# Preface

Surgery traditionally involves making a large incision to access the part of a patient's body that requires attention. This approach is referred to as open surgery. Minimally invasive surgery (MIS), also called endoscopic surgery, is an alternative to open surgery in which an endoscope (camera) and long instruments are inserted into the body cavity through small incisions about 1 cm across. Instead of looking directly at the area being treated, the physician monitors the procedure via the endoscope.

Because of the small incision size, MIS significantly reduces trauma to the body, post-operative pain and length of hospital stay compared to open surgery. It may potentially benefit the health care system through cost savings as well. For example, traditional gallbladder surgery requires a six-day hospital stay and up to six weeks for a full recovery and leaves a six-inch scar. However, if operated in a minimally invasive mode, gallbladder patients usually leave the hospital the same or the next day and are fully recovered after a week with the scar barely visible after a few months. Apart from societal benefits from faster recovery, this leads to savings on pain medications, nursing care and overhead costs in an expensive clinical setting.

Despite these benefits, endoscopic surgery has some drawbacks such as lack of dexterity and manipulation capability for the surgeon. Such problems can be overcome by using robots to assist surgeons during interventions. A surgical robot (slave) in conjunction with a computer controlled surgeon-robot interface (master), where a surgeon sits and performs the procedure while watching the surgical field via a 2-D or 3-D imaging system, can also make the surgeon less fatigued and the operations much more precise. A major deficiency of the current master-slave robotic systems for surgery is the lack of the sensation of touch, or haptic perception, for the



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surgeon. Haptic feedback has the potential to provide superior performance and reliability in master-slave robot-assisted interventions.

Motivated by this application, we have been investigating various issues associated with incorporating haptics in robot-assisted MIS. The results of the research are summarized in this monograph. A number of the key results are applicable to haptics-based teleoperated systems in general. The following is an outline of each chapter of the monograph and how the chapters relate to each other:

Chapter 1 starts by describing interventions that can take advantage of the benefits offered by robotics. Next, a classification of robotic tools and manipulators, which may be used in various types of surgery or therapy is provided. Then, to lay the ground for studying haptic interaction in robot-assisted interventions, some of the available haptic devices and the previous research on haptic surgical teleoperation are surveyed.

While Chapter 1 provides a broad overview of the types of surgeries and therapies that can benefit from robotics, the types of robots that can assist surgeons, and haptic interaction during robot-assisted surgery and therapy, Chapters 2 and 3 focus on a specific intervention (MIS) and a specific class of robotic systems (master-slave teleoperation systems) with the objective of incorporating haptic feedback. Studies in Chapters 4, 5, 6 and 7 are also done in the context of that specific intervention although they are not necessarily limited to it.

Chapters 2 to 7 deal with devices and methods required for incorporating haptic interaction in *master-slave robotic systems* for *minimally invasive endoscopic interventions*. In terms of devices, incorporating haptic feedback into a robotic MIS system calls for a surgical end-effector that can measure its interaction with tissue in the form of forces or torques, as well as a force-reflective user interface. Chapters 2 and 3 discuss the design of two such devices for an endoscopic surgery environment.

In Chapter 2, a novel robotic end-effector is described that meets the requirements of endoscopic surgery and is sensorized for force/torque feedback. The endoscopic end-effector is capable of non-invasively measuring its interaction with tissue in all degrees of freedom available during endoscopic manipulation. It is also capable of remotely actuating a tip and measuring its interaction with the environment without using any sensors on the jaws. The sensorized end-effector can be used as the last arm of a surgical robot to incorporate haptic feedback.

Chapter 3 discusses the design of a user interface that is capable of providing force feedback in all the degrees of freedom available during en-

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doscopic surgery. Using the Jacobian matrix of the haptic interface and its singular values, methods are proposed for the analysis and optimization of the interface performance with regard to the accuracy of force feedback, the range of applicable forces, and the accuracy of control.

It has been shown that fixed impedance-reflecting controllers cannot preserve master-slave position tracking when the environment impedance changes. In Chapter 4, a neural network is used to implement adaptive inverse dynamics control of a PHANToM haptic device, which is commonly used in haptics-based master-slave teleoperation research. Experimental results show that the neural network controller successfully represents the inverse dynamics of the PHANToM and can adapt to changes in the dynamics to maintain master-slave tracking.

In Chapter 5, the force-reflective user interface of Chapter 3 is used with the sensorized surgical instrument of Chapter 2 to form a master-slave test-bed for studying haptic interaction in an endoscopic surgery environment. For experiments involving a single degree-of-freedom surgical task on soft tissue (palpation), first the dynamics of the master and the slave including friction effects are modeled and the model parameters are identified (Appendix D). Since the master is not equipped with a force/torque sensor, a state observer based on the identified dynamical model of the master is utilized to estimate the force exerted by the operator's hand. In this chapter, the added benefits of using force sensors that measure hand/master and slave/environment interactions and utilizing local feedback loops on teleoperation transparency are investigated. We compare two-channel and the four-channel bilateral control systems in terms of stability and transparency, and study the stability and performance robustness of the four-channel method against non-idealities arisen during bilateral control implementation including master-slave communication latency and changes in the environment dynamics.

As mentioned before, providing a surgeon with information regarding contacts made between instruments and tissue during robot-assisted interventions can improve task efficiency and reliability. However, it has been established that due to major difficulties in design and technology, incorporating full haptic interaction in today's complex surgical systems demands fundamental system re-designs and upgrades as well as long-term financial and R & D commitments from the manufacturers. Therefore, in the short term and for some applications involving robotic surgery, it may be more cost-effective and advantageous to provide substitute modes of sensory feedback to the surgeon. In Chapter 6, alternative methods for feedback of such

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information to the surgeon are discussed. It is hypothesized that various modalities of contact feedback have the potential to enhance performance in a robot-assisted minimally invasive environment. To verify the hypothesis, the master-slave test-bed is used to compare users' performance in doing a single degree-of-freedom surgical task (lump localization) for different modalities of contact feedback. In this chapter, it is also studied whether haptic feedback or substitution for haptic feedback can help improve task performance under degraded visual conditions.

In master-slave telesurgery, the time delay experienced in the communication between the master and the slave can cause instability in the teleoperated system. A wave-based control architecture can theoretically make a bilateral teleoperation system insensitive to communication time delays through encoding velocity and force information prior to transmission. However, transparency of the teleoperation system is altered by this process. In Chapter 7, we propose two different approaches for improving transparency of a wave-based delay-compensated teleoperation system: direct force reflection in a two-channel control architecture, which uses the same number of channels as the traditional position error-based control scheme with wave variables and, four-channel wave-based control architecture, which is capable of achieving ideal transparency in the presence of time delays. In order to present a comprehensive performance comparison, we quantify the transparency of each approach through experiments on the master-slave system described earlier.

This monograph is primarily aimed at the medical robotics and haptics communities. Due to its practical nature, it will be of use to a wide range of readers with interests and background in robotics, teleoperation, haptics, virtual reality, sensor technology, human-machine interaction, and minimally invasive surgery and therapy.

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