Surgical and Interventional Robotics: Part III

Surgical Assistance Systems

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Part I of this tutorial described two broad paradigms of interventional assistance: surgical computer-aided design (CAD)/computer-aided manufacturing (CAM) and surgical assistance. Part II focused on the underlying concepts of surgical CAD/CAM, with a particular emphasis on percutaneous procedures. This final installment of our three-part tutorial series discusses surgical assistance. In this section, we introduce the basic concepts of a surgical workstation and briefly review several core robotic technologies used in surgical workstations.

The Surgical Assistance Concept

The Surgical Workstation

Broadly construed, most devices in the operating room (OR), from the simplest surgical tool to the most advanced imaging modality, provide assistance during an intervention. In particular, advances in imaging systems and computing technology have led to numerous innovations in methods for image acquisition and display during surgery [38]. This, in turn, has created entire new scientific and commercial opportunities in image guidance. However, despite the advantages conveyed by better imaging and visualization, most image-guided procedures still depend solely on the hand–eye coordination skills of a trained clinician to achieve a positive outcome.

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In this installment of our tutorial, we focus on systems that seek to enhance or extend the hands and eyes of the surgeon during the process of surgery. We define *surgical assistance systems* as systems that integrate robotics for manipulation with imaging for display to the surgeon. As a result, the general concept of a surgical workstation is a useful framework to guide our development. A surgical workstation contains robotic devices designed to aid or enhance the physical dexterity of the surgeon during the course of surgery. It employs real-time imaging devices to visualize the operative field during the course of surgery. Finally, the core of a surgical workstation is computing technology that mediates sensing and control and provides the basis for a wide variety of computer enhancements such as virtual fixtures ("Physical Assistance" section), information overlays ("Sensing and Information Assistance" section), and even recognition of surgical intent from task models [23] (Figure 1).

The most important element of any surgical system is the human interventional team. In particular, the clinician using a workstation provides the key element of decision making and judgment that no computational system, to date, possesses. Thus, in addition to the technical challenges of creating workstation capabilities, a designer must also consider the human–machine interface that allows the machine to operate cooperatively with the human operator. Thus, ergonomics, human factors, and integration into the surgical work flow are also essential elements of a successful workstation design.

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Medical Robots for Surgical Assistance

In contrast to manufacturing, where speed and accuracy are of paramount importance, robots employed in medicine must satisfy a variety of application-specific requirements. Interventions often rely on the surgeon's skills in hand–eye coordination, dexterity, and steadiness. Even the most gifted surgeons are subject to human limitations because of fatigue, tremor, and precision of motion. Furthermore, these skills may be vitiated by poor access to the surgical site. For example, minimally invasive laparoscopic surgery is often termed *chopstick surgery* because the intervention must be performed using long, thin laparoscopic instruments inserted through small incisions, which significantly reduces the dexterity of the instrument tip. Similarly, there is a growing interest in performing surgical tasks in situations where access to the surgical site is obtained via a flexible endoscope or even with mobile devices inside the patient's body [Figure 2(a)]. In these cases, the surgeon's ability to perform high-dexterity tasks with traditional manual cable actuation is severely limited, and robotic systems can help overcome these limitations.

There are several ways in which a robot can improve human manipulation. For example, the steady-hand robot developed at Johns Hopkins University (JHU) [Figure 2(b)] reduces hand tremor via a cooperative control paradigm. In cooperative control, the surgical instrument is mounted on the robot and moves in response to forces exerted on the instrument by the surgeon. The surgeon and the robot, thus, cooperatively manipulate the instrument. Steady-hand robot systems have been shown to reduce tremor by an order of magnitude from about 100 μm for a handheld instrument to about 10 μm for the steady-hand robot. Another approach is represented by the handheld micron robotic tool [40] [Figure 2(c)], which actively moves the instrument tip to cancel hand tremor. A robot can also improve human motion accuracy. One strategy is to use the robot to enforce virtual fixtures, which are described in the "Virtual Fixtures" section. Virtual fixtures have been implemented in clinical systems for knee surgery, such as Acrobot [20] [Figure 2(d)] and Mako Surgical Corporation's Haptic Guidance System, where the virtual fixture corresponds to the boundary of a knee prosthesis. In this system, the robot holds a cutting tool, and the surgeon can move the cutter, in a cooperative control mode,

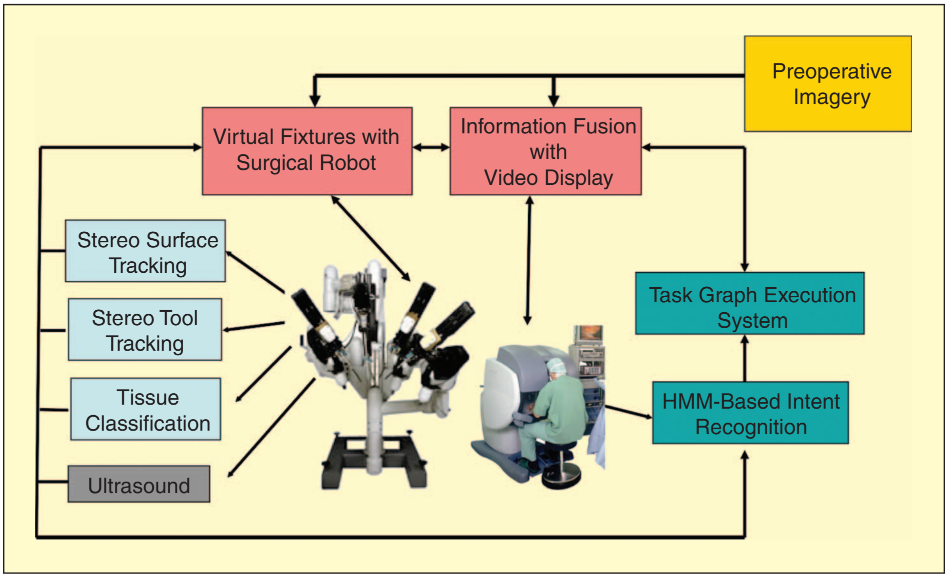


Figure 1. *The structure of a complete surgical assistant workstation including real-time sensor processing, physical and information augmentation using preoperative imagery, and a task-monitoring system.*

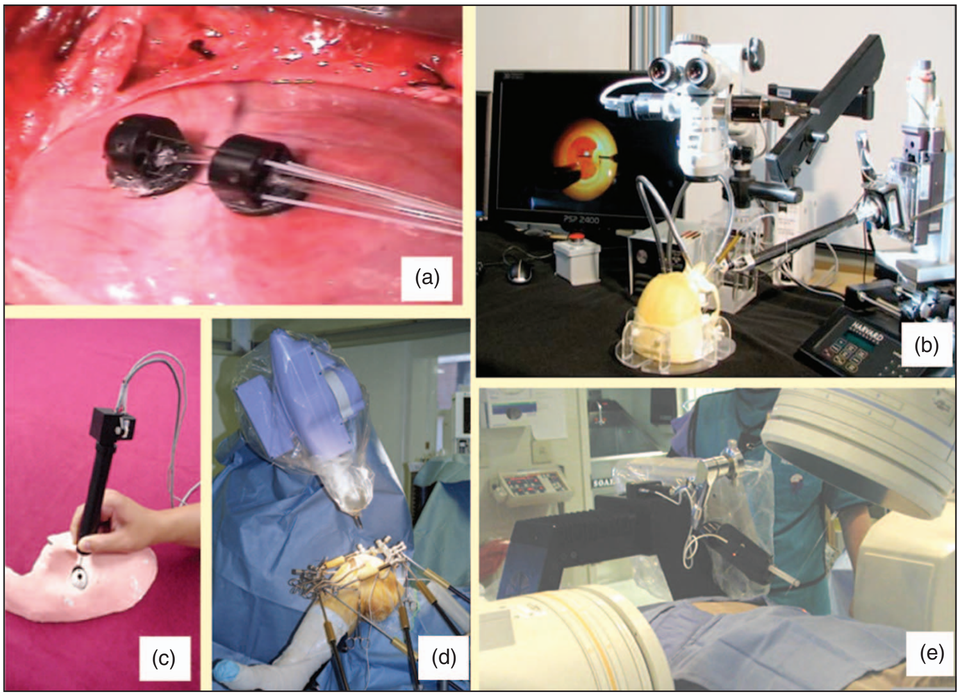


Figure 2. *Robots for surgical assistants. (a) The Heartlander [37]. (b) The JHU steady-hand robot for retinal surgery. (c) Carnegie Mellon University (CMU) micron. (d) Acrobot for knee surgery. (e) JHU remote center of motion (RCM) robot for nerve and facet blocks in clinical trial at Georgetown University.*

within the confines of the virtual fixture. The robot prevents motion beyond the boundaries of the virtual fixture.

A robot can allow the surgeon to bring his or her manipulation skills to areas of the body that are otherwise inaccessible. The da Vinci robot, for example, is a telesurgical system where the surgeon's actions at the master console are replicated by robotic instruments inside the patient [14]. Telesurgical robots can enable surgeons to operate on a patient while the patient is inside the bore of an imaging device, such as computed tomography (CT) scanners and magnetic resonance imaging (MRI) scanners, which might not otherwise be possible because of the limited bore size of these imaging devices [46]. Telesurgery can reduce the surgeon's exposure to the ionizing radiation used in imaging such as X-ray fluoroscopy and CT [8] [Figure 2(e)].

Many surgical procedures require more than two hands; thus, it is common for the surgeon to require assistance from other members of the OR team. This presents another opportunity for robotic assistance, especially when computer control can improve the efficiency or quality of assistance. Some of the earliest medical robots, such as Aesop [49] and LARS [47], were camera holders for minimally invasive procedures. In these systems, the surgeon used an alternate interface, such as a foot pedal or speech, to command the robot to reposition the camera. This has the potential to improve the efficiency of the procedure. Laparoscopes exhibit a pivot point at the insertion port; therefore, one must move the handle right to pan the laparoscope's field of view to the left. This potential source of confusion between a surgeon and a human assistant can be eliminated between a surgeon and a robotic surgical assistant. Another intriguing possibility occurs for tasks where the robot motion can be determined based on the surgeon's actions. For example, a surgeon can tie a knot with one hand if the other end of the suture is pulled by a robot. The knot can be centered by commanding the robot's motion in proportion to the surgeon's hand motion [22].

The design of robotic mechanisms for surgical assistance poses many challenges, including sterility, safety, actuation strength, and power transmission, providing high dexterity in confined spaces, compensating for patient and tissue motion, and offering compatibility with imaging devices. Design approaches tend to vary widely and depend on the constraints of differing environments. Rather than surveying the design space of surgical robot mechanisms in this tutorial, we focus on the role that robotic systems can use in sensing, patient models, and cooperative control to enhance the ability of surgeons to perform surgical tasks. Additional information about mechanical design options can be found in other medical robotics survey articles (e.g., [48]) and references therein.

Physical Assistance

A key element of human-in-the-loop robot-assisted surgical systems is the physical assistance provided by controlled robot behaviors. Examples include the following: 1) basic control methods that allow steady-hand operation or motion scaling between master and slave robots, 2) haptic feedback for reflection of environment properties, and 3) techniques for providing information-enhanced assistance, here termed *virtual fixtures*.

Control Methods

There are two major paradigms for surgical assistants: cooperative manipulation and teleoperation. The defining characteristic of each of these paradigms is the manner in which human input is mapped to the motions of surgical instruments.

Cooperative manipulation systems, in which the operator and the robot both interact directly with a surgical instrument, are typically nonbackdrivable and employ velocity-controlled actuators. The velocity of such admittance-type systems is typically controlled with a high-bandwidth servo controller to be proportional to the operator-applied force. The nonbackdrivability and natural stiffness of the robot are assumed to be sufficient to reject applied external forces from the operator and the environment not used by the controller. The point at which the human operator holds the robot is instrumented with a force sensor. These systems naturally assist the human operator by controlling the speed of the instrument to be smoother and more accurate than unassisted manual manipulation. For cooperative systems to be effective in assisting surgeons, they should be of the admittance type to allow successful force-to-motion scaling, e.g., [42]. Cooperative manipulation, however, inherently does not permit position scaling. Linear admittance-type device control is generally modeled by

$$V(s) = Y(s)F(s), \tag{1}$$

where F is the measured command force externally applied by the surgeon, Y is the controlled device admittance, and V is the robot's velocity. In many such models, the nonbackdrivable robot is assumed to reject all externally applied forces except as specified by the control law (1). The selection of Y determines the responsiveness of the system to human inputs, allowing significant scaling between human-applied force and robot velocity, which improves accuracy. Smoothness can be enhanced by thresholding and filtering the measured command force and by reducing unintentional motions and tremor. These properties make cooperative systems effective, especially in microsurgical tasks, in which surgeons operate near the limits of human performance. In addition, the direct interaction between the surgeon and the robotic surgical instrument may be more natural than the remote control afforded by a teleoperation system. The admittance value is limited by stability considerations. Admittance control can also be modified to provide haptic feedback and virtual fixtures, which will be described in the following sections.

In teleoperation systems, the operator manipulates a master input device and a slave, or patient-side robot follows the input. Teleoperators can include impedance or admittance masters and slaves in various combinations [16]. However, the impedance type is the most popular because of the lower costs (there are no force sensors) and high responsiveness to human inputs, providing a more natural operating mode for minimally invasive surgery than cooperative systems. Robots of the impedance type are typically backdrivable (with low inertia and friction) and employ force (or torque)-controlled actuators. A linear impedance-type device model that can describe a master or slave is

$$F(s) - F_a(s) = Z(s)V(s), \tag{2}$$

where F and F_a are the externally applied force (from the human or the environment) and the actuator force, respectively; V is the velocity of the device; and Z is the natural impedance of the device. F_a on the master and slave are then determined by their own dynamics and control laws, which define the mapping between them. Typically, the slave robot will follow the master with a variant of the basic proportional-derivative control:

$$F_{a,\text{slave}}(s) = Z_c(s)(aV_{\text{master}}(s) - V_{\text{slave}}(s)), \tag{3}$$

where $F_{a,\text{slave}}$ is the control force of the slave actuators, Z_c is the controller impedance defined in software, a is a position scaling gain, and V_{master} and V_{slave} are the velocities of the master and slave, respectively. The master does not need to have actuators unless haptic feedback or physical guidance is desired. The gains $Z_c(s)$ and a are limited by stability considerations, and the performance of the system is limited by the inherent dynamics of the robots $Z(s)$. An important advantage of teleoperation is the position scaling gain, which allows master motions to be mapped to smaller slave motions, thereby improving accuracy. This scaling can be nonlinear, such as found in mouse ballistics used for human–computer interaction. In addition, dexterous master motions can be mapped to motions inside the patient's body more easily in a teleoperator than a cooperative manipulator because practical mechanisms for dexterous input to cooperative systems are difficult to design. Hence, there is a lack of ubiquitous handheld minimally invasive surgical instruments with dexterous tip control.

Haptic Feedback

This section examines haptic feedback, the goal of which is to provide force and/or tactile feedback to the human operator to achieve a sense of transparency, in which the surgeon does not feel as if he or she is operating a remote mechanism but rather that his or her own hands are contacting the patient. This requires haptic sensors on the slave to acquire haptic information and haptic displays to convey the information to the surgeon. Haptic information can be kinesthetic (related to force and position in the joints and muscles) and/or cutaneous (tactile, related to the skin). Providing haptic feedback to the surgeon without sacrificing the size and dexterity afforded by surgical assistant systems is a major challenge. Moreover, the robot components, particularly disposable instruments, should be inexpensive and robust. Haptic feedback can be accomplished in both cooperative manipulators and teleoperators. A diagram of information flow for haptic feedback in teleoperators is shown in Figure 3.

In cooperative manipulation with admittance-type robots, haptic feedback is most naturally achieved through position-based force scaling [42]. An additional force sensor is used to measure the interaction between the surgical instrument and the environment, such as retina of the eye. The control law of (1) is modified so that the velocity of the robot depends on not only the human applied force but also the environment force. The desired environment force is scaled from the applied human force, and then the velocity of the robot is controlled to minimize the error between the measured and desired tip forces. A limitation of this technique is the need for appropriate force sensors; it is especially difficult to create robust, biocompatible, sterilizable, and small force sensors for microsurgical applications [3]. Using force feedback from such sensors, force amplification scale factors of over 60 have been achieved; this allows human operators to clearly feel small forces (e.g., 5 mN) that are otherwise imperceptible.

Teleoperator force feedback can be achieved without the use of force sensors. A controller similar to (3) can be applied to the master actuators, providing haptic feedback to the human operator through a technique known as position-position or position-exchange teleoperation [15], [26]. This is a force estimation technique in which the difference between the desired and actual position of the slave robot (where the desired position is that of the master manipulator) is an indication of forces being applied to the environment. However, the fidelity of such systems is limited because there are dynamic forces present in most robots that are difficult to model precisely and often mask the relatively minute forces of interacting with the patient [29]. A more promising technique for accurate haptic feedback is direct force sensing on the surgical tool, although the surgical environment again places severe constraints on size, geometry, cost, biocompatibility, and sterilizability. Although it is difficult to add force sensors to existing robotic instruments that were not designed with force sensing in mind,

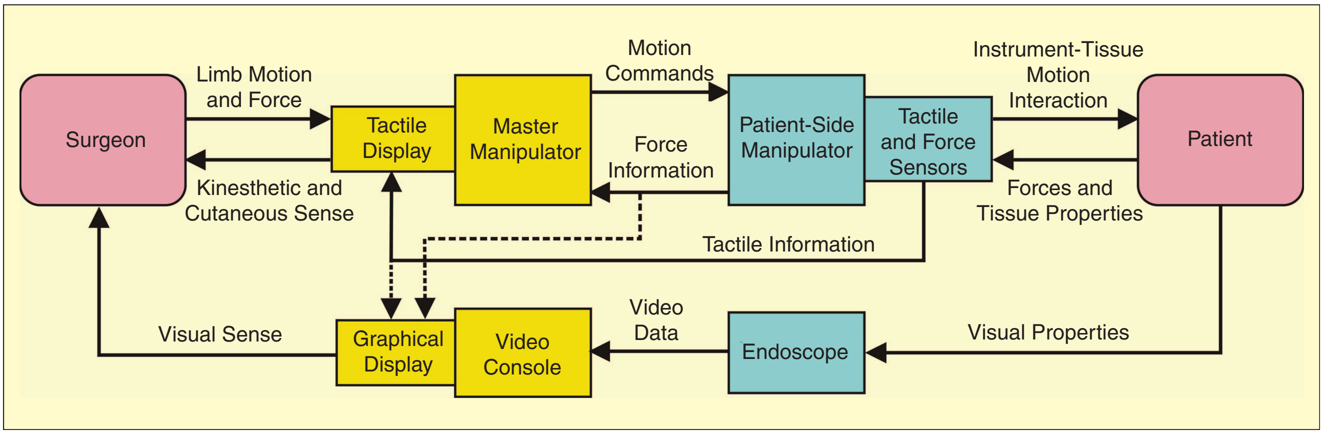


Figure 3. *The main components of a teleoperated robot for minimally invasive surgery with multimodal haptic feedback. Both force and tactile feedback are included in the model, and graphical display (one method of sensory substitution) is shown as a possible alternative to direct haptic feedback.*

some researchers have had success on this front by creating specialized grippers that can attach to the jaws of existing instruments [54]. Another approach is to integrate force sensors into dexterous instruments [24], [58]. An example of such a system is shown in Figure 4. Some novel robots can also use mechanics modeling and motion tracking to estimate forces [57]. Many studies have examined the role of haptic feedback in improving surgical performance, although most do so in limited degrees of freedom (DoF), e.g., [50]. Recently reported studies suggest that the role of haptic feedback may be different for novice and experienced robot-assisted surgeons [41], [35], [54].

Tactile feedback may be useful in surgical teleoperators, especially for exploratory tasks such as palpation, in which distributed pressure or deformation information can be used to identify hard lumps in surrounding soft tissue. Tactile sensors can detect local mechanical properties of tissue such as compliance, viscosity, and surface texture (all indications of the health of the tissue) or obtain information for direct feedback to a human operator, such as pressure distribution or deformation over a contact area [11]. It remains difficult to design both tactile sensors and displays that are compatible with the surgical environment. A few groups have integrated tactile feedback [18] and force feedback [12] on surgical teleoperators.

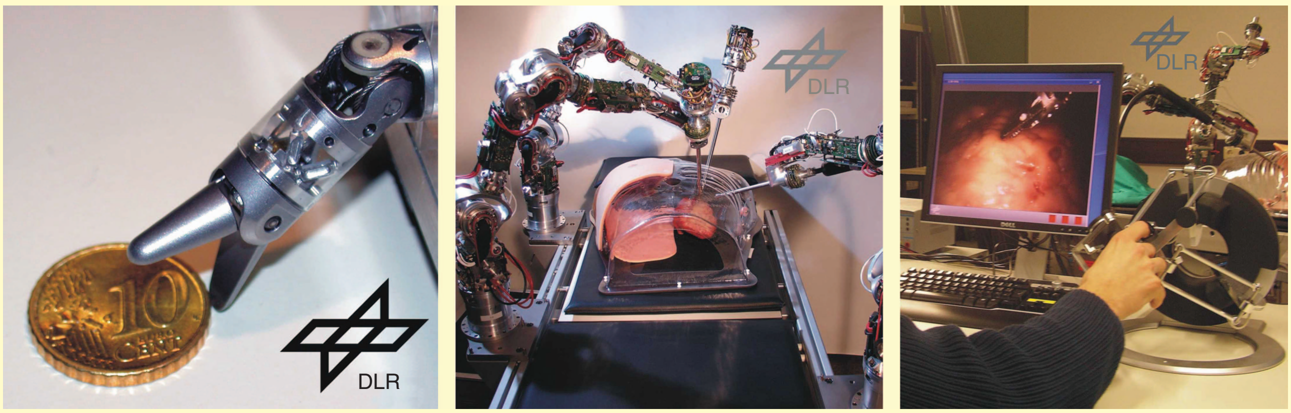
Haptic feedback can also be achieved through enhanced visualization (sensory substitution), as will be described in the "Sensing and Information Assistance" section. Although such sensory substitution may be more practical to implement, better performance should be achieved with direct force feedback; sensory substitution systems are unnatural and, thus, have a longer learning curve. Direct force feedback provides physical constraints that can help a surgeon make the correct motions simply because of dynamic force balance.

Virtual Fixtures

There is an alternative to force feedback from the environment that provides useful physical constraints: so-called virtual fixtures. These are software-generated force and position signals applied to human operators to improve the safety, accuracy, and speed of robot-assisted manipulation tasks [1]. We consider two categories of virtual fixtures: guidance virtual fixtures (GVFs), which assist the user in moving the manipulator along the desired paths or surfaces in the workspace, and forbidden-region virtual fixtures, which prevent the manipulator from entering into the forbidden regions of the workspace. Virtual fixtures can be applied to both cooperative manipulation and telemanipulation systems. Virtual fixtures have been shown to be effective in both artificial microsurgical tasks [23] and minimally invasive surgical tasks [36].

GVFs assist the user in moving the robot manipulator along the desired paths or surfaces in the workspace. GVFs can be of either the impedance or admittance type. Admittance-type GVFs generally change the value of Y in (1) in different directions. By eliminating the commanded motion due to the applied force in the nonpreferred directions, a passive guidance is created along the preferred direction. Varying the response to the nonpreferred force component creates different levels of guidance. Hard guidance refers to GVFs where none or almost none of the nonpreferred force component is permitted, leaving the user with no or little freedom to deviate from the preferred path. Soft guidance GVFs give the user the freedom to move away from the path by allowing some motion in the nonpreferred directions. Experiments in mock microsurgical environments with an admittance-controlled cooperative robot have demonstrated that operators will perform best in uncertain environments with a medium-level GVF because the VF planner is not perfect. Impedance-type GVFs act as potential fields, actively influencing the movement of the robotic manipulator.

Forbidden region VFs (FRVFs) are actually a subclass of GVFs for admittance-controlled, cooperative robots. The FRVFs are trivial to implement, by simply eliminating any commanded motion into the forbidden region. Inherently, the forbidden region is the nonpreferred direction defined in the GVFs. In telemanipulation, we are principally concerned with the penetration of the slave manipulator into the forbidden region. Penetration of the master device into the corresponding region



(a) (b) (c)

Figure 4. *A robotic surgery system for two-hand manipulation with integrated force feedback and 3-D vision, designed by researchers at the German Aerospace Centre (DLR), Germany. The system consists of a specially designed dexterous force-sensing instrument, robotic arms and teleoperation controller, and haptic device commercially available from Force Dimension, Inc. (Lausanne, Switzerland) as the master manipulator. Original figures used with permission from B. Kuebler, DLR.*

of its workspace is inconsequential. Impedance-type FRVFs can be implemented on telemanipulators by overlaying a penalty-based virtual wall on the existing telemanipulation controller. It is possible to implement the virtual wall on either the master or the slave side (or both simultaneously). Both have the effect of reducing movement of the slave into the forbidden region. However, each presents a different haptic experience for the user, depending on the underlying telemanipulation controller, and each provides different levels of disturbance rejection.

In addition to low-level virtual fixture controller design, it is useful to have a mathematical framework for describing and implementing virtual fixtures. Kapoor and Taylor [22] formulated the motion control of the robot as a quadratic optimization problem, in which constraints and optimization criteria are combined from multiple sources. These include the following: 1) joint limits and other kinematic constraints associated with the robot; 2) surgeon commands from a master hand controller, hands-on force sensor, or other input device; 3) real vision or other sensor data; 4) descriptions of desired behavior built up from simple primitives; and 5) registered anatomic models of the patient.

Sensing and Information Assistance

Robotic devices provide a means of extending and enhancing the capabilities of human hands. However, these hands must still know where to go and what to do when they get there. In traditional (nonrobotic) surgery, the primary source of feedback is human vision. For open surgery, visualization is direct, whereas minimally invasive or percutaneous interventions usually rely on indirect visualization using an endoscopic device or other real-time imaging such as ultrasound. Recent designs for magnetic resonance (MR-) and X-ray-compatible robots have opened the possibility of performing interventions using those modalities for visualization as well.

Once an imaging sensor and visualization system are chosen, there is still a question as to what information can be usefully computed and displayed. Information can be used to enhance the physical capabilities of the system, e.g., by setting up the geometry of virtual fixtures relative to tissue surfaces or delicate internal structures, or the information can be used to provide enhancements to the surgical display, e.g., by overlaying preoperative images registered to the anatomy. This section describes some of the core issues in this area and reviews related work.

Sensing Modalities

It is useful to divide our discussion of sensing modalities into real-time imaging, which can provide a continuous visualization of an area of interest, and non-real-time methods that are typically used for preoperative diagnosis and planning. A discussion of the latter can be found in Part II of this tutorial and in references such as [38] and will not be covered here. The most common examples of real-time sensors used during an intervention are video endoscopy and ultrasound, but real-time sensing can also include optical coherence tomography (OCT), spectroscopy, nuclear probes, and sensors that measure physiological properties such as temperature, oxygenation, and so forth. X-ray fluoroscopy and MR can also be used sometimes but require specialized imaging-compatible designs and are far less common today. Here, we will focus on endoscopy and ultrasound.

Video Endoscopy

Most video data acquired in the OR make use of a monocular endoscopic device. Endoscopes come in a wide variety of diameters and lengths. There are three predominant construction methods: 1) solid rod, 2) fiber-based, and 3) remote sensor. Rigid endoscopes may use any of these technologies; flexible scopes will be either fiber based or use a remote sensor. Fiber-based endoscopes are also common when a very small diameter is necessary. However, the fibers introduce a pixelization artifact that can degrade image quality and be challenging to common image-processing methods.

Endoscopic images can be processed to detect important visual cues, e.g., lesions or polyps, or they can be processed to extract geometric information. There is a rapidly growing literature on the former, whereas less progress has been made toward the latter. Some imagery, such as the retina, contains well-defined image features and is thus amenable to traditional feature matching techniques [44]. Body cavities, such as the sinuses, esophagus, bronchial tubes, and abdomen, are considerably more challenging. Major impediments include 1) a lack of surface texture, 2) a highly focused, moving illumination source, 3) significant surface specularities, and 4) nonrigid motion of observed surfaces.

Despite these challenges, various groups have applied structure and motion reconstruction techniques to monocular endoscopy. In [55], robust matching techniques were employed to reconstruct feature point locations from a pair of images. These points are then used to register to CT information and initiate a two-dimensional (2-D)/three-dimensional (3-D) motion tracking algorithm, e.g., [7]. In [33], shape from shading techniques were applied. In [47], the LARS system was used as an endoscope holder, and side-to-side motion was used to create a stereo baseline. A variety of groups have studied the visual tracking problem in endoscopic video, including tool tracking [53] and tracking of moving surface targets [45].

Stereo endoscopic devices have been available for over a decade but remain uncommon in the OR, in part, because of the difficulty of creating a stereoscopic display system that is both ergonomically acceptable and integrates well into the OR. Stereo visualization is widely available for microsurgical procedures, including many retinal and neurosurgical procedures, because they are usually performed with an optical stereo microscope. Also, laparoscopic surgeries performed with the da Vinci surgical system employ a stereo endoscope coupled to a high-quality stereo display system [14]. Two recent developments in the area of stereo imaging are a novel in-body robotic stereo camera system [19] and a new design for high-resolution stereo imagery using a remote sensor and a lenticular lens [6].

Although computational stereo is a well-studied problem, processing stereo video sequences from within the body poses challenges because of the lack of visual texture, extremes of lighting, and highly specular surfaces. Early work in this area [31] employed block matching, but with limited results. Recent work has made use of local surface smoothness constraints through local linearity [45] or dynamic programming stereo [51].

Ultrasound

Ultrasound provides a real-time view into tissue in a safe and cost-effective manner. However, the structure of ultrasound images is complicated by the fact that each image contains only a narrow 2-D slice of tissue, and the images contain a large amount of noise, known as ultrasound speckle. 3-D ultrasound systems, which produce a 3-D image, have been commercially available for over a decade. Their use is becoming more common, but processing 3-D ultrasound is challenging because of the high data rate of the images. It is also difficult to visualize 3-D ultrasound volumes. So-called open ultrasound, where it is possible to program the beam and to directly acquire the ultrasound RF signal, has also recently become available (Ultrasonix Inc., Richmond, BC, Canada).

The speckle phenomenon is not noise; it is, in fact, a fixed pattern arising from the interference of reflections from within the ensonified tissue. The speckle pattern is stable over large motions within the plane of the transducer and small out-of-plane motions of the transducer. Under certain conditions, the speckle pattern also decorrelates at a fixed rate with out-of-plane motion. As a result, speckle can be used for motion detection, motion tracking, and control [25]. Another use of motion tracking using speckle has been to compute tissue stiffness during compression [34]. Tracking in ultrasound has been performed for tools [32] and vascular structures [13].

Ultrasound-guided interventions are limited by the planar field of view of the interventional ultrasound's 2-D image. Robotic assistance to hold the ultrasound probe and to guide percutaneous interventions is described in [4]. Other groups have developed robot assistance for performing ultrasound exams [59]. More recently, there has been work to integrate ultrasound probes directly into telesurgical robots such as the daVinci system [27].

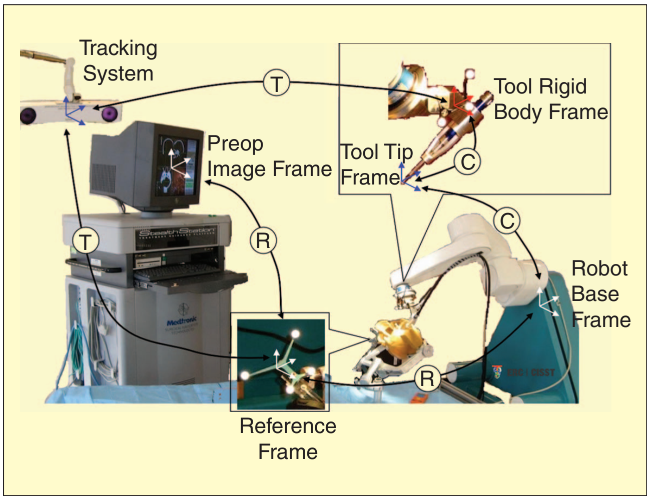


Figure 5. *Coordinate transformations for a sample image-guided robot system: (T) represents frames that are tracked; (C) represents kinematic calibrations; and (R) represents registration procedures.*

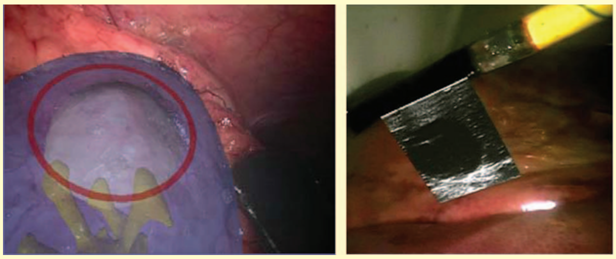


Figure 6. *(a) Image overlay through registration of stereo video to CT [51]. (b) Image overlay of ultrasound data through registration by video tracking of the probe [27].*

Tracking and Registration

Registration of coordinate frames is a fundamental enabler for any sensing and visualization capabilities. In Part I of this tutorial, a brief introduction to registration techniques was provided. The primary relationships of interest in a surgical workstation include the following: 1) the relationship between real-time sensing devices and the robot; 2) the relationship between the robot and the patient; 3) possibly the relationship between the patient and preoperative images of the patient; and 4) possibly the relationship between the observer and other elements of the system (Figure 5).

If the robot is kinematically linked to the sensing systems, as is the case in the da Vinci robot, then the relationship between the sensors and the actuators may be provided by the robot kinematics. However, surgical robots are often not rigid enough to provide reliable kinematics. For example, although the da Vinci robot provides exquisitely precise relative motion control, it is known to have relatively poor absolute positioning accuracy.

Many systems establish kinematic relationships through an external position measurement system. The Optotrak system (Northern Digital, Ontario, Canada) provides extremely high-accuracy (0.1 mm) 3-D optical tracking precision. The Polaris, a smaller version, has lower accuracy, but its compact size makes it easier to integrate into the OR. Optical methods suffer from the need to have line of sight at all times, and the targets for accurate 6 DoF pose estimates are large. A popular alternative is to use an electromagnetic (EM) field tracker such as the flock of birds (Acension Technology Corp., Burlington, VT) or the Antares system (Northern Digital, Ontario, Canada), although these systems suffer from field distortions because of metal and other electronics in the workspace. Ultrasonics and inertial sensors are also used, although they are less common.

A variety of groups are developing methods for direct registration through the sensing devices (Figure 6). Direct registration of video to preoperative volumes by geometric reconstruction has been described in [31], [51] for stereo video and in [7], [55] for monocular endoscopy. To perform video-volume registration in this manner, the volume of interest must be accurately segmented into visible surfaces that provide enough information for a unique registration. Typically, the segmentation problem is not hard as air-tissue boundaries are clearly defined in MR or CT. However, the visible field in the endoscope is limited and often does not define a unique registration, particularly in tubular structures such as the sinuses or the bronchial tubes. Other groups have addressed the registration problem by direct inference from intensity information that appears in endoscopic images using shape from shading ideas [5] or synthetic rendering techniques [30], [17].

Recently, there has also been interest in registering ultrasound to preoperative imagery [56], [28]. There are two broad approaches to this problem: 1) registration through extraction of common features and 2) registration by image simulation. To some degree, both approaches are organ and application specific as the type of features that are common to ultrasound and the complementary modality can vary widely. Mutual information-based registration has received a great deal of attention for this reason [39].

Information Presentation

Effective information presentation during an intervention is a significant challenge for surgical assistance systems. If the intervention is open, the surgeon will be forced to look away from the field to see any type of display. If the intervention is performed under video or ultrasound guidance, adding additional insets or overlays is convenient, but it may be distracting and might obscure other important information. Stereoscopic visualization is particularly challenging. As noted earlier, the da Vinci system solves this problem by providing a stereoscopic display integrated with the robot master manipulators. However, stereo video for more traditional MIS systems has been limited by the display devices available. Current head-mounted or see-through displays are often ergonomically unsuited for the OR and do not provide sufficient resolution. Flat panel displays are rapidly improving, but they still tend to lead to viewer fatigue and have a limited area where good 3-D perception is possible.

There is a long history of developing medical display systems that attempt to perform some type of augmented reality. One of the earliest examples of image overlay appears in [2], where a video see-through head-mounted display (HMD) is used to visualize ultrasound data on a patient. A more recent version of this idea implemented on the da Vinci system appears in [27]. Although this system uses a robot to hold both the ultrasound and endoscope, video tracking of the ultrasound head was used to localize the ultrasound system (Figure 6). An example of volume image overlay using an optical tracking system was the microscope-assisted guided interventions (MAGI) system [10] for image guidance during neurosurgery. One of the major challenges in augmented reality systems is to maintain accurate registration and to provide a clear and natural impression of depth in the display. We refer to [38] for an extensive review of approaches to these problems. A variety of nongraphical sensory substitution displays have been reported. For example, sound can be used to convey most linear quantities (e.g., force or oxygenation levels). Conversely, nonvisual quantities can be displayed visually, one example being a graphical display of tooltip force [43].

Future Directions

The last decade has seen surgery with robots move from a laboratory concept to a commercial reality. As a result, there is an ever-growing acceptance that surgical systems based on robots will play a large role in future health care. This will be driven in large part by the trend toward less invasive procedures to enhance patient care and to reduce the overall cost of medical interventions.

As surgical workstations based on robotics become more commonplace, there will be a need for standards for design and development. Mirroring the recent trend toward software toolkits for imaging, there are now nascent efforts to standardize software for surgical workstations [21], [9], [52].

A number of new trends and technologies are likely to play a role in driving future developments. One popular new area is natural orifice transluminal endoscopic surgery (NOTES). NOTES poses a host of new challenges for small-scale, high-dexterity mechanisms and will require new methods for visualization and navigation. Similarly, the recent development and deployment of capsule endoscopic systems has led a variety of researchers to consider how to incorporate robotic mobility and manipulation into such packages.

In summary, the future for robotics in surgery is extremely promising. Future decades can be expected to bring a host of new innovations and applications to improve patient care.

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Keywords

Surgical assistants, medical robotics, image-guided surgery, surgical CAD-CAM, robot safety.

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