INVITED PAPER

A Perspective on Medical Robotics

Robots are reducing surgeon hand-tremor, assisting in spine and joint-replacement, positioning surgical needle guides, and coordinating medical imaging with surgical procedures.

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ABSTRACT | This paper provides an overview of medical robotics, from the perspective of a researcher who has been actively involved in the field for 17 years. Like all robot systems, medical robots fundamentally couple information to physical action to significantly enhance humans' ability to perform important tasks—in this case surgical interventions, rehabilitation, or simply helping handicapped people in daily living tasks. Research areas include modeling and analysis of anatomy and task environments, interface technology between the "data world" and the physical world, and study of how complex systems are put together. This paper will discuss these research areas and illustrate their interrelationship with application examples. Although the main focus will be on robotic systems for surgery, it will also discuss the relationship of these research areas to rehabilitation and assistance robots. Finally, it will include some thoughts on the factors driving the acceptance of medical robotics and of how research can be most effectively organized.

KEYWORDS | Computer-integrated surgery; human-machine cooperative systems; medical robotics; rehabilitation robotics; robotic assistive systems; surgical assistants; telerobotics; telesurgery

I. INTRODUCTION

The ability of robotic systems to couple information to physical action in complex ways has had a profound influence on our society. Applications include such fields as industrial production, inspection and quality control, laboratory automation, exploration, field service, rescue, surveillance, and (as discussed below) medicine and health care. Historically, robots have often been first introduced to automate or improve discrete processes, such as painting a car or placing test probes on electronic circuits, but their greatest economic influence has often come indirectly as essential enablers of computer-integration of entire production or service processes.

As this paper will argue, medical robots have a similar potential to fundamentally change interventional medicine as enabling components in much broader computer-integrated systems that include diagnosis, preoperative planning, perioperative and postoperative care, hospital logistics and scheduling, and long-term follow-up and quality control. Within this context, surgical robots and robotic systems may be thought of as "smart" surgical tools that enable human surgeons to treat individual patients with improved efficacy, greater safety, and less morbidity than would otherwise be possible. Further, the consistency and information infrastructure associated with medical robotic and computer-assisted surgery systems has the potential to make "computer-integrated surgery" as important to health care as computer-integrated manufacturing is to industrial production.

This paper is not intended to be a survey, in the traditional sense. Other papers in this special issue provide a comprehensive overview of major technology themes in medical robotics, as well as related work on robotic systems for rehabilitation and human assistance. Other surveys may be found in a recent IEEE Transactions on Robotics special issue on medical robotics [1], [2] and elsewhere (e.g., [1], [3]–[5]).

Instead, the goal is to provide a perspective on how surgical, rehabilitation, and assistive robots relate to broader themes of computation, interface technology, and systems. This perspective is informed, first, by the discussion and experience reported in many workshops over

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AQ1

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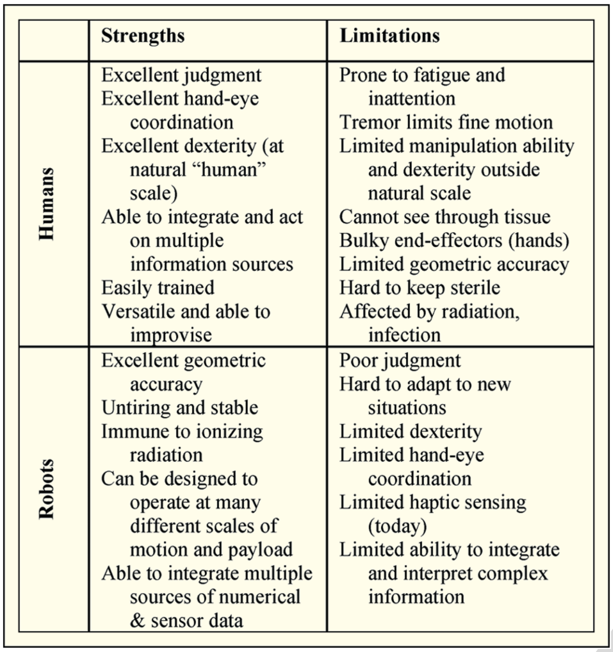
Table 1 Complementary Strengths and Limitations of Robots and Humans [4]



	Strengths	Limitations
Humans	Excellent judgment Excellent hand-eye coordination Excellent dexterity (at natural "human" scale) Able to integrate and act on multiple information sources Easily trained Versatile and able to improvise	Prone to fatigue and inattention Tremor limits fine motion Limited manipulation ability and dexterity outside natural scale Cannot see through tissue Bulky end-effectors (hands) Limited geometric accuracy Hard to keep sterile Affected by radiation, infection
Robots	Excellent geometric accuracy Untiring and stable Immune to ionizing radiation Can be designed to operate at many different scales of motion and payload Able to integrate multiple sources of numerical & sensor data	Poor judgment Hard to adapt to new situations Limited dexterity Limited hand-eye coordination Limited haptic sensing (today) Limited ability to integrate and interpret complex information

the past fifteen years (e.g., [6]–[10]); and, second, by my own experiences at IBM Research and at Johns Hopkins University (JHU). My primary focus will be on medical robotics and computer-integrated surgery (CIS) systems, which have been the major focus of my own research over the past 17 years. However, there are important synergies between robotics for CIS and for such fields as rehabilitation and assistance for elderly or handicapped people, and I will touch on these related areas as well.

II. BASIC SYSTEM CONCEPTS: MEDICAL ROBOTICS IN COMPUTER-INTEGRATED SURGERY AND REHABILITATION

A. Factors Driving Acceptance of Medical Robotics

Just as with manufacturing robots, medical robots and CIS systems must provide real advantages if they are to be accepted and widely deployed.

First, and perhaps most obvious, is the ability of computer-integrated systems to *significantly improve surgeons' technical capability*, either by making existing procedures more accurate, faster, or less invasive or by making it possible to perform otherwise infeasible interventions. In these cases, the advantages often come from exploiting the complementary strengths of humans and robotic devices, as summarized in Table 1. A second, closely related, advantage is the potential of computer-integrated systems to *promote surgical safety* by: 1) improved technical performance of difficult procedures; 2) on-line monitoring and information supports for surgical procedures; and 3) active assists such as "no fly zones" preventing robots from moving tools into dangerous proximity to delicate anatomical structures.

A third advantage is the inherent ability of medical robots and CIS systems to *promote consistency* while *capturing detailed online information* for every procedure. This "flight data recorder" information can be invaluable in mortality and morbidity assessments of serious incidents, but the true potential is much more far-reaching. Potentially, statistical analysis comparing outcome measures to procedure variables may produce both better understanding of what is most important to control and, ultimately, to safer and more effective interventions. This data can also be a valuable tool for training, skill assessment, and certification for surgeons.

Similarly, robotic systems for *rehabilitation* or for *assistance in daily living* must offer real advantages if they are to be adopted. Once again, acceptance will come from exploiting the complementary abilities of humans (who may have disabilities) and machines to accomplish tasks that might not otherwise be feasible or practical for unassisted humans. Typical benefits may include more efficient or consistent performance of exercise following injury or surgery; partial restoration of function through "intelligent" prostheses, either for long-term use or during recovery; and cooperative aids for our aging population. Acceptance in these areas will also be crucially dependent on economic and social factors such as cost, ruggedness, ease of use, and human–machine communication capabilities.

B. Surgical CAD/CAM

The basic information flow of CIS systems is illustrated in Fig. 1. Preoperative planning typically starts with two-dimensional (2-D) or three-dimensional (3-D) medical images, together with information about the patient. These images can be combined with general information about human anatomy and variability to produce a computer model of the individual patient, which is then used in surgical planning. In the operating room, this information

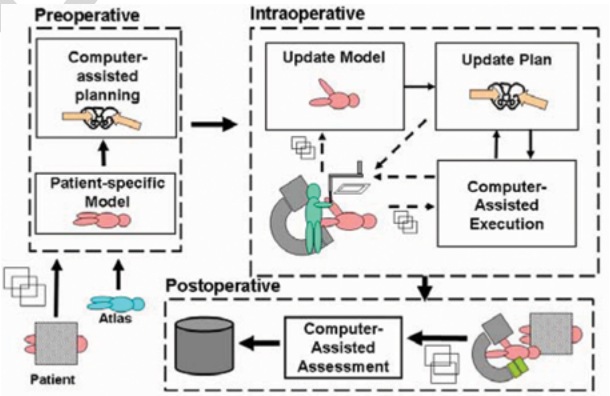


Fig. 1. *The information flow of CIS systems.*

is registered to the actual patient using intraoperative sensing, which typically involves the use of a 3-D localization, x-ray or ultrasound images, or the use of the robot itself. If necessary, the surgical plan can be updated, and then one or more key steps in the procedure are carried out with the help of the robot. Additional images or sensing can be used to verify that the surgical plan is successfully executed and to assist in postsurgical follow-up. The coupling of imaging, patient-specific models, and computer-controlled delivery devices can significantly improve both the consistency of therapy delivery and the data available for patient follow-up and statistical studies required to develop and validate new therapies.

We refer to the process of building a model of the patient, planning, registration, execution, and follow-up as *surgical CAD/CAM*, stressing the analogy with computer-integrated manufacturing. Typical examples of robotic surgical CAD/CAM are discussed in Section IV. The advantages provided by robotic execution in surgical CAD/CAM depend somewhat on the individual application, but include: 1) accurate registration to medical images; 2) consistency; 3) the ability to work in imaging environments that are not friendly to human surgeons; and 4) the ability to quickly and accurately reposition instruments through complex trajectories or onto multiple targets.

In addition to the technical issues inherent in constructing systems that can provide these advantages, one of biggest challenges is finding ways to reduce the setup overhead associated with robotic interventions. A second challenge is to provide a modular family of low-cost robots and therapy delivery devices that can be quickly configured into fully integrated and optimized interventional systems for use with appropriate interventional imaging devices for a broad spectrum of clinical conditions with convenience comparable to current outpatient diagnostic procedures.

C. Surgical Assistants

Surgery is a highly interactive process and many surgical decisions are made in the operating room. The goal of surgical robotics is not to replace the surgeon with a robot, but to provide the surgeon with a new set of very versatile tools that extend his or her ability to treat patients. We thus often speak of medical robot systems as *surgical assistants* that work cooperatively with surgeons. A special subclass of these systems are often used for remote surgery.

Currently, there are two main varieties of surgical assistant robot. The first variety, *surgeon extenders*, are operated directly by the surgeon and augment or supplement the surgeon's ability to manipulate surgical instruments in surgery. The promise of these systems, broadly, is that they can give even average surgeons superhuman capabilities such as elimination of hand tremor or ability to perform dexterous operations inside the patient's body. The value is measured in: 1) ability to treat otherwise untreatable conditions; 2) reduced morbidity or error rates; and 3) shortened operative times.

The second variety, *auxiliary surgical supports*, generally work side-by-side with the surgeon and perform such functions as endoscope holding or retraction. These systems typically provide one or more direct control interfaces such as joysticks, head trackers, voice control, or the like. However, there have been some efforts to make these systems "smarter" so as to require less of the surgeon's attention during use, for example by using computer vision to keep the endoscope aimed at an anatomic target or to track a surgical instrument. Their value is assessed using the same measures as for surgeon extenders, though often with greater emphasis on surgical efficiency.

D. Rehabilitation and Assistive Systems

As our population ages, robotic systems for rehabilitation and for helping deal with physical and cognitive disabilities will become more and more important [7]. Broadly, we can identify four areas of great promise: 1) systems assisting with physical therapy following injuries or surgery; 2) "smart" prosthetic devices; 3) systems designed to help disabled people in daily living activities; and 4) systems designed to help prevent or ameliorate cognitive and emotional decline.

III. THE STRUCTURE AND TECHNOLOGY OF MEDICAL ROBOTIC SYSTEMS

Fig. 2 shows the block diagram of a typical CIS system. These systems work cooperatively with humans (surgeons and other medical personnel) to couple information with action in the physical world to perform tasks. Broadly, research supporting these systems comprises three areas: computer-based *modeling and analysis* of images, patient anatomy, and surgical plans; *interface technology* relating the "virtual reality" of computer models to the "actual reality" of the patient, operating room, and surgical staff;

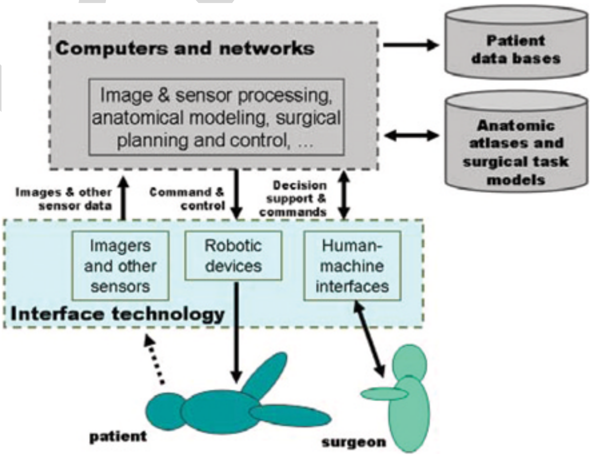


Fig. 2. *Block diagram of typical CIS system.*

Fig. 3. ***The daVinci surgical robot uses mechanically constrained remote-center-of-motion arms manipulate modular tools under surgeon teleoperator control. The tools use cable drives to provide high-dexterity manipulation inside the body. (Photo: Intuitive Surgical Systems).***

AQ2

and *systems science and analysis* permitting these components to be combined in a modular and robust way with safe and predictable performance.

A. Modeling and Analysis

As medical robotic systems evolve, computational modeling and analysis will become more and more important. There is a robust and diverse research community spanning an equally broad range of research topics and techniques.

The core challenge is to develop computationally efficient methods for constructing models of individual patients and populations of patients from a variety of data sources and for using these models to help perform useful tasks. A related challenge is modeling the tasks themselves and the environment in which the tasks are performed—whether the operating room, intensive care facility, clinic, or home. Some common themes include:

- medical image segmentation and image fusion to construct and update patient-specific anatomic models;
- biomechanical modeling for analyzing and predicting tissue deformations and functional factors affecting surgical planning, control, and rehabilitation;
- optimization methods for treatment planning and interactive control of systems;
- methods for registering the "virtual reality" of images and computational models to the "physical reality" of an actual patient;
- methods for characterizing treatment plans and individual task steps such as suturing, needle insertion, or limb manipulation for purposes of planning, monitoring, control, and intelligent assistance;
- real-time data fusion for such purposes as updating models from intraoperative images;
- methods for human–machine communication, including real-time visualization of data models and natural language understanding, gesture recognition, etc.;
- methods for characterizing uncertainties in data, models, and systems and for using this information in developing robust planning and control methods.

Of course, these themes are highly interrelated and mutually supportive. For example, modern medical image segmentation methods are intimately associated with registration methods.

Statistical methods have long been important in medical robotics, and their importance is increasing. Examples include the following.

- Construction of statistical "atlases" characterizing anatomic variation over large populations of individuals. Such atlases provide a natural framework for consolidating a wide variety of information about disease states, biomechanical modeling results, surgical plans, outcomes, etc.
- Methods for "deformably" registering atlases to individual patient images to produce "most probable" patient models, based on available information. Such models also naturally incorporate prior information about possible treatment plans, biomechanical simulations, expected outcomes, etc.
- Methods for correlating information about treatment plans and actual procedure execution with outcome variation, in order to identify key factors affecting outcomes and safety.

Fig. 4 shows one typical example of the use of these techniques for brain tumor treatment planning. Other examples include statistical modeling of the location of prostate cancer based on histology specimens, followed by deformable registration of this atlas to ultrasound or MRI images to

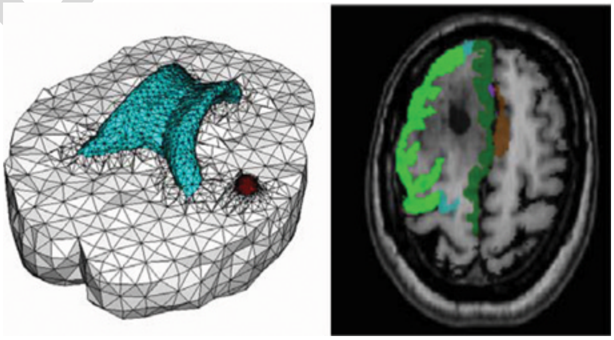


Fig. 4. ***Patient-specific model of a brain tumor patient based on a deformable registration to a statistical atlas incorporating finite-element simulations and functional data [99], [100].***

create optimized patient-specific biopsy plans [11], [12], the use of statistical atlases to create 3-D bone models from 2-D x-ray images [13]–[15], and statistical analysis of procedure variability in hip arthroplasty [16], [17].

Although the use of patient-specific models for rehabilitation planning has so far been relatively limited, the potential for applying similar atlas-based techniques incorporating biomechanical simulations has great future potential.

B. Interface Technology

Robotic systems inherently involve interfaces between the data world of computers and the physical world. One consequence of this is that robotics has always been a highly interdisciplinary field involving many branches of engineering research. For medical robotics, the core challenge is to fundamentally extend the sensory, motor, and human-adaptation abilities of robotic systems in an unusually demanding and constrained environment.

1) Specialized Mechanism Design: Early medical robots (e.g., [18]–[23]) frequently employed conventional industrial manipulators, usually with modifications for safety and sterility. Although this approach had many advantages and is still frequently taken for laboratory use or rapid prototyping, surgery and rehabilitation applications impose special requirements for workspace, dexterity, compactness, and work environment. Consequently, the trend has been more and more toward specialized designs. For example, laparoscopic surgery and percutaneous needle placement procedures typically involve passage or manipulation of instruments about a common entry point into the patient's body. In response, two basic designs have been widely used. The first, adopted by the Aesop and Zeus robots [24], [25], uses a passive wrist to allow the instrument to pivot about the insertion point. The second, adopted by a variety of groups, using a variety of design approaches (e.g., [26]–[33]), mechanically constrains the motion of the surgical tool to rotate about a "remote center of motion (RCM)" distal to the robot's structure.

A second problem is the need to provide high degrees of dexterity in very constrained spaces inside the patient's body, and at smaller and smaller scales. Typically, the response has been to develop cable actuated wrists (e.g., [34], [35]. However, the difficulties of scaling these designs to very small dimensions have led some groups to investigate bending structural elements (e.g., [36]–[39]), shape memory alloys [40], microhydraulics [41] or other approaches (see Fig. 6). The problem of providing access to surgical sites inside the body has led several groups to develop semiautonomously moving robots for epicardial or endoluminal applications (e.g., [2], [42]–[44], Fig. 5).

The necessity of providing robots that conform to human biomechanics and physical constraints has similarly led researchers to develop specialized designs for rehabilitation or assistive applications (e.g., [45]–[49], Fig. 7).

Fig. 5. ***Autonomous motion inside the body. Left: CMU HeartLander [44]. Right: S. Supiore Sant'Anna endoluminal robot [101].***

2) Teleoperation and Hands-On Control: Many surgical robots (e.g., [24], [25], [31], [35]) are teleoperated. Two potential drawbacks of this approach are that more equipment (i.e., a "master" control station) is needed, and the surgeon is often somewhat removed from the operating table, thus necessitating significant changes in surgical work flow. Early experiences with ROBODOC [21] and other surgical robots (e.g., [50], [51]) showed that surgeons found a form of "hands-on" admittance control, in which the robot moved in response to forces exerted by the surgeon directly on the surgical end-effector, to be very convenient and natural for surgical tasks. Subsequently, a number of groups have exploited this idea for precise surgical tasks, notably the JHU "Steady Hand" microsurgical robot [52] and the Imperial College Acrobot orthopedic system [53]. These systems (Fig. 8) provide very high stiffness and precision and eliminate physiological tremor while still permitting the surgeon to exploit his or her natural kinesthetic sense and eye-hand coordination. Other groups have developed completely freehand instruments that sense and actively cancel physiological

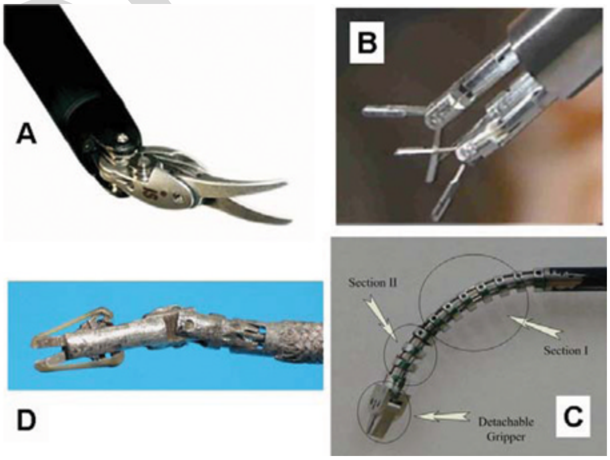


Fig. 6. ***Dexterity inside the body. (A) daVinci wrist. (B) Waseda dual-arm end effector for MIS flexible endoscopy [102]. (C) JHU bendable "snake" robot [36]–[39]. (D) Five degrees of freedom, 3-mm-diameter microcatheter robot [103], [104].***

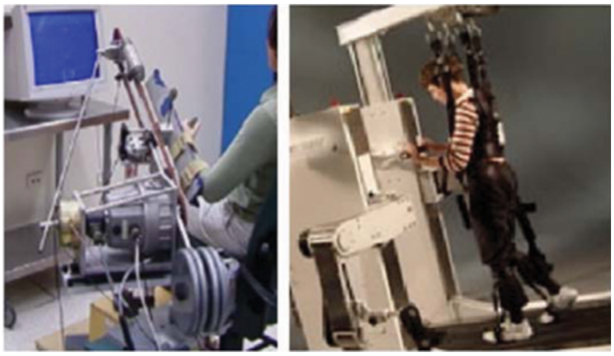


Fig. 7. ***Typical rehabilitation robots. Left: Rehab. Institute of Chicago Manipulandum [49]. Right: Tsukuba Gaitmaster 2 [49].***

tremor (e.g., [54], [55]). Still other groups have developed passive or semiactive mechanisms for assisting surgeons manipulate tools or body parts (e.g.,[56]–[59]).

3) Human–Machine Cooperative Systems: Although one goal of both teleoperation and hands-on control is often "transparency," i.e., the ability to move an instrument freely and dexterously, the fact that a computer is actually controlling the robot's motion creates many more possibilities. The simplest is a safety barrier or "no-fly zone," in which the robot's tool is constrained from entering certain portions of its workspace. More sophisticated versions include virtual springs, dampers, or complex kinematic constraints that help a surgeon align a tool, maintain a desired force, or perform similar tasks. The Acrobot system shown in Fig. 8 represents a successful clinical application of the concept, which has many names, of which "virtual fixtures" seems to be the most popular (e.g., [60]–[64]). A number of groups (e.g., [65]–[67]) are exploring extensions of the concept to active cooperative control, in which the surgeon and robot share or trade off control of the robot during a surgical task or subtask. As the ability of computers to model and "follow along" surgical tasks improves, these modes will become more and more important in surgical assistant applications.

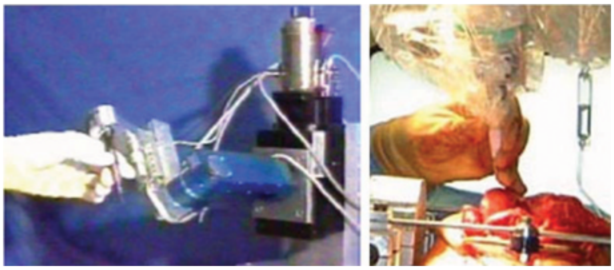


Fig. 8. ***Cooperatively controlled surgical robots. Left: The JHU "Steady Hand" robot [105]. Right: the Acrobot orthopedic robot [53].***

Both teleoperation and hands-on control are likewise used in human–machine cooperative systems for rehabilitation and disabilities assistance systems. Constrained hands-on systems offer special importance for rehabilitation applications and for helping people with movement disorders. Similarly, teleoperation and "intelligent" task following and control is likely to be vital for further advances in assistive systems for people with severe physical disabilities.

4) Augmented Reality Interfaces: Once a surgical procedure has begun, a surgeon's attention is necessarily focused on the patient's anatomy. Traditionally, surgeons have relied on their natural hand–eye coordination, either with direct visualization or (more recently) using endoscopic video images. Additional information, such as medical image data, has traditionally been posted on a light box somewhere in the operating room. The ability of the computer to coregister and visualize images, models, and other task-specific data provides an opportunity to significantly improve the surgeon's ability to assimilate and use all this information. Accordingly, there has been significant interest in creating "augmented reality" information displays and in using interactive means such as laser pointers in surgical assistant systems (Fig. 9). Similar interfaces have also been exploited in rehabilitation systems, for example, in directing a patient's motions for exercise.

C. Systems Science

Medical robots are complex systems that necessarily involve many interacting subsystems, including computational processes, sensors, mechanisms, and human–machine interfaces. As such, they share the same underlying needs for good system design and engineering practice: modularity, well-defined interfaces, etc. However, the fact that they are to be used in clinical applications or otherwise directly interact with people imposes some unusual requirements. The most obvious of these is safety. Although there may be multiple valid approaches to robot safety in specific circumstances, a few principles are common [68], [69]. The most important of these is redundancy: no single point of failure should cause a medical robot to go out of control or

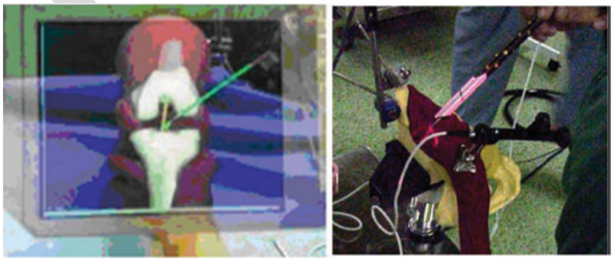


Fig. 9. ***Typical augmented reality interfaces for CIS. Left: CMU image overlay system [106]. Right: Osaka/Tokyo laser guidance system [107]. See also Figs. 12 (upper left) and 13.***

endanger a patient. A second, and often equally important, principle is that the computer's model of the task environment must correspond accurately to the actual environment. This is especially important for robotic systems that execute plans based on preoperative images. With careful design and implementation, it is possible to practically eliminate the possibility that the robot will somehow "run away" or make an inappropriate motion. But this does little good if the image, robot, and physical patient coordinate systems are not correctly registered to each other. Similarly, it is vital to ensure that the procedure is planned correctly and appropriately. Surgical robots are not surgeons. They are surgical tools that must be used correctly by surgeons. Consequently, it is vital that the surgeon have a clear understanding of the capabilities and limitations of the robotic system.

It is important to realize that surgical robots can often *enhance* patient safety. First, the robot can provide better control over process parameters (force, precision, etc.) that can affect outcomes. Second, the robot typically does not suffer from momentary lapses of attention, although (of course) the human operator may. Third, a robotic system can be programmed to include "virtual barriers" preventing the surgical tool from entering a forbidden region unless the surgeon explicitly overrides the barrier. Achieving these advantages requires careful design and validation, as well as rigorous testing and validation.

Another safety-related issue of special concern to regulatory bodies is careful documentation and rigorous procedures in development, testing, and maintenance of medical robots. Sterility and biocompatibility are of specific concern for surgical robots; these considerations can impose unusual design constraints, especially in choice of materials.

Other systems considerations are of practical interest mainly for researchers and developers. The most important of these is the vital importance of integration testbeds. Medical systems, especially those involving image guidance, are extremely difficult to develop without access to all the pieces needed to do complete experiments.

IV. EXAMPLES OF MEDICAL ROBOTICS SYSTEMS

A. Robotic Orthopedic Surgery

Geometric precision is often an important consideration in orthopedic surgery. For example, orthopedic implants used in joint replacement surgery must fit properly and must be accurately positioned relative to each other and to the patient's bones. Osteotomies (procedures involving cutting and reassembly of bones) require that the cuts be made accurately and that bone fragments be repositioned accurately before they are refastened together. Spine surgery often requires screws and other hardware to be places into vertebrae in close proximity to the spinal cord, nerves, and important blood vessels. Further, bone is rigid and relatively easy to image in CT and x-ray fluoroscopy. These factors have made orthopedics an important application domain in the development of Surgical CAD/CAM.

One of the first successful surgical CAD/CAM robots was the ROBODOC system [21], [70], [71] for joint replacement surgery, which was developed clinically by Integrated Surgical Systems from a prototype developed at IBM Research in the late 1980s. Since this system has a number of features found in other surgical CAD/CAM robots, we will discuss it in some detail.

In ROBODOC joint replacement surgery, the surgeon selects an implant model and size based on an analysis of preoperative CT images and interactively specifies the desired position of each component relative to CT coordinates. In the operating room, surgery proceeds normally up to the point where the patient's bones are to be prepared to receive the implant. The robot is moved up to the operating table, the patient's bones are attached rigidly to the robot's base through a specially designed fixation device, and the transformation between robot and CT coordinates is determined either by touching multiple points on the surface of the patient's bones or by touching preimplanted fiducial markers whose CT coordinates have been determined by image processing.

The surgeon hand guides the robot to an approximate initial position using a force sensor mounted between the robot's tool holder and the surgical cutter held by the tool holder. The robot then cuts the desired shape while monitoring cutting forces, bone motion, and other safety sensors. The surgeon also monitors progress and can interrupt the robot at any time. If the procedure is paused for any reason, there are a number of error recovery procedures available to permit the procedure to be resumed or restarted at one of several defined checkpoints. Once the desired shape has been cut, surgery proceeds manually in the normal manner.

Fig. 10. ***The ROBODOC system for hip and knee surgery was one of the first successful applications of robotics to surgical CAD/CAM [21], [70], [71].***

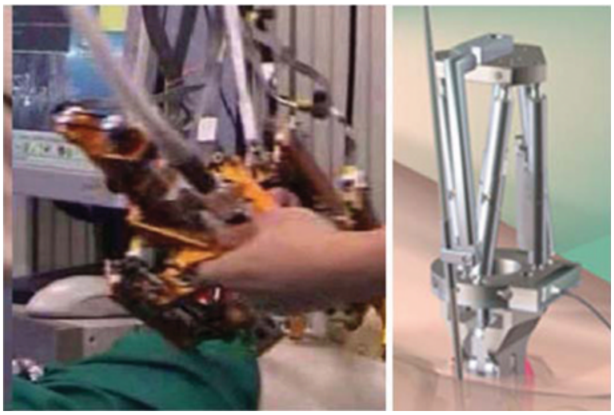


Fig. 11. ***Parallel link robots that attach directly to the patient's bone. The left system [108] is used for hip surgery and the right system [109] is intended for spine surgery.***

After preclinical testing demonstrated an order-of-magnitude improvement in precision over manual surgery, the system was applied clinically in 1992 for the femoral implant component in primary total hip replacement (THR) surgery. Subsequently, it has been applied successfully to both primary and revision THR surgery, as well as knee surgery [72]–[74].

A number of other robotic systems for use in joint replacement surgery were subsequently proposed, including the CASPAR system [75], which was very similar to ROBODOC, and the cooperatively guided Acrobot [53] (Fig. 8, right). More recently, several groups have proposed small parallel-link robots attaching directly to the patient's bones (Fig. 11). Similarly, there has been extensive progress in so-called surgical navigation for orthopedics (e.g., [8], [76], [77]), in which the surgeon manipulates tools freehand while a computer generates corresponding displays based on 2-D or 3-D images.

One significant consequence of the ability of medical robots and navigation systems to help surgeons carry out plans accurately is that the planning itself becomes more valuable. In turn, this has increased the potential importance of 3-D modeling of bone from 2-D and 3-D images, finite-element biomechanical analysis, and methods for image-based real-time registration of bone models to x-ray and ultrasound images.

B. Robotically Assisted Percutaneous Therapy

One of the first uses of robots in surgery was positioning of needle guides in stereotactic neurosurgery [18], [20], [78]. This is a natural application, since the skull provides rigid frame-of-reference. However, the potential application of localized therapy is much broader. Percutaneous therapy fits naturally within the broader paradigm of Surgical CAD/CAM systems. The basic process involves planning a patient-specific therapy pattern, delivering the therapy through a series of percutaneous access steps, assessing what was done, and using this feedback to control therapy at several time scales. The ultimate goal of current research is to develop systems that execute this process with robotic assistance under a variety of widely available and deployable image modalities, including ultrasound, x-ray fluoroscopy, and conventional MRI and CT scanners.

Current work at JHU and related work at Georgetown University is typical of this activity. This approach has emphasized the use of "remote center-of-motion" (RCM) manipulators to position needle guides under real-time image feedback. This work has led to development of a modular family of very compact robotic subsystems [79]–[83] optimized for use in a variety of imaging environments, as well as a simple image overlay device for use in CT environments (Fig. 12). These devices have been used clinically at JHU and have been evaluated for spine applications at Georgetown [84], [119]. Many other groups have also investigated the use of robotic devices with real-time x-ray and CT guidance, including [85]–[87].

A number of groups have developed robotic devices for use with ultrasound-guided (e.g., [88]–[90]) and MRI-guided (e.g., [91]–[94] needle placement. In-MRI systems represent both an unusual challenge and an unusual opportunity for medical robotics. On the one hand, the strong magnetic fields and very stringent electrical noise requirements of MRI significantly limits design flexibility. On the other hand, MRI imaging offers unprecedented tissue discrimination and imaging flexibility that can be exploited by compact robots operating inside the scanner environment.

Fig. 12. ***Needle placement under image guidance. Top left: in-CT freehand placement with image overlay device [110]. Top right: x-ray guided nephrostomy needle placement [81]–[83]. Bottom: in-CT kidney biopsy with fiducial structure on needle driver to assist robot-to-scanner registration [111], [112].***

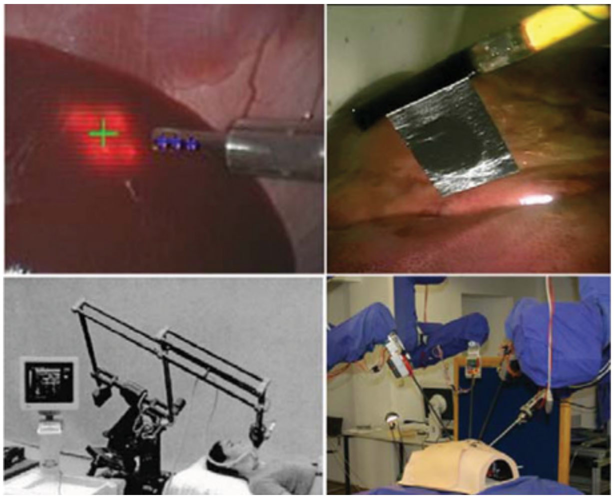


Fig. 13. ***Some surgical assistant systems. Clockwise from upper left: visual servoing of laparoscopic instrument relative to organ [113]; stereo video overlay of visually tracked laparoscopic ultrasound image in daVinci robot [114]; image feedback controlled laparoscopic ultrasound robot [115]; and laboratory setting for "skill acquisition" for suturing and similar tasks [116]–[118].***

C. Minimally Invasive Robotic Surgery

Teleoperated robots have been used for close to 15 years to assist surgeons in minimally invasive procedures, first, to hold endoscopes or retractors (e.g., [24], [50], [95], [96]) and, later, to manipulate surgical instruments (e.g., [24], [25], [31], [35]). Although there have been some spectacular long-distance demonstrations (e.g., [31], [32], [97], [98]) most uses still occur within a local operating room environment. Currently, practical clinical use is more or less limited to surgeon extender uses, in which the robot mimic the surgeon's hand motions, and the surgeon relies on visual information from endoscopic cameras for feedback.

However, sufficient progress in modeling and analysis has now been made so that medical robots with characteristics of true surgical assistants. Some examples are shown in Fig. 13. Research challenges associated with the development of more capable assistants include: 1) interactive fusion of preoperative models with real-time images and manipulator feedback, especially for deforming organs; 2) development of ways to describe surgical tasks and task steps that can be related in real time to these models; 3) development of effective menus of assistive capabilities that can be adapted to these models in real time; and 4) development of ways for the computer to "follow-along" the progress of the procedure so as to offer exactly the most appropriate assistance at any given time.

D. Rehabilitation and Assistance in Daily Living

Although this paper has focused on robotic systems for surgery and other direct medical interventions, robots also have great potential in rehabilitation and in providing more general assistance in daily living activities for the infirm or disables. Although this area is not strongly tied to my own expertise and experience, I will discuss these applications briefly here. An excellent survey and detailed discussion of the relevant research problems may be found in a recent of the International Advanced Robotics Program workshop reporton medical robots [7].

Interactive systems for physical therapy and rehabilitation share many of the characteristics of surgical assistance. Exercise robots such as those in Fig. 7 usually must come in contact with the patient, and often must constrain the patient as well. This raises obvious safety and ergonomic challenges, which may also be viewed as research opportunities. The potential of these systems to customize individual treatment plans based on patient-specific biomechanical simulations and real-time monitoring of patient performance represents a significant opportunity.

Another, longer term, opportunity is the possibility of combining the capabilities of surgical systems with rehabilitation robots. In this scenario, a patient might present with symptoms such as pain or mobility difficulties and would receive suitable diagnostic tests and imaging to permit a patient-specific model to be developed. An appropriate therapy plan would be developed from this model. If the plan includes surgery, the procedure would be carried out with the assistance of appropriate technology, such as robots or navigation aids. A customized and updated rehabilitation plan would then be executed, taking account of any unexpected events in surgery. Patient progress would be monitored both to promote optimal recovery and to provide statistical data correlating procedural variables (plan, patient anatomy, execution variability) with outcomes for the purposes of improving overall care.

One of the most rewarding things for any engineer is to develop technology and systems that directly help people. Surgical and rehabilitation robots clearly fulfill this criterion. But systems helping individuals with severe disabilities, such as the assistive robot in Fig. 14 (left) are in a special category. These systems pose many of the same human–machine research challenges as surgical assistants,

Fig. 14. ***Robots for assistance in daily living. Left: exact dynamics assistive robot manipulator [49]. Right: CMU Nursebot [49].***

such as modeling tasks and work environments, understanding human intentions, providing meaningful assistance and feedback without being unduly intrusive, etc. There are some obvious differences, as well. In particular, better means must be found to develop patient-specific human–machine interface, while at the same time finding common elements that can be standardized on. Over time, research on methods of direct coupling of systems to brain and nerve signals to robots and sensors will enable a new, more capable generation of prostheses and assistive devices. Interestingly, fitting of such devices to individual patients may be enabled by more precise and delicate surgical robots.

As our population ages, we will all become more susceptible to the physical and mental frailties that come with growing older. This will inevitably pose enormous challenges for our working population. Nursing and daily living care personnel will be stretched thinner and thinner, and old people may become increasingly isolated. Robotic systems such as the “Nursebot” in Fig. 14 (right) have significant potential to help improve both the ability of human care givers to help other people and of people needing help to sustain independent lives. Progress is likely to be incremental, as general robotic capabilities improve. Conversely, as these systems become more important economically, they are likely to serve as testbeds for developing a broad range of multiuse robotic capabilities.

V. PERSPECTIVES: WHITHER ARE WE TENDING AND HOW CAN WE GET THERE?

In less than two decades, medical robotics has developed from a subject of late-night comedy routines into a growing field engaging the attention of hundreds of active researchers around the world. If work on related technical areas such as medical image analysis is included, there are thousands of researchers involved.

This research is challenging, interdisciplinary, and synergistic. Progress is needed across the board in the modeling and analysis required for medical robotic applications, for the interface technologies required to relate the “data world” to the physical world of patients and clinicians, and to the system science that makes it possible to put everything together safely, robustly, and efficiently. Progress in these areas will most fruitfully be made within the context of well-defined applications or families of application. Careful attention must also be paid to the advantages that the robotic subsystem will provide, at least potentially, within the larger context of the application and hospital, clinic, or home environment in which it will be deployed.

Academic researchers, such as the author of this paper, can contribute to progress in these areas, but we cannot do it alone. To an even greater extent than in other subspecialties of robotics, industry has unique expertise that is absolutely essential for successful development and deployment of medical robot systems. Also, the surgeons who will use these systems have unique insights into the problems to be solved and into what will and will not be accepted in the operating room. All groups must work together for progress to be made, and they must work together practically from the very beginning. Our experience has been that building a strong researcher/surgeon/industry team is one of the most challenging, but also one of the most rewarding aspects of medical robotics research. The only greater satisfaction is the knowledge that the results of such teamwork can have a very direct impact on patients' health. Medical robotics research is very hard work, but it is worth it. ■

Acknowledgment

Although this paper is intended as a personal perspective on the field of medical robotics, this perspective has necessarily been shaped by the author's experiences in working with others. The author is grateful to all of these many colleagues and collaborators. Similarly, one notable trend over the past several years has been the explosion of excellent work in the field. It is no longer possible to produce a truly inclusive survey. The author is acutely conscious that much excellent work has gone uncited. To those who have been passed over, please accept the author's apologies. Finally, the author expresses appreciation to the many government and industry partners who have partially funded some of the work reported here.

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