

Medical Robotics in Computer-Integrated Surgery

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Abstract—This paper provides a broad overview of medical robot systems used in surgery. After introducing basic concepts of computer-integrated surgery, surgical CAD/CAM, and surgical assistants, it discusses some of the major design issues particular to medical robots. It then illustrates these issues and the broader themes introduced earlier with examples of current surgical CAD/CAM and surgical assistant systems. Finally, it provides a brief synopsis of current research challenges and closes with a few thoughts on the research/industry/clinician teamwork that is essential for progress in the field.

Index Terms—Applications, computer-integrated surgery (CIS), human-machine cooperative systems, image-guided surgery, medical devices, medical robotics, micromanipulation, microsurgery, surgical assistants, surgical CAD/CAM, teleoperation, telerobotics, telesurgery.

I. INTRODUCTION: COMPUTER-INTEGRATED SURGERY

ROBOTIC systems for surgery are computer-integrated surgery (CIS) systems first, and “medical robots” second. In other words, the robot itself is just one element of a larger system designed to assist a surgeon in carrying out a surgical procedure that may include preoperative planning, intraoperative registration to presurgical plans, use of a combination of robotic assist and manually controlled tools for carrying out the plan, and postoperative verification and follow-up.

Medical robots may be classified in many ways: by manipulator design (e.g., kinematics, actuation); by level of autonomy (e.g., preprogrammed versus teleoperation versus constrained cooperative control), by targeted anatomy or technique (e.g., cardiac, intravascular, percutaneous, laparoscopic, microsurgical); intended operating environment [e.g., in-scanner,

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Under a licensing agreement between Image Guide (IG), Inc. and the Johns Hopkins University, Drs. Taylor (R.H.T.) and Stoianovici (D.S.) are entitled to a share of royalties received by the University on sales of some of the JHU robots presented in this paper. Also, both R.H.T. and D.S. are members of the Scientific Advisory Board of IG. The authors and the University hold options to IG stock, which is subject to certain restrictions under University policy. D.S. is a paid consultant to IG. Under a private license agreement, D.S. is entitled to royalties on IG sales of products embodying the Ball-Worm technology. The terms of these arrangements are being managed by the Johns Hopkins University in accordance with its conflict of interest policies.

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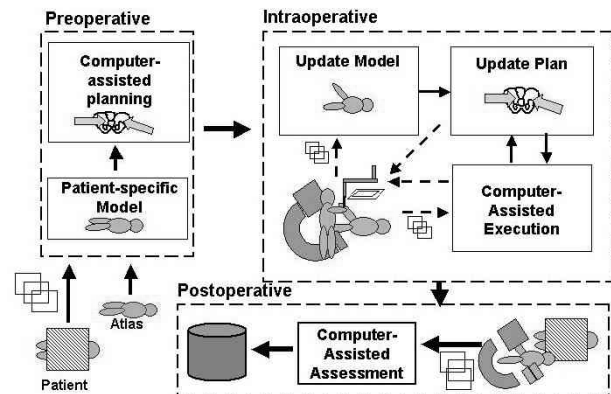


Fig. 1. Information flow of CIS systems.

conventional operating room (OR)], etc. In this paper, we have chosen to focus on the role of medical robots within the context of their role in CIS systems. We classify the systems into two broad families: surgical CAD/CAM and surgical assistants. These families are described below. As with industrial robots, the first consideration in design of medical robots is identifying the advantages provided by the robot that would justify its incorporation into a clinical system. These themes are also briefly introduced for each system family.

Section II will describe common technical design issues and themes, and Sections III and IV will use specific systems to illustrate current research. Section V will conclude with a brief assessment of where the field is tending and offers some thoughts about how research should proceed.

A. 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 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 III. 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 the 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.

B. 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.

Typical examples of surgical assistant systems will be discussed in Section IV.

II. TECHNOLOGY AND DESIGN ISSUES IN SURGICAL ROBOTICS

A. General Design Considerations

Initial surgical robotic systems in the 1980s employed general-purpose industrial manipulators, either directly or with minor modifications (e.g., [1]–[4]). Industrial robots are still being used today as research and validation tools where immediate clinical use is not contemplated or specialized kinematic design is not essential (e.g., [5] and [6]). Such systems are robust, available, and often have open interfaces suitable for experimentation. It is generally acknowledged, however, that the use of specially designed robotic hardware is desirable for most clinical applications (e.g., [7]–[11]).

Surgical robots must be compatible with the operating theater. The robot must have sufficient strength, accuracy, and dexterity for its intended use. It must be placed where it can work on the patient while also allowing access by clinical staff. Usually, this is done by mounting the robot to the operating table (e.g., [12] and [13]) or placing it on the floor beside the patient (e.g., [14] and [15]). However, ceiling mounts [14], [15] and attachment to the patient [16], [17] are occasionally used. There is no ideal solution. Ceiling mounts offer unimpeded access to the patient but require the hospital to dedicate an operating room and restrict where the table can be placed. Table mounts are convenient if the table must be reoriented during surgery, but they restrict payload, make it hard to provide rigidity, and must be manually carried and mounted on the table. Floor-mounted systems permit higher payloads and are easy to introduce or remove for individual surgical steps, but they tend to get in the way more when used. Patient mounts adapt to patient motion, but robot weight, stability of mounting, and access may be problems.

Any part of the robot that can come into contact with the patient or which may contaminate the surgical field must be sterilized or covered with a sterile cover. The most common practice thus far has been the use of presterilized bags covering most of the robot and the sterilization of the end-effector, instrument holder part. Usually, gas or soak sterilization is used if end-effectors contain motors or sensors, but new sensor and actuator technology that would permit easier sterilization (e.g., autoclaving) or is cheap enough to be disposable could represent an important research opportunity.

Image-guidance applications impose additional demands with respect to compactness, image "translucency", and ability to operate with the imaging device. Magnetic resonance imaging (MRI)-compatible robots are an especially challenging problem requiring research. [18], [19]. MR scanners use magnetic fields of very high density, on the order of 1–1.5 T. Ferromagnetic materials exposed to such fields undergo very high forces.¹ Concurrently, MR imagers use pulsed magnetic and radio frequency fields, thus inducing electricity in conductive elements, creating electrical interference, and overheating. For these reasons, most of the classic robotic components do not apply. Despite these difficulties, there is strong motivation for building MRI-compatible robots because of the imaging capabilities of this technology, especially for soft tissue applications.

¹For example, a 10 cm × 10 cm × 1 cm steel plate in a 1-T magnetic field can experience a force of about 4000 N, depending on orientation.

Safety is obviously very important in medical robots and must be addressed at all phases of design, manufacture, and application [20]. Although there are no hard and fast rules, some basic principles include: redundancy in safety-critical systems; avoiding unnecessary speed or power in actuators; rigorous design analysis, documentation, and testing protocols (e.g., ISO9000); multiple emergency stop and checkpoint/restart facilities; factored designs allowing not-critical components to be disabled; etc.

One of the oldest debates in industrial robotics concerns the tradeoff between very general-purpose robots and simpler, more specialized systems that may be cheaper, more reliable, and better suited to a particular task. Not surprisingly, this same debate also applies to medical robots, especially since so much of the cost of these systems is related to development and regulatory approval costs rather than manufacturing. It is desirable that a surgical robot be readily adapted to multiple tools or end-effectors, if that can be done without increasing the complexity too much.

On the other hand, there are large classes of useful applications that can be done with a restricted subset of function. Robots for percutaneous needle insertion, for example, need only two degrees of freedom (DOF) to orient a needle about a skin entry point and a third to control insertion depth [21], [22].

Passive encoded arms [23]–[26] often suffice for guidance applications. Passive systems with dynamic constraints such as [27] or completely passive mechanisms with appropriate kinematic constraints such as [28] often can facilitate positioning or simple trajectory tasks while absolutely preventing “run-away robot” safety problems.

Development of reduced size, lightweight manipulators with limited range of motion [7], [29], [30] is important in many medical applications. Intuitively, small, reduced power robots offer safety and ergonomic advantages compared to large, powerful robots for surgical applications [31]. Active surgical work volumes are often quite small, and scaling the mechanism accordingly is very appropriate. One difficulty with this approach is positioning the active volume at the right place relative to the patient. A common approach is the use of a passive arm with some sort of locking mechanism (e.g., [14], [32], and [33]). More generally, we believe that there is a strong need for a *modular* family of active and passive robotic mechanisms that can be combined quickly to produce a variety of clinical systems.

B. Remote Center-of-Motion Kinematic Architectures

Many surgical tasks are characterized by relatively large angular mobility about a single point or within a limited spatial volume. In laparoscopic surgery, for example, the instruments pivot about the point at which they enter the patient’s body. In percutaneous access procedures, for example, a needle is initially placed with its tip at the skin entry point and then oriented about that pivot point for targeting. Open microsurgery may require only small displacements of tool tips but may have moderately large reorientations. Craniofacial osteotomies [32] similarly can involve moderate-to-large bone fragment reorientations with only small displacements.

These considerations have led us and others to develop mechanisms that naturally decouple rotational and translational motions of tools at a point some distance from the mechanical structure of the robot. Many surgical robots include such a *remote center-of-motion (RCM)* as a central design feature. One advantage of an RCM robot is that it permits translational actuators to be disabled (or omitted) if only pivoting motions are needed. Another advantage is that it permits actuators and drive gear ratios to be sized appropriately for their respective motions. This also permits large orientation angles for the instrument to be achieved with a compact mechanism. Finally, system control and some safety checking can be simplified.

Surgical robots have used a number of designs to produce mechanically constrained RCM manipulators, including goniometer arcs [20], [32], [34], [35], parallelogram designs using either parallel-bar linkages [14], [36]–[39] or chain or belt drives [22], [40]. These RCM mechanisms have two DOF rotational mechanisms with coincident axes at an RCM point located distal from the mechanism. Commonly, these axes are of normal relative direction, but nonorthogonal, adjustable axes have also been proposed [22]. Our RCM robotic module [22] is one of the more compact implementations of the parallelogram category using a double belt drive and adjustable, nonorthogonal pivot axes facilitating various end-effector usages.

In RCM mechanisms, the RCM pivot is defined and mechanically locked by the kinematics of the mechanism. For *programmable* RCM types, the pivot is achieved under coordinated control of multiple joints. Such motion can be achieved with a large variety of high-DOF robots, including industrial types, under coordinated joint control. An example is the hybrid serial/parallel manipulator [41] reported by Stacco and Salcudean. The approach has serious advantages of pivot flexibility, increased maneuverability, and overall versatility. For surgical applications, however, we consider mechanical RCMs to be safer due to their reduced DOF, decoupled motion, controller simplicity, and locked pivot features. Moreover, RCM mechanisms typically allow for achieving higher angular mobility about the pivot in a confined space, such as closed-bore imager types.

The AESOP robot (Computer Motion, Inc., Goleta, CA) involves a *passive* RCM type [42]. The last two revolute joints of the AESOP robot are passive with intersecting axes. The intersection of these axes is neither remote from the mechanism nor located at the laparoscopic port level. The laparoscopic instrument occupies a free orientation between the end of the robot and the laparoscopic entry port. In that, the AESOP is not a genuine RCM mechanism, but rather a floating RCM, which provides a safe way of pivoting the laparoscope in case of accidental patient motion. Some researchers believe that the passive RCM type is safer than mechanically locked RCM types, but even though this is still debated, safety is achieved at the expense of motion accuracy and stiffness. Other examples of robots using passively constrained RCM approaches include [43], [44].

A new type of compliant, cable-driven RCM was recently reported [45] for endoscope manipulation. Other examples are included in Tables I and II, presenting a summary of surgical robotic systems and some of their characteristics.

TABLE I
A SAMPLER OF SURGICAL CAD/CAM SYSTEMS

System	Institution	Country	Year	Guidance/Control	Clinical Area	Applied to	Commercial / Regulatory Status	Mount	Positioning Arm	DOF	RCM Type	Back-drivability	Ref
Acrobot	Imperial College	UK	2001	Synergetic	Orthopedic	Human	-	Floor trolley Table clamps	6 dof active + brakes	3	-	Low	[158]
Arthrobot	KAIST	Korea	2002	Gauge-Based	Orthopedic	Phantom	-	Bone	-	4	Programmable	Low	[17]
Brigham MRI	AIST / Brigham & Women Hospital	Japan / USA	1999	MRI Guided	Prostate Brachytherapy	Phantom	Non-commercial	MRI Scanner	-	5	-	Low	[19]
Breast MRI System	Karlsruhe University	Germany	2000	MRI Guided	Breast Biopsy	Animal	-	Scanner Table	-	6	-	Low	[91]
CyberKnife	Accuray	USA	1999	X-Ray Guided	Radical surgery	Human	Commercial	Floor	-	6	-	Very Low	[159]
GRIGOS	Helmholz Inst; TIMC-IMAG	Germany; France	1997	Surgical CAD /CAM	Orthopaedics	Phantom	-	Table	-	6	-	Low	[77]
KEN-MRI	University of Tokio	Japan	1995	MRI Guided	Neurosurgery	Phantom	-	Table	-	6	Goniometer Arc	Low	[93]
Minerva	University of Lausanne	Switzerland	1993	X-Ray Guided	Neurosurgery	Human	-	Floor	3 transl dof	3	-	Low	[160]
IGOR	Grenoble University	France	1992	Preoperat. Imaging and Tracking	Neurosurgery	Human	Non-commercial	Floor	-	6	-	Very Low	[78]
Neuro Mate	Integrated Surgical Systems	France / USA	1996	Preoperat. Imaging and Tracking	Neurosurgery	Human	Commercial / FDA Cleared	Floor Trolley	-	6	-	Very Low	-
PAKY-RCM	Johns Hopkins	USA	1998-2003	X-Ray Guided	Percutaneous Access	Human	Transfer/FDA - IDE	Table Mount	7 dof	3	Belt Parallelogram	Very Low	[22]
PADyC	TIMC/IMAG	France	1995 - 2001	Synergetic	Cardiac	Animal	-	Floor	-	6	-	Very High with Brakes	[27, 161]
PinPoint	Philips / Marconi Medical Systems	USA	2000	CT Tracker Arm	CT Interventions	Human	Commercial	Ceiling	6	-	-	Very High	[26]
PROBOT	Imperial College	UK	1995	US Guided	Urology	Human	Non-commercial	Floor	Slider	3	Goniometer Arc	Low	[162]
ROBODOC	Integrated Surgical Systems	USA	1992	CT-based preop. plan	Orthopedic	Human	Commercial/ Cleared in Europe	Floor with fixator to bone	Modified SCARA	6	-	Low	[69, 70]
Robards-breast	Robards Research Inst.	Canada	2001	Ultrasound	Breast biopsy	animal	-	Table	Cartesian	3	-	Low	[94]
RX-90	Karlsruhe University / ortoMarquet	Germany	1999	Synergetic	Maxillofacial	Animal	Commercial	Floor	-	6	-	Low	[163]
Siemens CT	Siemens, AG	Germany	2000	Manual + Active	In-CT percutaneous	Animal	-	Table	Passive arm + 2dof active	2	5 bar parallel linkage	Low?	[38]
SS-Orthop	Scuola Superiore Saint' Anna	Italy	1998	CT-based preop plan	TKA	Cadaver	-	Floor?	-	5	-	Low	[164]
AcuBot	Johns Hopkins / Georgetown University	USA	2001	X-ray & CT Guided	Percutaneous Access	Cadaver	Transfer / FDA - IDE	Bridge Scanner Table Mount	7 dof	6	Belt Parallelogram	Very Low	[84]
WAM	Z-KAT Inc. / Barrett Technology	USA	2002	Synergetic	Spine	Phantom	-	Floor	-	4+1	-	Low	[29]

C. Stiffness, Drive Philosophy, and Redundancy

There are differing opinions about whether surgical robot drives should exhibit high stiffness and low backdrivability, or should be easily back-drivable using direct drive or lightly geared actuation. There are valid arguments on both sides, and Table I contains examples of both. Back-drivable systems permit tool-to-tissue forces to be reflected to the actuators. Limiting actuator torque limits the force that a tool can exert on a patient and possibly makes some forms of compliance control easier. Also, if the system loses power, the surgical tool may

be pulled out of the way manually. On the other hand, it can be harder to achieve high precision with these systems, especially if tool loads vary, and there is also the possibility of dropping a heavy tool on the patient if power is lost. Also, for direct-drive actuation with even moderately powerful actuators, a control failure can cause undesirable high accelerations.

Our own preference has been to use high-ratio, nonback-drivable transmissions. This permits us to achieve high precision and good load-carrying capabilities with relatively low-power actuators. "Pulling the plug" causes the robot to freeze, and a clutch or detachment means is required for removing the robot's

TABLE II
A SAMPLER OF SURGICAL ASSISTANT SYSTEMS

System	Institution	Country	Year	Guidance/Control	Clinical Area	Applied to	Commercial / Regulatory Status	Mount	Positioning Arm	DOF	RCM Type	Back-drivability	Ref
AESOP	Computer Motion	USA	1992	Pad, Foot, Voice, Remote	Laparoscopy	Human	Commercial / FDA Cleared 1994	Cart and Table Mount	-	3	Passive	Low	[12]
BlueDRAGON	University of Washington, Seattle	USA	2002	Haptic Device	Laparoscopy	Phantom	-	Table	-	4	Bar Parallelogram	Very High	[165]
CLEM	TIMC/IMAG	France	2002	-	Laparoscopy	Phantom	-	Table	-	3	Compliant	High	[45]
daVinci	Intuitive Surgical	USA	1999	Master-Slave	Laparoscopy	Human	Commercial / FDA Cleared 2000	Floor Trolley	Passive, breaks	2*6+4	Bar Parallelogram	High	[14]
LARS	IBM	USA	1995	Synergetic / Image Guided	Laparoscopy / Percutaneous Access	Animal	-	Floor Trolley	-	6	Bar Parallelogram	Low	[37]
SCALPP	LIRMM	France	2001	Surgical Assistant	Skin harvesting	?	-	Floor	Augmented SCARA	6	-	?	[133]
SS-Colon	Scuola Superiore Saint'Anna	Italy	1997-2002	Surgical Assistant; Master-slave	Colonoscopy	Cadaver	-	Free mount	-	1?	-	Low	[143]
Steady Hand	Johns Hopkins	USA	1999	Synergetic	microsurgery	cadaver	Non-commercial	Table	-	7	Belt Parallelogram	Mixed	[123, 124]
SurgiScope	Humboldt University / Jojunarie Intelligente Instrumente /Elekta	Germany	1997	Navigation + Surgeon inputs	Microscope holder; brachytherapy	Human (microscopes); animals (brachytherapy)	Commercial	Ceiling	Parallel	6	-	Low	[166]
TER	TIMC/IMAG	France	2001	Master-slave	Tele-Echography	phantom	-	Table/patient	Parallel	2	Constraint at entry port	High	[156]]
UBC-US	University of British Columbia	Canada	1999	3D Ultrasound	Arterial exams	Human	-	Floor Trolley	-	6	5 Bar Parallelogram	High	[142]
UBC-MW	University of British Columbia	Canada	1997	Master-slave	Microsurgery	phantom	-	Table	6DOF active robot	6	-	High	[104]
UCB/UCSF	UC Berkeley UC San Fran.	USA	1999, 2003	Master-slave	Laparoscopy	Animal	-	Floor trolley	6 DOF	6	Passive	High	[167, 168]
UT-LAP	University of Tokyo	Japan	1999	Gyro Sensor / Foot	Laparoscopy	Phantom	-	Table	-	4	Passive (Bar Parallelogram Included)	High	[39]
Zeus	Computer Motion	USA	1998	Master-Slave	Laparoscopy	Human	Commercial	Table Mount	-	3	Free wrist with constrained isocenter	Low	[13]

tools, but such mechanisms are readily designed. Force compliance is achieved by variations on “force loop around position/velocity loop” schemes, using specific sensors.

High transmission ratios can lead to problems with mechanical backlash, which can hurt precision. The relatively small size of medical robots and constraints on lubrication can make design approaches common in industrial robots unattractive. The most common type of transmission for precise linear motion is the *ball-screw* mechanism, which, except for its noisy high-speed operation, is a fine minimal backlash mechanism. The most common rotary transmission used in surgical robots is the *cable/belt* drive, because it allows the motors to be located toward the base of the robot, reducing size and simplifying sterilization procedures for components near the end-effector. Cables and belts are backlash free, yet compliant, thus compromising stiffness. For this reason, such mechanisms are predominantly used in master-slave augmen-

tation systems, in which the operator naturally compensates for absolute positioning error. *Harmonic drives* also provide backlash-free rotational reductions. Even though their flexible splines are elastic elements, stiffness is often acceptable. Spur and beveled *gears* can often be set for minimal backlash if a clean design with fine adjustable distance between the axes is used. These offer significantly increased stiffness over cables. In our experience, small-size *worm gears* are impossible to reliably tune for minimal backlash. Even though sometimes worms seem advantageous to use due to their high transmission ratios and orthogonal axes, their operation is based on sliding friction causing wear and deteriorating backlash, is energy inefficient, and requires sustained lubrication. Our original RCM module [22] used worm gears. This made us develop a ball-worm gear (a ball-screw principle applied to a worm transmission) for the second-generation RCM. For both the worms and spur gears, the backlash-free small types using

spring preload are commonly impractical because of their reduced range of backlash-free operation.

At a very fine scale (e.g. [46] and [47]), an alternative is to use direct actuation schemes, such as shape-memory, to allow actuators to directly deform structural elements.

Passive *gravity balance* is an important safety feature of surgical robots by allowing for the use of reduced power actuation. Active gravity balance of manipulators, sometimes involved in industrial designs, is insufficiently safe in our case, because a faulty controller could potentially exert a down force that is at least double the weight of the manipulator. Nonback-drivable or locked arms are power-fail safe, but not controller-fail safe. *Counterweights* are not the ideal because of increasing overall weight and size. *Nitrogen springs* are compact and give relatively good linearity but introduce static friction. In our experience, springs, especially *constant force springs*, are preferable because of their simplicity, frictionless operation, size/weight, and reliability.

Redundancy in kinematics and sensing gives a great deal of confidence in safety. Sensing redundancy is commonly employed in surgical robots by using position encoders on the gear-motor assembly for the control and (often) redundant encoders at/near the end of the transmission chain for consistency checking. However, redundant designs can increase complexity, especially for the mechanical parts, but also for the additional bulk of wiring.

D. Human–Machine Interfaces

Computer-based systems that work cooperatively with humans must communicate with them, both to provide information and to receive commands and guidance. As with surgical robots, surgical human–machine interfaces (HMI) have a great deal in common with those for other application domains, and they draw upon essentially the same technologies (speech, computer vision and graphics, haptics, etc.) that have found use elsewhere. In many cases, HMI subsystems that have been developed for other uses may be adapted with little change for surgical use. However, attention must be given to the unusual requirements of surgical applications [48]. Surgeons tend to have very strong expectations about system responsiveness and transparency and they have very low tolerance for interfaces that impede their work. On the other hand, they can also be quite willing to put up with great inconvenience if the system is really performing a useful function that truly extends their capabilities.

Surgeons overwhelmingly rely on vision as their dominant source of feedback during surgery. Indeed, the explosion in minimal-access surgery over the past decade has very largely been the result of the availability of compact, high-resolution video cameras attached to endoscopic optics. In these cases, the surgeon's attention is naturally focused on a television monitor. In such cases, it is often possible for the computer to add computer graphics, text, and other information to the video stream (e.g., [49]). Surgical navigation systems (e.g., [32], [50]–[55]) provide computer graphic renderings and feedback based on tracked surgical instrument positions. Important challenges in such systems include: 1) finding ways to communicate useful information while also conveying limitations in registration accuracy; 2) providing surgeons with means of controlling the information displayed; 3) updating models and display in real time

in soft-tissue environments; and 4) integration of navigation and display with robot systems.

One very important challenge in the design of such systems is providing useful information about the imprecision of the system's information, so that the surgeon does not make decisions based on a false determination of the relative position of a surgical instrument and target anatomy. One common approach is to display a circle or ellipse representing likely registration uncertainty, but significant advances are needed both in the modeling of such errors and in the human factors associated with their presentation.

One limitation of so-called video overlay systems is the limited resolution of current-generation video cameras. This is especially important in microsurgical applications, where the structures being operated on are very small, or in applications requiring very good color discrimination. Consequently, there is also interest in so-called optical overlay methods, in which graphic information is projected into the optical path of a microscope (e.g., [56]) or presented on a half-silvered mirror (e.g., [57] and [58]), so that it appears to be superimposed on the surgeon's field of view in appropriate alignment. The design considerations for these systems are generally similar to those using video displays, but the registration problems tend to be even more demanding and the brightness of the displays also can be a problem.

All of the common interfaces (mice, joysticks, touch screens, push buttons, foot switches, etc.) used for interactive computer applications are used to provide input for surgical systems as well. For preoperative planning applications, these devices are identical to those used elsewhere. For intraoperative use, sterility, electrical safety, and ergonomic considerations may require some design modifications. For example, the LARS robot [49] repackaged the pointing device from an IBM Thinkpad computer into a three-button "mouse" clipped onto the surgeon's instruments. As another example, a tracked stereotactic wand has been used to provide a reconfigurable "push button" interface, in which functions are selected by tapping the tip of the pointer onto a sterilized template [59].

Surgeons routinely use voice to communicate with operating room personnel. Further, their hands (and feet) are frequently rather busy. Accordingly, there has long been interest in using voice as a two-way command and control system for surgical applications. Examples include [43], [44], [49], [60], and [61].

Force and haptic feedback is often important for surgical simulation (e.g., [61]–[63]) and telesurgery applications (e.g., [34], [64]–[68]). Again, the technical issues involved are similar to those for other virtual reality and telerobotics applications, with the added requirement of maintaining sterility and electrical safety.

One crucial problem, which is not unique to medical robotics, is ensuring that the surgeon has all pertinent information known to the system but is not overwhelmed by detail. Part of the solution is doubtless careful human factors design. Beyond this, research enabling the surgical workstation to model and "follow along" a surgical procedure or step and customize both information display and robot control characteristics appropriately would clearly have a major effect on the effectiveness of these systems.

III. TYPICAL SURGICAL CAD/CAM SYSTEMS

A. Robotic Orthopaedic Surgery

Geometric precision is often an important consideration in orthopaedic surgery. For example, orthopaedic 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 placed into vertebrae in close proximity to the spinal cord, nerves, and important blood vessels. Further, bone is rigid and relatively easy to image in computed X-ray tomography (CT) and X-ray fluoroscopy. These factors have made orthopaedics an important application domain in the development of surgical CAD/CAM.

One of the first successful surgical CAD/CAM robots was the ROBODOC system [15], [69], [70] for joint replacement surgery, which was developed clinically by Integrated Surgical Systems from a prototype developed at IBM Research in the late 1980's (see Fig. 2). Since this system has a number of features found in other surgical CAD/CAM robots, we will discuss it in some detail.

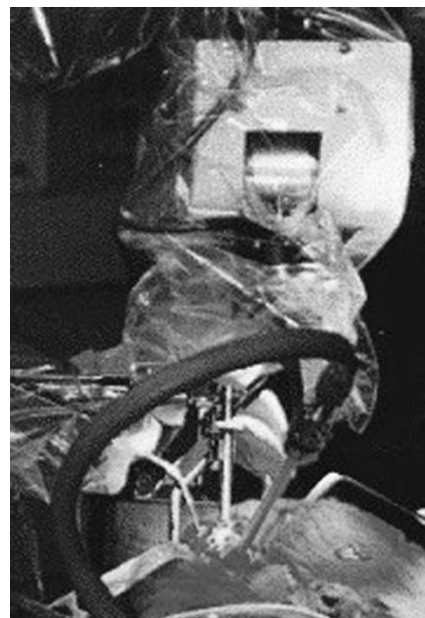
In ROBODOC joint replacement surgery, the surgeon selects an implant model and size based on an analysis of preoperative CT images and interactively specifies the desired position of each component relative to CT coordinates. In the operating room, surgery proceeds normally up to the point where the 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's 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.

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 [71], [72]. As of 2002, approximately 70 systems had been deployed in hospitals, and something over 10 000 procedures had been performed without a fracture or other serious complication due to the robot [73].



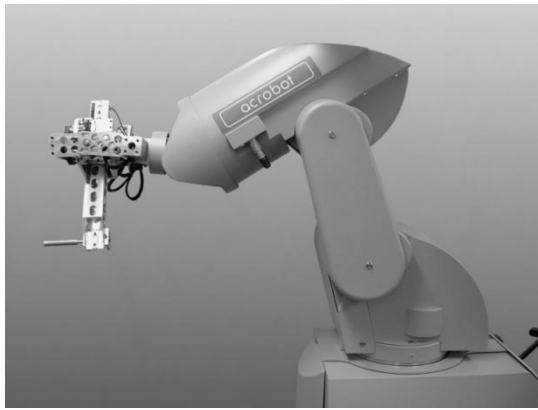
(a)



(b)

Fig. 2. ROBODOC system for hip and knee surgery [15], [69], [70] (Photos: Integrated Surgical Systems).

An interesting approach [31] (shown in Fig. 3) uses constrained hand guiding to perform the bone machining operation. The surgeon moves the robot by pulling on a force-sensing handle in a manner resembling that used to preposition ROBODOC prior to bone cutting. In this case, the cutter is turned on and the robot motions are constrained by software so that the cutter remains within a volume corresponding to the bone to be removed. This approach may be appealing to some surgeons, because the surgeon remains more directly "in the loop" during bone shaping. However, crucial factors affecting outcome, such as the registration accuracy between robot and patient, are the same whether the robot is machining bone autonomously under surgeon supervision or is being hand guided.



(a)



(b)

Fig. 3. ACROBAT hand-guided knee replacement robot [31] (Photos: B. Davies).

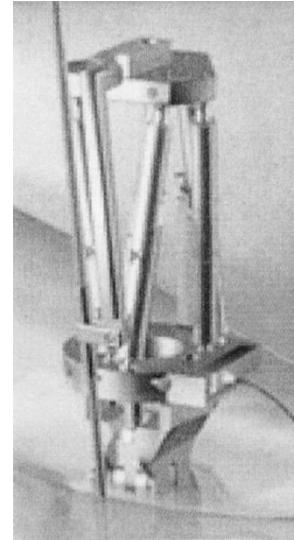
A number of other robotic systems for use in joint replacement surgery have subsequently been proposed. The system most closely resembling ROBODOC is the CASPAR system [74]. Kwon *et al.* [17] have proposed an alternative approach, shown in Fig. 4(a), in which a small robot is mounted directly onto the patient's femur. In this system, the surgeon uses a mechanical device to determine the desired position and orientation of the implant hole manually, and the robot machines the desired shape.

Both ROBODOC and CASPAR have been applied to knee surgery [74], [75]. Other robotic systems have been proposed or (in a few cases) applied in knee surgery. For example, Garbini [2] and Kienzle [76] separately proposed using a robot to position passive saw guides for TKR.

There has also been some interest in using robotic systems to assist in placing pedicle screws in spine surgery. One very interesting approach proposed by Shoham *et al.* [16] uses a small (5 cm x 3.5 cm x 3.7 cm, 150 grams) parallel link robot mounted directly on the vertebral body. The same group has also proposed a similar, though somewhat larger, robot for intramedullary nailing. Other uses of parallel link robots for a variety of orthopaedic procedures include [17] and [77].



(a)



(b)

Fig. 4. Two parallel link robots that attach directly to the patient's bone. (a) System [17] used for hip surgery. (b) System [16] intended for spine surgery.

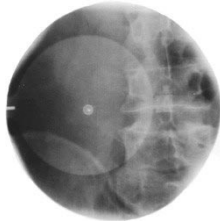
B. Robotically Assisted Percutaneous Therapy

One of the first uses of robots in surgery was positioning of needle guides in stereotactic neurosurgery [1], [78], [79]. 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.

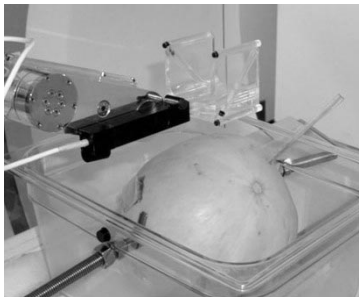
Current work at The Johns Hopkins University (JHU), Baltimore, MD, is typical of this activity. Our approach has emphasized the use of RCM manipulators to position needle guides under real-time image feedback. One early experimental system used a modified LARS robot *in-vivo* on pigs to place needles under biplane image guidance into the kidney [80], [81] and to place patterns of pellets planned from preoperative CT into the liver [80], [81]. Based upon this experience, we have subsequently focused on development of a modular family of very compact robotic subsystems optimized for use in a variety of imaging environments. Fig. 5 shows use of JHU RCM robots



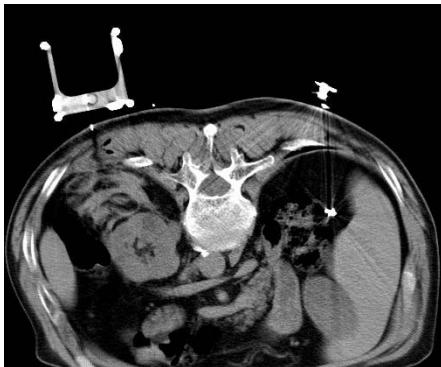
(a)



(b)



(c)



(d)

Fig. 5. X-ray compatible needle driver (PAKY) developed at JHU [21], [86], [87] and adaptations for CT. (a) PAKY applied clinically to nephrostomies. (b) Typical X-ray image seen by the surgeon. (c) Preclinical evaluation of an adaptation for use in a CT scanner [82], [88]. (d) Typical real-time CT image of clinical use for a kidney biopsy [83].

with radiolucent end-effectors designed to drive needles under X-ray and CT guidance [82]. These devices have been used clinically [83] at JHU and have been evaluated for spine applications at Georgetown University, Washington, DC [84], [169]. Other groups have also investigated the use of robotic devices with real-time X-ray and CT guidance, including [26], [38], and [85].

Related work at Brigham and Women's Hospital, Boston, MA, is illustrated in Fig. 6(a). This system [19] is designed to



(a)



(b)

Fig. 6. Robotic systems for in-MRI percutaneous therapy. (a) [19] System designed for use in an open MRI system for such applications as percutaneous prostate therapy. (b) [91] System designed for breast biopsy in a conventional scanner. (Photos: K. Chinzei and H. Fischer).

operate in an open-magnet MRI system and uses a common control architecture developed jointly by Massachusetts Institute of Technology (MIT), Cambridge, MA, Brigham and Women's Hospital, and JHU [89], [90]. One early application will be MRI-guided prostate therapy. Fig. 6(b) shows another MRI-compatible robot system, this one designed for breast biopsy [91]. Other examples of MRI-compatible robots include [92] and [93].

There is also current work to develop robotic biopsy devices suitable for use with ultrasound. Examples include breast biopsy [94], [95] and ultrasound-guided prostate brachytherapy [Fichtinger, 2002 #1350].

C. Other Surgical CAD/CAM Examples

Commercial beam therapy systems [96] such as the Clinac [97] have many of the characteristics of surgical robots. Indeed, some radiosurgery systems such as the Accuray Cyberknife [98] now use modified commercial robots to position the radiation therapy delivery device properly with respect to the patient. As with other surgical CAD/CAM systems, these systems must integrate image-based pretreatment planning, intraoperative registration of the plan to the patient, and monitoring of therapy. Indeed, radiation therapy planning (e.g., [99]) has very high synergy with many aspects of planning for other application domains. Further, lessons learned from beam planning often apply directly to percutaneous therapy plans (e.g., [100], [101]).

IV. SURGICAL ASSISTANT SYSTEMS

A. Surgeon Extenders

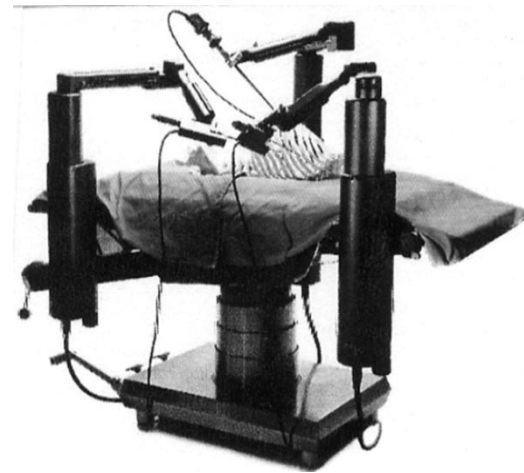
Much of the past and current work on surgical augmentation (e.g., [14], [34], [44], [66], [102]–[105]) has focused on teleoperation. There is considerable interest in the use of master–slave manipulator systems to improve the ergonomic aspects of laparoscopic surgery. Fig. 7 shows typical examples (the Intuitive Surgical DaVinci system [14] and Zeus [13]). In these cases, three slave robots are used. One slave holds an endoscopic camera and two others manipulate a variety of surgical instruments, some of which have high-dexterity wrists. Several of these systems have the ability to feed back forces to the surgeon through the master manipulator, although limitations in the ability of current slaves to sense tool-to-tissue forces can somewhat limit this ability. One significant problem with endoscopic surgery, whether robotically assisted or freehand, is the effect of entry port placement on the manipulation dexterity at the surgical site. Several authors [106], [107] have addressed this subject, but there is much more research to be done, both in planning and in development of robots with higher distal dexterity. Another significant problem is motion of the anatomy being operated upon, especially in cardiac cases, and several groups are exploring approaches to accommodate such motion [108]–[110].

The manipulation limitations imposed by human hand tremor and limited ability to feel and control very small forces, together with the limitations of operating microscopes, have led a number of groups to investigate robotic augmentation of microsurgery. Several systems have been developed for teleoperated microsurgery using a passive input device for operator control. Guerrouad and Vidal [35] describe a system designed for ocular vitrectomy in which a mechanical manipulator was constructed of curved tracks to maintain a fixed center of rotation. A similar micromanipulator [111] was used for acquiring physiological measurements in the eye using an electrode. While rigid mechanical constraints were suitable for the particular applications in which they were used, the design is not flexible enough for general-purpose microsurgery and the tracks take up a great deal of space around the head. An ophthalmic surgery manipulator built by Jensen *et al.* [112], [113] was designed for retinal vascular microsurgery and was capable of positioning instruments at the surface of the retina with submicron precision. While a useful experimental device, this system did not have sufficient range of motion to be useful for general-purpose microsurgery. Also, the lack of force sensing prevented the investigation of force/haptic interfaces in the performance of microsurgical tasks.

Many microsurgical robots (e.g., [34], [104], [114]–[117]) are based on force-reflecting master–slave configurations. This paradigm allows an operator to grasp the master manipulator and apply forces. Forces measured on the master are scaled and reproduced at the slave and, if unobstructed, will cause the slave to move accordingly. Likewise, forces encountered by the slave are scaled and reflected back to the master. This configuration allows position commands from the master to result in a reduced motion of the slave and for forces encountered by the slave to be amplified at the master.



(a)



(b)



(c)

Fig. 7. Two commercial telesurgical systems. (a) and (b) Master control station and slave robots for the Computer Motion Zeus system [44]. (c) Intuitive Surgical DaVinci system [14] in use in Leipzig, Germany. (Photos: Computer Motion and Intuitive Surgical).

While a force-reflecting master–slave microsurgical system provides the surgeon with increased precision and enhanced perception, there are some drawbacks to such a design. The primary disadvantage is the complexity and cost associated with the re-

quirement of providing two mechanical systems, one for the master and one for the slave. Another problem with telesurgery in general is that the surgeon is not allowed to directly manipulate the instrument used for the microsurgical procedure. While physical separation is necessary for systems designed to perform remote surgery, it is not required during microsurgical procedures. In fact, surgeons are more likely to accept assistance devices if they are still allowed to directly manipulate the instruments.²

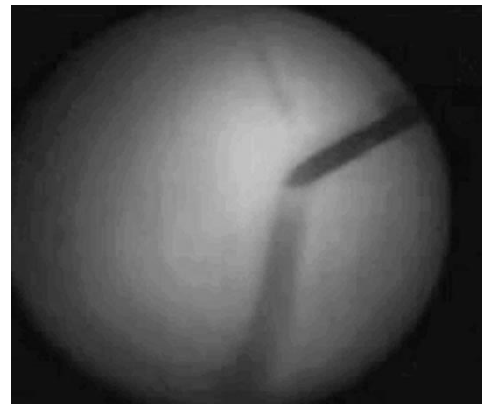
The performance augmentation approach pursued by the CIS group at Johns Hopkins University, which has also been explored independently by Davies, *et al.* [8], [118], [119], and which has some resemblances to the work of Kazerooni [120], emphasizes cooperative manipulation, in which the surgeon and robot both hold the surgical tool. The robot senses forces exerted on the tool by the surgeon and moves to comply. Initial experiences with this mode in ROBODOC indicated that it was very popular with surgeons and offered means to augment human performance while maximizing the surgeon's natural hand-eye coordination within a surgical task. Subsequently, this mode was incorporated into the IBM/JHU LARS system [121], [122], and has been more recently applied to the JHU "Steady Hand" robot system shown in Fig. 8. In this system, separate force sensors detect the force exerted by the surgeon on the tool and by the tool on the tissue. The compliance loop is closed using a scaled combination of these forces. The result is a manipulation system with the precision and sensitivity of a machine, but with the manipulative transparency and immediacy of hand-held tools for tasks characterized by compliant or semirigid contacts with the environment [123]. The JHU group has begun evaluation of this system for a variety of microsurgical tasks in ophthalmology and otology and has also been exploring control extensions beyond the basic steady-hand paradigm [65], [124]–[126].

An interesting alternative approach to tremor reduction in microsurgery uses a purely hand-held instrument, with no robotic "arm" [127], [128]. In this case, inertial sensors detect tremor motions and fast, low-amplitude actuators cancel it inertially. The advantages of this approach are that it leaves the surgeon completely unencumbered and that it minimizes the changes required in the operating room setup. The drawbacks include: the robot cannot provide physical support for heavier instruments; instruments cannot be positioned and left stationary; and it is more difficult to provide active controlled motions for sensing or task assistance, beyond very small motions such as may be needed for microvessel puncture.

Although applications of master–slave and cooperative force-controlled robots have mostly emphasized direct extension of the surgeon's own motions, several groups are beginning to explore more sophisticated ways to use the robot's capabilities to assist the surgeon. Much of this work extends the "active constraint" idea used by Davies *et al.* in the knee surgery system discussed earlier to develop sensor-mediated "virtual fixtures" (e.g., [129]–[131]) that constrain the robot's motion or create haptic feedback directing the surgeon to move the surgical in-



(a)



(b)

Fig. 8. JHU "Steady Hand" microsurgery robot, showing (a) the use of the system to evaluate robotically assisted stapedotomies [124] and (b) a microendoscopic view of the puncture of 100 μm retinal blood vessels.

struments in a desired direction. There have also been a few cases (e.g., [65], [125], and [132]–[134]) in which more complex behavior has been modeled and implemented for prototype interactive surgical tasks.

B. Auxiliary Surgical Supports

The use of robotic systems to assist surgeons by performing routine tasks such as laparoscopic camera manipulation is becoming commonplace. Examples include [42], [49], [135], and [136]. Some of the manipulator design issues associated with such systems were discussed in Section II. For human–machine interfaces, these systems provided a joystick or foot pedal to permit the surgeon to control the motion of the endoscope. However, other interfaces have included voice, tracking of surgeon head movements, computer vision tracking of surgical instruments, indication of desired gaze points by manipulating a cursor on the computer screen, etc. Fig. 9(a) shows a typical installation of a voice-controlled commercial system (the AESOP™, developed by Computer Motion, Inc. (CMI) [42], [60]).

More recently, there has been interest in robotic systems for manipulating ultrasound probes [138]–[141] Fig. 9(b) shows a typical example [137], [142]. Most of this activity has targeted diagnostic procedures such as systematic examination of carotid arteries for occlusions. However, these systems have the potential to become as ubiquitous as the robotic endoscope holders discussed above. Our research group at JHU has begun to ex-

²Although master–slave systems often place the surgeon some distance from the patient, this is not essential. For example, Salcudean's microsurgery system [105] uses a robot to hold the master and slave devices in rough alignment to the patient in the surgical field.



(a)



(b)

Fig. 9. Two robots for manipulating imaging devices. (a) CMI AESOP endoscope holder [12]. (b) Experimental system for ultrasonography [137]. (Photos: CMI and S. Salcudean).

plore applications such as precise ultrasound-guided biopsies and other interventional procedures.

There has also been work in the use of flexible robotic devices for intraluminal applications such as colonoscopy and angioplasty. Examples include [46], [47], and [143]–[148]. Generally, these devices are snakelike, though there have been a few efforts (e.g., [47], [143], [146]) to develop autonomous crawlers. One interesting aspect of [47] is the use of small clamping devices to grasp the walls of the intestinal tract.

An innovative approach for creating an actively steered catheter with multiple DOFs driven by micro hydraulic actuators is pursued at Nagoya University, Nagoya, Japan. The catheter uses an ingenious new principle of actuating

multiple hydraulic cylinders through a single pressure line, in a miniaturized design involving special microfabrication methods [149].

C. Remote Surgery Systems

Although the primary impact of teleoperated robots in surgical applications over the next years will probably be in applications in which the surgeon remains close to the patient, there has also been considerable interest in remote telesurgery (e.g., [13], [34], [116], [141], [150], [151]). In addition to the design issues associated with local telesurgery, these systems must cope with the effects of communication delays [152] and possible interruptions on overall performance.

Initial experiments involved telementoring and control of laparoscopic instrumentation such as the AESOP robot in urological applications [153] and other specialties. Remote control of additional instrumentation such as the electrocautery [154], insufflators, camera controls [30], and simultaneous control of two robots have also been reported [155]. Several remote systems for ultrasound diagnostic using master–slave architecture have also been reported [141], [156], [157].

One of the more successful and complex recent remote telesurgical operation was “Operation Lindbergh” [13] using the Zeus robotic system for laparoscopic surgery (Computer Motion, Inc., Goleta, CA) performed in September 2001. The surgeon located in New York, NY, performed a laparoscopic gall bladder operation on a patient located in Strasbourg, France. The study incorporated a 10 Mb/s private virtual circuit based on an ATM OC-3 transatlantic link.

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

One very significant fact about medical robotics is the speed at which the field is expanding. As recently as five years ago, it would still have been possible, though difficult, for a survey paper such as this to cite and discuss essentially *every* research or clinical effort using a robotic device in interventional medicine. This is no longer really practical, as new work is reported at several major international conferences and in journals. Table I provides a *partial* summary of some of the systems that have been reported, including several that are in routine clinical use around the world. Although this table is incomplete, it nevertheless gives a reasonable indication of the breadth of current activity. If we draw an analogy to industrial robots, we have passed the “1965” stage, when there were just a few robots performing very simple tasks. We are perhaps around “1972,” with increasing research and much greater integration of sensors, real-time imaging, and software into what is being attempted. This is encouraging, but complacency is not called for. Very significant research, engineering, and societal barriers remain before medical robots have widespread impact on health care.

Some of the key technical barriers have already been discussed in this paper, but it is perhaps useful to summarize them as follows.

Imaging, modeling, and analysis: Advances are needed in techniques for building patient-specific anatomical models

from preoperative images and real-time sensor data, for incorporating biomechanical information into these models, and for using this information to help control the robot. Similarly, we need much better ways of modeling surgical procedures and of using this information both in pretreatment planning and real-time execution.

Interface technology: Broadly, surgical robots need to become more precise, dexterous, and sensitive, while also becoming much more compact and inexpensive. It will become more and more important to design systems that can incorporate a wide range of biomedical sensors and that can work with multiple imaging modalities. Robots are surgical tools, not surgeons, and better surgeon-machine interfaces are needed. An equally important need is more rigorous methods for evaluating the performance of human-machine systems in surgical environments.

Systems: As we stated in the introduction, surgical robots are not primarily discrete, stand-alone devices. They are elements of complete systems designed to work in an operating room. No one system will ever meet all needs, and the engineering overhead and certification cost of medical devices is very high. Consequently, the development of highly modular architectures that permit a high degree of reuse of certified components, with open interfaces between major subsystems, will be a major challenge, both technically and socially within the medical robotics community. Similarly, research is needed into better ways to characterize medical robot systems and to predict and optimize their performance.

Progress in these areas will most fruitfully be made within the context of systems targeted at 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 CIS system context.

Academic researchers, such as the authors 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.

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