they move under his direction. An additional element of immersion is gained through force feedback, or haptic technology, to reproduce the contact forces of surgery. When the arm encounters resistance inside the patient, that resistance is transmitted back to the console, where the surgeon can feel it. Taking advantage of the multimodal synergy of haptic and visual feedback, the surgeon is easily able to perform dissection, cutting, suturing, and other surgical procedures, even on very small structures.

From a clinical point of view, a tiny mechanical joint called the EndoWrist is a key component of the Intuitive system. The EndoWrist gives the surgeon the ability to reach around, beyond, and behind delicate body structures, and is connected to the rest of the system by sophisticated, mechanical cable transmissions. Its motion 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 open-surgery hand movements into the same movements of the instruments, entirely avoiding the reverse movements of traditional MIS. The wrist can roll, pitch, yaw, and grip, allowing the surgeon a total of seven degrees of freedom for each hand.

With current minimally invasive procedures, it's not unusual to see a surgeon contort his body dramatically to obtain the correct angle for suturing. The EndoWrist delivers these angles right at the surgical site, offering control so precise that the Intuitive system could place a needle through the period at the end of this sentence. Moreover, the system can apply a fraction of an ounce in force for delicate suturing—or the several pounds of force necessary to retract large tissue structures.
Putting seven degrees of freedom in a tiny package was a challenge for mechanical design as well as for materials selection. In addition to being durable and sterilizable, the materials had to be biocompatible.

The instrument tips—or end effectors—are a combination of standard surgical instruments and completely novel mechanism designs by Intuitive. The very ends of the tool tips are made to resemble conventional tools used in open surgery. Surgeons want to have the exact same interaction with the tissue they have always had. They recognize—as does the Intuitive system—that conventional surgical tools are the result of 150 years of surgical experience in manipulating and cutting various types of human tissue. The rest of the instrument design, however, is entirely new. The instruments are sterilizable, easy to interchange during surgery, and cost-effective to manufacture. Central to Intuitive's approach is that the tools provide surgeons with a feeling and performance similar to their traditional tools.

Most telerobots don't require people to work closely with the slave; in all other applications, the slave is located in a place where people would rather not be. But in surgery, the assisting surgeon and the nurses interact frequently with the slaves in removing and changing surgical instruments. This requires very safe and human engineering on interfacing with the slaves. Telerobotic surgery also requires fail-safe operation. Most telerobots have simple safety systems that protect themselves in the event of failure. That's because in less complex applications, the robot is the high-value item. The Intuitive system has to protect the patient first, and the robot second. During a procedure, the Intuitive system monitors itself continuously, and will shut down or alert the surgeon if a problem arises.

**Enabling Technologies**

The success of the Intuitive system draws on technologies enhanced or developed by the development team in several key areas.

Robotic surgical tools combine the highly mobile four-degree-of-freedom (three for orientation, one for grip) EndoWrist and a three-degree-of-freedom robot for large range of motion to provide the surgeon with access to task orientations and locations. Precise mechanical
motions permit access to extremely small structures in the body. Sutures that are as small as 7-0 (approximately 0.05 millimeters, or 0.002 inch) have been used in human surgeries, with even smaller ones used in experimental settings. A wide variety of quickly exchangeable tools has been developed, including those required for needle grasping, cutting, cautery, and clip application. The size, mobility, and force range requirements for handling needles and tissue with the same tool placed stringent demands on mechanism design.

A high-resolution 3-D video imaging and display system provides the surgeon with an exquisitely clear and bright view of his work, delivering 800 lines of resolution with a signal-to-noise ratio of more than 62 decibels. The optical system minimizes geometric distortion across the field of view, enabling stereo image fusion even near the edges of the image. To minimize chromatic distortion, the system also provides the surgeon a highly accurate color rendition.

With magnification, a coronary artery a few millimeters in diameter may look as large as a garden hose.

Incorporating more than 250 megaflops of processing power makes it possible to bring the visual and robotic frames of reference into precise registration—a key element in giving the surgeon a sense of immersion in his work. The processing power also permits scaling of motions, tremor reduction, clutching (indexing) between master and slave, smooth control at workspace limits, and gravity compensation.

The master input device has a large workspace that accommodates the full range of motion required by the surgeon seated at the control console. Its low mass and friction, and precise tracking of motion enable exacting commands to be transmitted to the robot. Force feedback lets the surgeon feel contact interactions and tells of robot workspace limits.

Safe and fail-safe operations are ensured by redundant sensors and several levels of system health checking. With robot arms and camera mounted on mobile setup joints, the system can be conveniently brought to and removed from the surgical site.
The technology is the result of work by a team of more than 100 engineering, medical, and management personnel, guided by feedback from the surgical community. It embodies a combination of capabilities aimed at enabling radically new ways of performing surgery.

While much of Intuitive's engineering effort has gone into accurately translating the surgeon's movements to the robotic arms, remote duplication of a surgeon's existing skill set is only part of telesurgery's potential.

The fact that a computer—rather than hardware—provides the interface between the surgeon's hands and the robotic arms provides the system with another aspect of its potential: extending the surgeon's capabilities beyond conventional surgical techniques to add new capabilities that are simply not possible in conventional surgery. Although these possibilities are just beginning to be explored, many of them will undoubtedly lie in miniaturization and microsurgery.

The telerobotic system may also overcome one of the most basic human limitations—the availability of only two hands. During telesurgery with the Intuitive system, the surgical team can utilize "dynamic assignment"; that is, one surgeon can theoretically manipulate one arm, leave it in place, then switch his attention to another arm. In fact, multiple robotic arms that can be controlled, in theory, by a single surgeon, may be used in the future. Alternatively, in team surgery, the use of a surgical robotic arm can be taken over by another member of the team, or several surgeons may be able to operate at the same time by cooperatively sharing and trading control of the surgical tools.

While the dream of bringing expert surgeons' hands to remote and hazardous battlefield locations may eventually be realized, the real value of the Intuitive system is expected to be in bringing the advantages of minimally invasive surgery to a whole host of new procedures and permitting solutions to previously impossible surgical problems.

The Intuitive system and others like it mark the beginning of a potentially huge wave of surgical applications for telerobots. With the assistance of surgical telerobots, surgeons will extend their healing skills to places within the body that are currently out of reach. The continuing
evolution of telerobotic surgery holds the promise of immense benefits in healing that cannot yet be imagined.