Chapter 1

Introduction

Robotics technology has recently found extensive use in surgical and therapeutic procedures. The purpose of this chapter is to give an overview of the robotic tools which may be used in various types of surgery or therapy. The chapter starts with a general classification of interventions that can take advantage of the benefits offered by robots. Next, the literature is surveyed regarding robotic tools and manipulators for applications in surgery and therapy. Both the current commercial components and those components still under development are reported. Finally, to lay the groundwork for studying haptic interaction in robot-assisted surgery and therapy, some of the available haptic devices and previous research on haptic surgical teleoperation are surveyed.

1.1 Robot-Assisted Intervention: Benefits and Applications

Using robots in medical interventions can offer benefits including high accuracy, fine manipulation capability, good repeatability, high reliability, lack of fatigue, etc. The use of robots can also benefit the patients through reducing morbidity, traumas, errors and operation times.

Most of the interventions that can take advantage of the above benefits are either accurate procedures or interventions involving minimal access to the body organ that needs attention. Accurate procedures can either be on a scale uncomfortable for an unaided hand (e.g., eye surgery or microsurgery [63]) or can require high geometric accuracy (e.g., orthopedic surgery [66]). Another example of accurate procedures requiring “super-human” precision is neurosurgery where tissue damage must strictly be avoided [81]. Minimal access procedures are procedures performed through incisions made into the patient's body (e.g., cardiac surgery [78] or urologic surgery [128, 50]), interventions performed through natural orifices in the human body (e.g., through the gastrointestinal tract [111]), intravascular interventions (e.g., intravascular neurosurgery [98]), etc. While minimally invasive surgery makes procedures less traumatic, the precision, dexterity and reliability of surgical maneuvers can be considerably enhanced by the use of robots.

1.2 Robotics Technology for Surgery and Therapy

Devices and systems for surgery and therapy can either be directly used by a surgeon to perform an intervention (augmenting devices) or can perform secondary functions to support the surgeon (supporting devices) [135]. Each of these types can be classified into different groups, as discussed next.

1.2.1 *Augmenting devices and systems*

As the name implies, an augmenting device extends the surgeon's ability in performing an operation. Depending on their modes of interaction with the surgeon, robotic devices or systems can be categorized into the following groups:

1.2.1.1 *Hand-held tools*

One advantage of using hand-held tools is that they do not constrain the surgeon and involve minimal changes to the operating room. The down side is that with purely hand-held instruments, a robot cannot be used to physically support heavier instruments. Also without any robotic arms, instruments cannot be locked in position and precisely controlled maneuvers (e.g. as required during microsurgery) are not possible [135]. The hand-held devices are mostly sensorized and can be divided into several categories as follows depending on their functionalities:

Master-slave combined instruments Unlike master-slave *telemanipulators*, a master-slave combined instrument comprises of a master interface and a slave tool that are combined through the instrument body and enable the surgeon to operate the instrument near the patient together with other conventional surgical tools. Master-slave combined instruments can be used to enhance the surgeon's situational awareness and/or capabilities during surgery. A master-slave combined instrument for suturing and ligaturing tasks during general surgery is discussed in [90]. The surgeon is responsible for large and quick motions of the instrument while the master handle embedded in this instrument directs the fine motion of the tip.

The idea of master-slave combined teleoperation can also be applied to enhance manipulation of tissue by enabling the surgeon to better sense the instrument's interaction with tissue. The tool described in [25] has a steerable tip with sensors for detecting the tip's interaction with the tissue. This device can be used as a hand-held tool for traditional arthroscopy or as part of a system for computer-assisted arthroscopy. The device has a semi-automatic collision avoidance feature for preventing contact between the tip and some pre-selected environments.

Instruments for reducing hand tremors Hand tremors can be critical in delicate procedures such as ophthalmological and neurological surgery especially when the surgeon becomes fatigued. A totally hand-held instrument for tremor reduction in microsurgery is discussed in [4]. In this device, hand motions are first detected by sensors. Next, a frequency-domain algorithm is used to identify the tremors from the desired motions of the hand. Then, the tremors are compensated for by piezoelectric actuators embedded in the manipulator system of the hand-held device.

Instruments for increased dexterity and navigation capability During intravascular interventions and interventions through natural orifices, long and slender catheters are used for diagnosis purposes or treating abnormalities. In intravascular neurosurgery, for example, a micro-catheter is advanced through vessels toward the brain while the surgeon monitors the location of the catheter using an X-ray display. When the tip of the micro-catheter reaches the targeted site, various substances or drugs can be delivered or a narrowed portion of the blood vessel can be opened up by inflating a micro-balloon attached to the tip [98]. However, due to the lack of dexterity of present micro-catheters, guiding them through complex vessels and branches is a difficult task for the surgeon.

To develop highly dexterous intravascular catheters, continuous flexible stems that can be bent using smart actuators may be used. Fukuda et al. [37] discuss a shape memory alloy (SMA) based micro-catheter with two degrees of freedom. Haga et al. [47] discuss an active micro-catheter actuated by distributed SMA coils and equipped with a miniature ultrasonic transducer to perform intraureteral ultrasonography of kidney. Electrostrictive polymer actuators are also proving to be another possible alternative for controlled bending of catheters [118, 75]. Narumiya proposes the integration of sensors at the tip of a micro-catheter to inform the surgeon about the interactions occurring between the catheter and the blood vessels for optimizing the micro-catheter's travel path with least resistance (i.e. least trauma to the patient) [97].

Instruments for measurement purposes Hand-held tools can be sensorized and used for measuring the mechanical properties of tissues. The experimental data collected from the sensors can help to find tissue models for surgical simulators both in terms of deformations and force reflections. A sensor-equipped grasper for in-vivo detection of tissue force-deformation properties is discussed in [12]. Similarly, indentors or tissue stretchers have been developed for this purpose [108].

Sensorized hand-held devices can also be used for defining and assessing desirable surgical performance by measuring interactions occurring between the surgeon and a tool [114], or between a tool and tissue [95]. The data obtained from the sensors can be used for objective surgical skills evaluation [113], and for surgical robot design.

1.2.1.2 *Cooperatively-controlled tools*

In cooperative manipulation, the surgeon and the robot both hold the surgical device – the surgeon provides control and the robot provides precision, sensitivity and guidance. Such devices act as guidance systems with which the surgeon's motions are constrained. Cooperatively-controlled devices can be active (force controlled) or passive mechanisms as discussed next.

Force controlled devices Force-controlled cooperatively-controlled robots try to minimize the forces exerted on the robot's end-effector through complying with the surgeon's hand movements. For example, in the Steady-Hand robot [134], force sensors measure the force exerted by the surgeon on the tool and by the tool on the tissue. Using these measurements, the Steady-Hand slows the surgeon's motion and mechanically filters tremor. This system is being evaluated for microsurgical tasks in ophthalmology and otology [116, 76].

Another example of force-controlled cooperatively-controlled robots is the ROBODOC system [137] for joint replacement surgery. When the patient's bones are ready to receive the implant, the patient's bones are fixated to the robot's base. Since the robot is force controlled, the surgeon's hand can guide it to an initial position. After this cooperative manipulation phase, the robot cuts the desired shape according to the pre-operative plans while monitoring cutting forces, bone motion, etc. The cooperative mode of operation seems to be popular with surgeons because they become more involved and remain more in control during the procedure. The ROBODOC system has been used during primary and revision total hip replacement surgery [13], and knee surgery [149].

The cooperative control mode has been also incorporated into the LARS system [136], the Neurobot system [125], and the ACROBOT system [67]. While ROBODOC was cooperatively controlled during the initial positioning only, some of the other systems have been used for cooperative control during the intervention itself.

Passive devices A passive guidance mechanism that is held cooperatively by the robot and the surgeon and constrains the possible actions of the surgeon to what is authorized in the planning is described in [119].

1.2.1.3 *Teleoperated tools*

In Teleoperated (or master-slave) surgery, the movements of a surgical robot (slave) are controlled via a surgeon's console (master). Master-slave robotic operations can solve many of the problems encountered in conventional surgery in terms of ergonomics, dexterity, fine manipulation capability, and haptic feedback capability for the surgeon.

The most prominent commercial surgical robotic systems are the da Vinci and the Zeus systems [8]. The latter is no longer available. In these dual-handed systems, two slave robots manipulate the surgical instruments and another slave robot controls the camera (see Figure 1.1). In the da Vinci, a fourth arm is also available. With these systems, the surgeon becomes less fatigued sitting at a comfortable and ergonomic console. The end-effector of the da Vinci robot includes a wrist that adds three rotations and one tool tip actuation (i.e. pitch, yaw, roll, and gripping at the wrist) to the degrees of freedom. The Zeus wrist adds one rotation. Both the da Vinci and the Zeus systems allow precise movements through scaling the hand motions (up to a factor of 5:1 for the da Vinci and 10:1 for the Zeus), and filter out hand tremors. These systems eliminate the motion reversal experienced with conventional endoscopic tools (chop-stick effect), yet do not presently provide feedback of tactile/force (haptic) sensations to the surgeon.

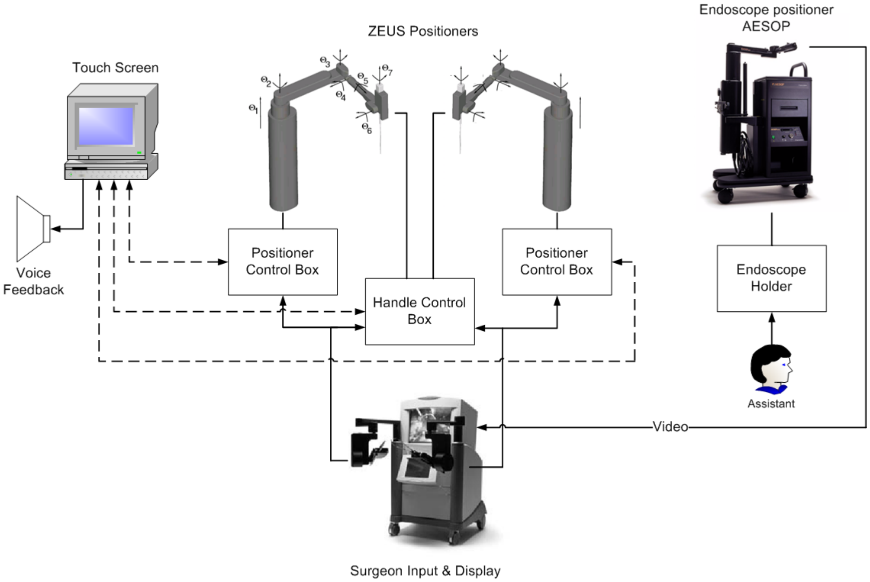


Fig. 1.1 A block diagram of the Zeus system from Intuitive Surgical, Inc.

Sensorized tools for incorporating haptic interaction A miniature tactile sensor array has been mounted at the tip of a laparoscopic tool [45]. This sensor consists of an array of capacitive sensor cells whose capacitance will changes in response to pressure, thus detecting any contact with the environment. A similar example is a tactile sensor array mounted on the jaw of a grasping tool [60]. In this example, signals from the sensor are transmitted to a tactile display so that surgeons can sense pressure distribution on the instruments for localization of arteries and tumors.

An actuated and sensor-equipped grasper capable of grasping force control and position sensing is reported in [115]. This tool is used with an actuated and sensor-equipped finger loop interface capable of providing force feedback to the surgeon. A laparoscopic grasper that can measure interactions with tissues in three degrees of freedom is reported in [142].

Tools for increased dexterity in teleoperation Articulation can be used to provide rotational movement at the distal end of a robotic end-effector using one joint. Compared to multi-joint articulation, the advantages of single-joint design include relative simplicity and low space requirements for movement inside the body. The disadvantages are that the joint does not leave much room for other linkages to pass through and has a very sharp bending angle [33].

An articulated robotic end-effector (together with a haptic-enabled user interface) for laparoscopic surgery is reported in [20]. The dexterous manipulator allows complex surgical operations to be performed.

1.2.1.4 *Autonomous tools*

Autonomous instruments A robotic system that can perform certain tasks autonomously can reduce the strain on the surgeon and shorten the operation time. A robotic end-effector for autonomous suturing and knot tying is discussed in [69].

Autonomous systems Surgeons are more interested in assist tools with a degree of intelligence and reaction capability than in full-fledged systems that automate the surgeons' role by using imaging and robotics technology. The Minerva system for neurosurgery is an example of the technological opportunities and the clinical dismay [26]. However, there is interest in developing autonomous robotic systems for biopsy (e.g. PAKY-RCM [23]), orthopedic surgery (e.g. ROBODOC [137], Arthrobot [77]), neurosurgery (e.g. NeuroMate [65]), etc.

1.2.2 ***Supporting devices and systems***

Unlike augmenting devices which are directly used by surgeons to perform interventions, supporting devices perform secondary functions such as holding endoscopes or surgical instruments. It is desirable to improve these systems so that they become more independent of the surgeon and operate with more autonomy.

1.2.2.1 *Positioning/stabilization purposes*

Positioning stands for tools A positioning stand can help the surgeon to position and lock endoscopic tools without the need for an assistant surgeon. The optimal design of the kinematic configuration of such a positioning stand is discussed in [31].

Camera positioners/stabilizers In conventional endoscopic surgery, an assistant holds and manipulates the endoscope through commands from the surgeon. In this mode, the camera may not be positioned accurately or timely enough mainly due to the fatigue and hand tremors of the assistant.

Instead, a robotic manipulator can be used for endoscopic camera manipulation as reported in [103]. In these systems, the surgeon's command can be issued through a joystick, foot pedals, voice, head movements, facial expressions, etc. Alternatively, surgical instruments can be visually tracked [43], thus providing the information on the desired position of the endoscope to the positioner robot's control loop [154].

Ultrasound probe positioner More recently, there has been interest in robotic systems for manipulating ultrasound probes [92, 1] . Most of this activity has targeted diagnostic procedures. However, these systems can potentially be used, for example, during precise ultrasound-guided biopsies and other interventional procedures.

Stabilizers for surgeon's hand A moving support for the surgeon's hand that can track the heart motions, thus allowing for coronary artery bypass grafting (CABG) surgery on the beating heart, is discussed in [144].

1.2.2.2 *Increasing device dexterity or autonomy*

During endoscopic surgery, an endoscope is inserted into a natural orifice/incision and navigated inside the patient's body, which is a difficult task given the lack of dexterity of the endoscopes available currently. Mechatronics technology can be used to develop highly dexterous or autonomous endoscopes as discussed next.

Dexterous endoscopes In the tendon-actuated endoscope discussed in [32], the rotational movement is distributed among a number of joints. In this design, it is possible to bend the stem to the desired angle and lock it in that orientation. Compared to the single-joint design, the multi-joint design has the advantages of a wide rotational range and a gradual bend capability although it requires a large space to bend to a desired orientation. Sturges and Laowattana discuss a tendon-actuated bead-chain endoscope [127]. Slatkin et al. have developed a robotic endoscope actuated by inflatable balloons and rubber bellows [123]. Suzumori et al. discuss an electro-hydraulic actuated endoscope whose distal tip can be controlled [130].

Autonomous endoscopes Some endoscopes are designed to travel through human cavities with greater autonomy. For demanding applications such as colonoscopy, in which a colonoscope is manipulated around a winding colon, autonomous endoscopic devices can be helpful. (Semi-) autonomous crawlers for colonoscopy, angioplasty, inspection of the intestine and colon have been reported in the literature [111, 7]. Devices that crawl in the gastrointestinal (GI) tract and in the colon with shape memory alloy steerable and telescopic tips have been developed [110]. For the GI tract and other tubular organs, other autonomous endoscopes are reported in [62, 123, 143, 99]. In addition to inspection and diagnosis, therapies can also be delivered when miniaturized tools are added to these endoscopes [109].

1.3 Haptics for Robotic Surgery and Therapy

Incorporating haptic sensation to robotic systems for surgery or therapy especially for minimally invasive surgery, which involves limited instrument maneuverability and 2-D camera vision, is a logical next step in the development of these systems. To do so, in addition to instrumentation of surgical tools, appropriate haptics-enabled user interfaces must be developed.

1.3.1 *Haptic user interface technology*

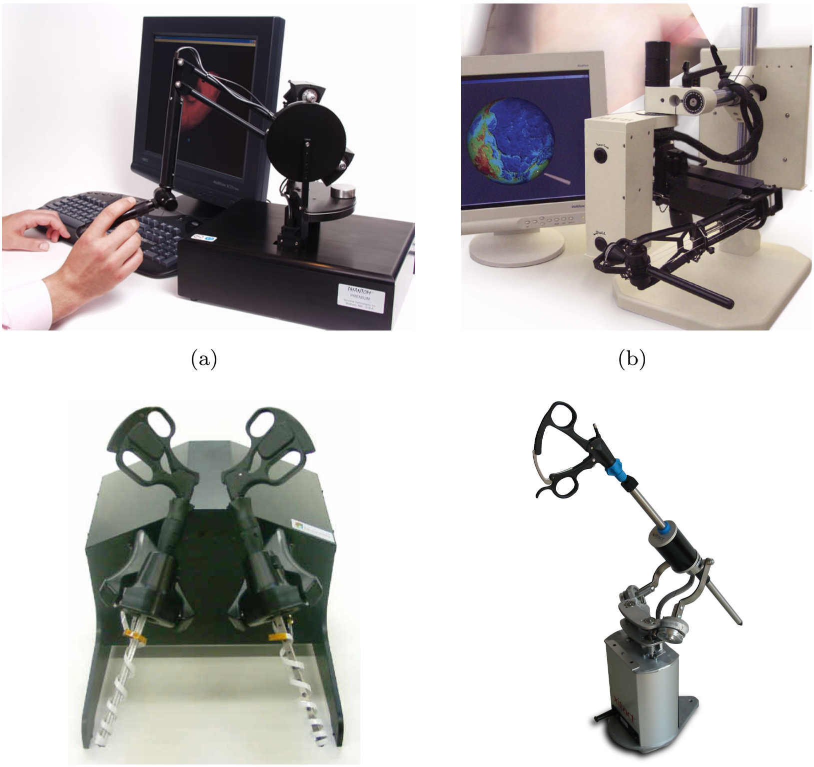
In the following, examples of the currently available haptic devices are described. For a more complete survey of haptic devices, see [55].

1.3.1.1 *PHANToM*

The PHANToM from Sensable Technologies Inc. (www.sensable.com) is one of the most commonly used haptic devices and comes in a number of models with different features. PHANToM 1.5A provides six DOFs input control. Of the six DOFs of the arm, depending on the model, some or all are force-reflective. In Figure 1.2a, a PHANToM 1.5/6DOF with force feedback capability in all of the six DOFs is shown.

1.3.1.2 *Freedom-6S*

The Freedom-6S shown in Figure 1.2b is a 6-DOF device from MPB Technologies Inc. (www.mpb-technologies.ca) that provides force feedback in all of the six degrees of freedom. The position stage is direct driven while the orientation stage is driven remotely by tendons. The Freedom-6S features static and dynamic balancing in all axes (see [54] for further design details).



(a) (b)

(c) (d)

Fig. 1.2 (a) The PHANToM® Premium 1.5/6DOF of Sensable Technologies Inc., (b) the Freedom-6S of MPB Technologies Inc., (c) the Laparoscopic Surgical Workstation of Immersion Corp., and (d) the Xitact IHP of Xitact SA.

1.3.1.3 *Laparoscopic Impulse Engine and Surgical Workstation*

Originally as part of a laparoscopic surgical simulator, the Laparoscopic Impulse Engine was designed by Immersion Corp. (www.immersion.com). The device can track the position of the instrument tip in five DOFs with high resolution and speed while providing force feedback in three DOFs. More recently, Immersion has developed the Laparoscopic Surgical Workstation (Figure 1.2c), which is capable of providing force feedback in five DOFs. An application example is the Virtual Endoscopic Surgery Trainer (VEST) from Select-IT VEST Systems AG (www.select-it.de). The VEST system uses the Laparoscopic Impulse Engine as its force-feedback input interface for simulating laparoscopic surgery interventions.

1.3.1.4 *Xitact IHP*

The Xitact IHP$^{\mathrm{TM}}$ from Xitact Medical Simulation (www.xitact.com) is a 4-DOF force feedback manipulator based on a spherical remote-center-of-motion mechanical structure and was originally designed for virtual reality based minimally invasive surgery simulation [42]. It features high output force capability, low friction, zero backlash and a large, singularity-free workspace. A picture of the Xitact IHP is shown in Figure 1.2d.

1.3.2 ***Haptic surgical teleoperation***

It has been shown that incorporating force feedback into teleoperated systems can reduce the magnitude of contact forces and therefore the energy consumption, the task completion time and the number of errors. In several studies [122, 147, 15], addition of force feedback is reported to achieve some or all of the following: reduction of the RMS force by 30% to 60%, the peak force by a factor of 2 to 6, the task completion time by 30% and the error rate by 60%.

In [106], a scenario is proposed to incorporate force feedback into the Zeus surgical system by integrating a PHANToM haptic input device into the system. In [85], a dextrous slave combined with a modified PHANToM haptic master which is capable of haptic feedback in four DOFs is presented. A slave system which uses a modified Impulse Engine as the haptic master device is described in [30]. In [107], a telesurgery master-slave system that is capable of reflecting forces in three degrees of freedom (DOFs) is discussed. A master-slave system composed of a 6-DOF parallel slave micromanipulator and a 6-DOF parallel haptic master manipulator is described in [150]. Other examples of haptic surgical teleoperation include [93] and [11]. The haptics technology can also be used for surgical training and simulation purposes. For example, a 7-DOF haptic device that can be applied to surgical training is developed in [56]. A 5-DOF haptic mechanism that is used as part of a training simulator for urological operations is discussed in [146].

1.4 Technological Challenges of the Future

The previous sections presented an overview of the different types of robotic systems for surgery and therapy. Although technological advances mainly in the last two decades have been significant, further improvement in the design and technology of such systems is required for their widespread use. Some of the challenges faced by the field of surgical robotics are as follows.

For providing a surgeon with haptic feedback, the development of specialized, force-reflective user interfaces and the integration of force sensors into surgical robots remain two major challenges. While currently the sterilization requirements are addressed through the use of gas or pre-sterilized drapes to cover the robotic end-effectors, it is necessary to develop actuators and sensors that can go through a relatively inexpensive sterilization process such as autoclaving. Furthermore, to make surgeries less invasive and to facilitate operation in very small spaces such as in pediatric minimally invasive surgery, it is needed to miniaturize the instruments – in the case of pediatric surgery, to less than 3 mm in diameter. It would also be useful to develop intelligent instruments that provide sensory control and guidance, e.g., limit the forces applied to tissue to avoid damage, record hand motions for performance records, or sound alarms when approaching dangerous conditions.

The initial and subsequent costs associated with purchasing and maintaining surgical systems are currently high, limiting the introduction of surgical robots into operating rooms. Such a high cost is mainly due to the highly challenging and lengthy process of obtaining regulatory approval for safety and reliability of a surgical system before it can be commercialized. Optimization and streamlining this process by regulatory agencies and making the surgical systems' software and hardware more modular and standardized can ultimately make the systems cost-effective and affordable.