Haptic Feedback in Tele-Operated Surgical Robots

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***Abstract*—Robotic surgery is revolutionising contemporary surgical practice, not only by improving traditional surgical techniques but also by bringing novel robot-assisted approaches that expand physicians' skills. Robots now serve as a collaborative means for information tranfer between a human operator and a robotic dveice. This paper explores haptic technology employed in Robot Assisted Surgeries with a special focus on Minimal Invasive surgeries. Additionally, objectives, benefits and challenges of deploying haptic technologies in surgical robotics is discussed and a systematic review is performed on three major literature works. A case study of a haptic interaction based sensorized endoscopic end-effector allows us to study and analyze the design of such devices and challenges to their implementation and deployment in a real world operating room.**

***Index Terms*—Haptics, Robot-assisted Minimal Invasive Surgery, MIS, Challenges, Surgical Robots**

I. Introduction

SINCE the dawn of robotics in the Operating Room about three decades ago, their usage and the technological advantages they bring to surgical assistance continue to gain momentum as research unravels more possibilities day by day. Currently, robotics focuses on revolutionizing Minimally Invasive Surgery (MIS) (also termed as RMIS - Robot assisted Minimally Invasive Surgery) to help with reduced recovery times and prevent scarring. This is a critical application that requires attention to many details to resource allocation and implementation. Surgical robotic systems are broadly divided into two categories based on their level of autonomy. Autonomous systems, carry out specified activities without the need for human involvement. In contrast, non-autonomous systems attempt to replicate the surgeon's motion in a master-slave teleoperated setting. Non-autonomous robots are more prevalently used in the medical field. This is primarily because the criticality of the field demands high precision, reliability, and adaptability. Rendering the procedure completely autonomous can create technical complications. Undoubtedly the advancements in the field are very promising but can not yet replace medical practitioners entirely. Rather, surgical robots are being used to supplement and extend medical personnel's abilities and enable surgeries that would otherwise be impossible.

II. Terminology

Before delving deeper, it is essential to get familiar with terms related to surgical robots and MIS used throughout the paper.

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A. Somatic senses

Practically touch is induced by several modalities including pressure, force, stretch, vibrations, and temperature. The term somatic sense is used to encompass all these elements to give a description of touch. Information obtained from the touch mechanism is classified into two types: Cutaneous information refers to the distribution of pressure over the touch surface and is sensed by skin mechanoreceptors. On the other hand, Kinesthetic information is obtained through sensory receptors in muscles and tendons which sense the kinetic and force data. These together are vital for efficient movement and physical interaction [1].

B. Haptic Interface Classification

Haptic devices are commonly classified into two types based on the somatic elements and information they sense and display. Kinesthetic devices produce the force and torque feedback to stop or encourage users' motion in some direction usually by using electric actuators [1]. As a result of force, a cutaneous sensation is generated which is a sensation triggered by the physical contact of the tool on the skin. Second type of haptic devices are the tactile displays that convey contact information to the skin, with negligible effect on kinesthetic sensation [1]. In contrast to using actuators, these use electromagnetically actuated needles, shape-memory materials, piezoelectric crystals, pneumatic systems, and heating systems to deliver cutaneous sensation. As the construction suggests, tactile displays are more challenging to manufacture hence kinesthetic displays are being used most commonly.

C. Admittance vs Impedance

In the mechanical-electrical domain, the two primary analogies to define the systems and control variables are admittance impedance. System notation denotes quantities like velocity and acceleration as flow variables and force as effect variable. Impedance is the ratio of an effort variable over a flow variable and conversely, admittance is the ratio of a variable of flow over an effort variable [1]. Linking it with mechanical devices, an admittance device is a haptic device that measures force and displays or reflects motion while an impedance device measures motion and displays the force. Simpler design and lower costs has led to the impedance device being commercially used everywhere

D. Teleoperated vs Hands-On Surgical Robots

Surgical robots are often classified into two types. Teleoperated surgical robots are a pair of robots – master and slave. The master robot is operated by the medical practitioner and his actions are reflected to the slave robot which performs the task on the patient. A bilaterally controlled teleoperator is a special case in which the interaction forces of the slave robot are reflected at the master side as well. In hands-on robot, the master and the slave manipulator are the located on the same device making the surgeon and robot cooperatively move the surgical instrument [1].

III. Robot-Assisted Minimally Invasive Surgery

Minimally invasive surgery is a surgery technique that has helped doctors revolutionize surgery performance through smaller incisions which impede scarring and reduced recovery time among patients [2]. While having its pros, the technique has its drawbacks: The images capture by the endoscopic camera are displayed on a 2D monitor causing loss of depth perception in the operating field; The rigid instruments are controlled at a distance which causes fatigue among the doctors; Lastly, the long-shafted instruments are operated through small incisions and deprive the surgeon of direct haptic sensation - touch feedback, which may include both force/kinesthetic and tactic/cutaneous feedback. RMIS - Robot assisted Minimally Invasive Surgery emulates a human hand motion without mirrored movement, and adds additional degrees of freedom (dofs) in the wrists, thereby increasing dexterity and improving instrument control [2]. Secondly, Motion scaling and filtering enables more precise motions within the patient. Thirdly, a magnified 3D enhanced computer vision system provides a view of the operating site with greater clarity than open surgery. However, RMIS systems are large, expensive and time consuming to set up, they also require training of the surgeon and the nursing staff and provide less information than traditional MIS and open surgery.

IV. Does Robot-Assisted MIS Need Haptics?

A major limitation to current RMIS systems is the lack of sensitive haptic feedback but many surgeons find the visual cues like tissue deformation adequate for force information. Since the fragility of the tissues and sutures can vary between procedures and patients, the usefulness of the haptic feedback is therefore dependent on the skill of the surgeon and the specific surgery to be performed. Through a research of studying the difference between applied suture forces, it was found that if RMIS can be imbued with similar kind of kinesthetic feedback provided by hand-held instruments, repeatability would be improved. Multiple experiments were done and developments made to study the need for haptic feedback in RMIS, all of which indicate that absence of force feedback increased the average and peak force magnitude applied to the tissue, as well as the number of errors that damaged tissue, thereby elucidating that surgeon performance and patient outcomes would significantly improve through the incorporation of haptic feedback. The advancements are: A laparoscopic grasper with force feedback capability to help surgeons differentiate tissue stiffness through a haptic interface [2]. Although, this device was superior to a standard laparoscopic Babcock grasper but not as good as the gloved hand for rating sample compliance. Using a similar system, it was found that providing both vision and force feedback leads to better tissue characterization than only vision or force feedback. Further experiment with a representative dissection task using surgeon subjects found that haptic feedback reduced unintentional injuries, but increased operating time compared to a manual intervention.

This leads us to conclude that haptic feedback gives an additional sense to the doctor in terms of movement within the patient's body and therefore allows for cautious motion thus preventing deep probing or internal injury. However, this would require more attention to details and increased time for intricate surgical processes as compared to manual proceeding where the hand is used to automatic operation through practice.

V. Sensing and Estimation of Force

Although bilateral telemanipulation can occur with or without the use of force sensors, it has been shown that theoretically, force sensing will improve teleoperator performance [2]. These few sections aim to minimize the reliance on force sensing - keeping in mind, the challenging surgical environment, simplified system designs will be used. Force sensors would ideally be placed in locations on the robot or its instruments that are outside the patient's body but this will not only acquire force data for the delicate interactions between instruments and tissues etc but also outside forces such as friction, body wall forces; torques applied on the instrument for insertion into the patient's body and are large enough to mask the instrument-tissue interaction forces that should be displayed for the surgeon.

Another location for sensors could be instrument shafts but the internal shaft forces wary widely during manipulation if the surgical system - like that of Da Vinci - has cable-driven 'wrist' degrees of freedom at the tip of the instrument and these internal forces are a magnitude higher than the instrument-tissue interaction forces [2]. Calibration for removal of such internal forces fails because of heavy dependence on uncertain starting conditions; creating an extra internal shaft with force sensing capability limits the degrees of freedom that can be actuated at the gripper [2]. Another solution was the attachment of a standard force sensor to a modified trocar, which allows for undisturbed measurement of manipulation forces. Whereas this would reduce cost and sterilizability demands, it does not allow position scaling or dexterity at the instrument tip.

Force sensors, ideally, are to be placed near the tip of the instrument inside the patient. Their material should be able to withstand the harsh sterilization process and because they interact with warm tissues and fluids, they must be designed to reduce sensitivity to changing temperature. More challenges are explained in the Challenges section. Force/Torque sensors add significant cost to a surgical instrument especially if the measurements are to be made in many degrees of freedom. Alternatively, interaction forces between the instrument and tissue maybe estimated using observers, adaptive controllers, and detailed robot models.

Another defined approach, which correlates to the materials studied in class, is a controller based on a proportional control law with additional model-based feed-forward terms that cancel the dynamic properties of the manipulators [2]. The teleoperator transmits the impedance of a soft environment to the operator when the proportional gains of the controller are very high and the dynamic terms of the manipulators are cancelled. However, the high gains and complete cancellation of the dynamic terms of the manipulators can make the teleoperator unstable: Llewellyn's criteria for absolute stability to limit the controller parameters to values that keep the teleoperator stable during interactions with any passive user and environment, helps here. The main drawback to this approach is that the pre-sliding forces from the trocar are not considered.

An idea that we have in mind, which would likely be less accurate than the approaches defined above, is to use the properties of the instrument and/or the tissue itself, along with some sort of visual measurement feedback for the estimation of the applied forces. Furthermore, certain degrees of freedom could be utilized for forces' sensing while others for their estimation. This might give desirable results but would obviously be subject to limitations such as precision and knowledge of the different types of internal tissues that poses adherence to common surgeries and those that are very rare.

VI. Methods for Force Feedback

Several methods have been evaluated for providing force information to the surgeon during RMIS: There is the direct force feedback, in which forces are directly applied to the surgeon's hands using a haptic enabled master manipulator, and Sensory substitution, in which force information is displayed through an alternative sensory channel, such as vision or audition [2].

Appropriate gain level for feedback is an important consideration in direct force feedback. When the level of force feedback is low, the feedback would only consist of information and the system dynamics would remain intact. Increasing force feedback gains generates physical constraints for eg, preventing a user from probing too deeply in the tissue. If the gains are made too high, however, that would lead to fatigue and decreased performance because of excessive stress application and estimation from the operator side [2].

Another important consideration is the number of degrees of freedom of force feedback. In some RMIS systems, certain degrees of freedom make the placement of force sensors or force estimation accuracy too challenging, thus only partial force feedback can be implemented. It was found that, in a task using an additional gripping degree of freedom, the loss of grip force feedback, or conversely all translational force feedback, does significantly affect performance in terms of applied force; likely due to the decoupled dynamics of internal and external hand forces [2].

VII. Sensory Substitution - Other Alternatives

Considering the limitations of haptic technology, research on sensory substitution is underway. In teleoperation, sensory substitution often refers to the transmission of environmental information by engaging other alternative sensory channels rather than providing kinesthetic feedback on the master site [1]. Substitutes for kinesthetic feedback include visual, auditory, and tactile channels. Since they do not require active actuation, they are less vulnerable to instability and can be effective in providing the operator with simple haptic information. However, they are not suitable for complex tasks due to perceptive and cognitive overload [1].

Sensory substitution is an attractive alternative (although does perform as well) to direct haptic feedback because it eliminates the cost of a haptic master device, can be easily integrated into existing systems, and, in some cases, may even be able to display more accurate forces than direct haptic feedback because system stability it not a concern [2]. (If forces are estimated, the force fed back to the user's haptic device may be lowered conservatively to maintain stability.

Auditory feedback is a natural method of sensory substitution, since surgical teleoperation does not inherently involve auditory feedback [2]. The changes in sensed or estimated force can be displayed to the operator continuously through frequency and/or amplitude modulation, or through non-continuous signals like beeps. It was found that vibration feedback improved performance in terms of probing depth error, time, and maximum force for a tissue stiffness differentiation task.

The most promising approach for clinical adoption is visual display of forces. The consistency of applied forces during RMIS suture tying aided by visual feedback or combined auditory-visual feedback sensory substitution has been found to be superior to that achieved both with hand ties and RMIS with no feedback [2]. Improving on this display, it now has ability to track instruments and overlay force information over the tips using semi-transparent dots that change color or bars that change length and color with the magnitude of sensed/estimated force. Visual force feedback (VFF) has resulted in reduced suture breakage, lower forces, and decreased force inconsistencies among novice robot-assisted surgeons, although elapsed time and knot quality were unaffected. In contrast, VFF did not affect these metrics among experienced surgeons. These results suggest that VFF primarily benefits novice robot-assisted surgeons, with diminishing benefits among experienced surgeons.

One challenge for sensory substitution is how to convey all the degrees of freedom of force information that may be available through sensing or estimation [2]. In the above approaches, only the net bending force of the instruments was sensed and displayed. Further experiments are being conducted to improve upon ideas of comparison between visual force display and direct force feedback.

In light of the fact that the amount of useful information that can be conveyed through visual and auditory channels is limited, force feedback is a more natural technique for conveying haptic data to the surgeon. Conclusively, we believe that although force feedback seems to be an intuitive and convenient choice, a better approach is to select sensory channels based on task at hand.

VIII. Active Constraints in Haptic Feedback

An active constraint or a virtual fixture is a computer-generated constraint that makes the robot move in certain directions and avoid forbidden regions to ensure a safer and faster operation [1]. This was implemented in the hands-on robot-assisted knee replacement surgery where the robot showed resistance to movement in forbidden regions. Virtual fixture showed a tradeoff between performance and surgeon control however a general improvement was noticed in the robot's performance. Although they are a very promising feature for surgical robots, Organ displacement and deformability is a challenge to active constraints. The constraint's dynamics must be mapped to the organs' at all times even when they move or deform. This is challenging especially with robots that have fewer trackers and sensors on the device. Active constraints work finely with rigid organs for example in orthopedic surgeries. Research is happening as an effort to improve active constraint construction. We believe that active constraints can be a brilliant approach to avoid delicate regions and completely reform the arena of surgical robotics. However for very rare surgeries, it will be difficult to train the active constraints equipped robots and assess them because of the rarity of them happening. For critical surgeries, active constraints will conflict with doctor's intuition and workflow in case of emergency situation and can compromise the procedure.

IX. Other Usecases of Haptics in Surgical Tasks

In the cited literature, many teleoperated robots for various tasks in medical fields have been reviewed in great detail. In this section, some of those use-cases are reviewed. A general gist of all the applications suggest that safety enhancement must be given high priority. Studies indicate that haptic feedback has shown to be beneficial in performing surgical tasks with complex kinematics and can help improve motor skills of the user. Furthermore, the absence of haptic feedback increases the surgical time as the surgeon has to look for visual hints instead [1]. A potential reason for delays could be those encountered in positioning the end-effector accurately. We have explained each of the use-cases in further detail. Table 1 tabulates present day surgical robots with haptic feedback technology [1].

TABLE I
List of Surgical Robotic Systems with Haptic Feedback Capabilities

Name	Producer	Availability	Procedures
RIO System [90]	MAKO Surgical Corp., US	Commercially available	Orthopaedic Surgery (Hands-on)
ALF-X [178]	TransEnterix, US	Upcoming for commercial exploitation	RMIS
SPORT (Formerly Amadeus) [179]	Titan Medical Inc., Canada	Upcoming for commercial exploitation	Single-site RMIS
ACTIVE [180]	European FP7 consortium, led by Politecnico di Milano, Italy	Research prototype	Neurosurgery
Steady-hand Eye robot [131]	Johns Hopkins University, US	Research prototype	retinal microsurgery
M7 [181]	Stanford Research Institute, US	Research prototype	RMIS for battlefield and space applications
MiroSurge [182]	German Aerospace Center, Germany	Research prototype	RMIS
SOFIE [183]	Technical University of Eindhoven, the Netherlands	Research prototype	RMIS
RAVEN II [41]	Applied Dexterity, US	Research prototype	RMIS

A. Instrument Positioning

Haptic based surgical assistance robots have proven to be very useful in accurate positioning of the instrument within patient's body. In Hands-on robotics, the surgeon manually guides the surgical instrument end-effector to the desired position. In this case, the interaction forces depend on the dynamics of the robot. Stiffer robots can induce excessive tension by deteriorating contact force perception [1]. This is not suitable in surgeries involving delicate regions like the brain cortex. One solution is to scale forces. In this strategy, the interaction forces produced by the tissues are increased to provide an elevated haptic sense during the tool placement. In one of the studies mentioned in the literature, a torque-based impedance controller with force scaling was used for cooperatively assisted surgical brain cortex stimulation which resulted in 30% reduction in tissue indentation for medical experts [1]. Here, we think that scaling factor for force scaling needs to be decided not just based on the constraints but after rigorous testing as too much high of a force feedback can confuse the surgeon and he might cause rash movement. Too less feedback, on the other hand can slow down the operating procedure.

B. Needle and Catheter Insertion

Most surgical operations require the insertion of needles and catheters into the soft tissues. Without any real-time imaging mechanism, the surgeon has to rely on the kinesthetic feedback from the tool and his knowledge and visualization of the body's anatomy [**?**]. Perception of needle interaction force can be advantageous to the user as it could help identify soft tissues and avoid forbidden regions. Studies showed that the addition of force feedback reduces error in the detection of transitions between tissue layers by 55% and as can be expected, the addition of real-time visual feedback improved user performance by 87% [1]. This technique though, also faces a challenge. The feedback information obtained is slightly distorted because the force-feedback rendered to the user includes both the tip contract force and the frictional force between tissues and needle shaft when only the former is required. As studied in class, one approach can be to model the frictional force as a disturbance and design the system in a way that the control strategy takes care of the disturbance. Secondly, a computed force controller can be devised to minimize the error to zero but then it will have to be specific to each application. Different Control algorithms are being researched to counter these issues.

C. Microsurgical tasks

Microsurgery is a delicate field that requires magnified(up to 20 or 30 times) visual analysis of the surgical area and requires manipulation on the submillimeter scale [1]. Neurosurgery, ophthalmic surgery, and reconstructive surgery all come under the microsurgery umbrella. These are often very demanding procedures with extremely small workspace and small force requirements. The failure consequences are very high too. In the case of microsurgery, interaction forces produced by the tool and tissues are non-perceptible by human senses, and applying a higher force can be harmful to organs. In this scenario a combination of haptic and optical feedback can be used by providing an amplified interaction force that can allow the user to perceive and safely apply delicate forces. Infact, Stanford Salisbury Lab has developed a 6-DoF haptic device for teleoperated robot microsurgery treatment [4]. In light of the studied literature, we believe that it will be quite a challenge to design and work with robots that in addition to complexity due to haptic technology, also have to incorporate high-definition magnification technology. Furthermore, as discussed in previous section, microsurgery robots will also have to scale the feedback force and motion because the sensed forces might be too low otherwise.

X. An In-Depth Case Study: Haptic interaction in robot-assisted endoscopic surgery: a sensorized end-effector

Endoscopy is a minimally invasive medical procedure in which an endoscope is inserted into the body using small incisions. Compared to open surgery, this is less painful and traumatic to the body and results in a reduced postoperative hospital stay. However, it has its limitations.

A. Limitations

1) The camera attached to the endoscope is unstable and is subject to vibrations by the practitioner's hand and can cause visual interruptions and distortions. The hand-eye coordination of the practitioner is not very intuitive and straightforward.
2) Any disturbance at the surgeon's end for example tremor gets magnified in the body because of the long length instrument
3) An endoscope has very limited degrees of freedom because it can only pivot about the entry point and thus compromises dexterity.
4) There is a loss of tactility and no cutaneous sensation because the surgeon cannot access the surgical field directly.

To cater to these issues, the cited paper explores the design and analysis of a particular case – a sensorized endoscopic end effector that can be utilized in research and training and can be used to analyze the sensory and motor skills of residents and surgeons [3]. Mastering endoscopy takes a lot of time and effort. More so, learning gets disrupted due to difficult hand-eye coordination as mentioned in the limitations. This tool provides force feedback that assists the surgeon to obtain a correct viewpoint and re-calibrate hand-to-eye mapping to perform better surgery.

B. Methods and Materials

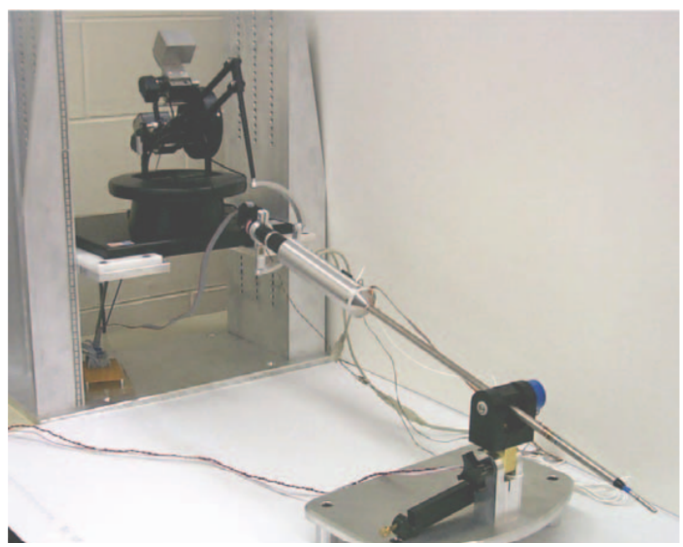
[3] For force reception during robotic endoscopic surgery, two things are needed:

1) An endoscopic surgical instrument that acts as the last arm (end-effector) of the slave surgical robot and is properly sensorized to measure instrument/tissue interactions in the form of forces or torques.
2) A force-reflective interface that mediates between the surgeon and the robot, transferring hand movement commands to the robot and instrument/tissue interaction measurements to the surgeon's hand.

We will focus on the robotic endoscopic end-effector that measures any force/torque interaction it has through contact with its environment.

C. Force Reflection Methods

Position error-based force reflection accounts for an inferior teleoperation transparency as compared to force reflection using a force sensor at the slave side in a master-slave system [**?**]. It was observed that due to the compliance of the low-stiffness object, the position error between the master and slave robots is small in detecting palpitations of soft objects. Since the force reflected to the user is proportional to this position error, in order to have a perceivable force, the corresponding gain should be high [3]. If the gain is not high enough, the user may damage the tissue by incurring excessive deformation. A high gain, however, causes some force to be reflected to the hand even when the slave robot is moving in free space due to any control inaccuracies. Therefore, with a tradeoff on the force feedback gain, the dynamic range of perceivable forces is limited. This technique, along with a properly sensorized end-effector, adverse effects of sensor-less force feedback are excluded from the haptic teleoperation loop. Figure below shows the end-effector along with the master slave system designed.



D. Design Requirements

Developing a robotic end-effector that is sensorized and actuated in accordance with the requirements of endoscopic surgery involves some challenges:

1) Currently available sensors that measure forces and torques in all six degrees of freedom are wider than 10mm and therefore cannot enter the body [3]. Location outside the patient causes distortions in forces' sensation because it picks up unwanted abdominal wall friction and stiffness at the trocar site .
2) The pivotal motions of the tip that is, grasper jaws need to be actuated by a linear motion from outside

the patient due to space limitation [3]. This produces another challenge: the force sensor that is being used must be hollow to accommodate the rod whose linear motions actuate the tip.

3) Since it is desirable to use tips that can be detached and disposed of after use for sterilizability reasons, the sensor for measurement of force applied by the tip's jaws on the tissue should not be mounted directly on the jaws [3].

The first problem is catered by non-invasive measurements of interactions using strain gauges integrated into the endoscopic end-effector. For the second and third challenges, a linear motor and load cell mechanism is used to actuate a detachable tip and measure its interaction with the tissue.

E. Twist and Tip Motion

A mechanism for the roll motion – twist about the main axis – of the end-effector is needed: a geared motor, combination responsible for instrument twist can be placed at the base of the assembly. A free wrist can be attached to the roll motor and is built such that if the motor faces resistance while trying to rotate the instrument (and the tissue), the wrist will not twist into itself.

Depending on the kinematic properties of the surgical robot, the endoscopic end-effector can be used with or without the free wrist. With the wrist, the end-effector will be compatible with any robot that provides 3D space positioning and with a spherical-joint fulcrum placed at the trocar to form a constrained isocenter (the role of the fulcrum is to support the end-effector so its movement does not damage the tissue near the trocar) [3]. Without the wrist, however, the end-effector is limited to use with a robot that provides spherical movement at a Remote Center of Motion (RCM) located at the entry point. In a master-slave system, one issue to consider with the end-effector is how to use the tip's position and force models. The surgical end-effector's tip is controlled by a handle at the surgeon's console in a robotic master-slave setting therefore it is important to preserve the same tip/handle relationships to minimize the perceptual and motor mappings that an endoscopic surgeon would have to learn to perform robotic endoscopic surgery.

1) Tip Actuation: The tools used in endoscopic surgery to grasp, cut, or dissect tissue have their jaws pivotally moved relative to one another by a linear motion actuator [3]. For the end-effector developed in the cited literature, there are three concentric tubes – outer, middle and inner. The inner tube is displaced with respect to the middle one by a linear motor in order to control the tip jaws. The reason for having an additional outer tube is discussed in the Interaction Measurements section.

2) Tip Model: To control the jaw's angular position, it is necessary to find its relationship with the linear displacement that actuates it. Here, $\alpha = \theta + \alpha_0$ and the jaw angle θ can be found from the linear displacement x using the equation:

$$sin(\theta + \alpha_0) = \frac{L}{D - x} \tag{1}$$

3) Tip Identification: The value of d is determined to be 22mm. The parameters α_0, L and D of the above equation are to be computed empirically. and the linear position x as well as the angle 2h were registered. The mean values for all these parameter estimates obtained using four trials of an experiment (in which the linear motor moved the tip to 30 positions corresponding to the angle between the two jaws of the tip ranging from 0 to 63 degrees; linear position x as well as the angle 2θ were registered. Then Gauss-Newton method for non-linear minimization was used to best satisfy the above equation) are listed in Table 1. A consistency measure has been defined as the ratio of the standard deviation of the estimates to their mean value.

	Mean	Standard deviation/Mean
α_0	25.15°	2.1 %
L	2.34 mm	3.9 %
D	5.91 mm	1.7 %

F. Interaction measurements

For the force model; the balance of moments about the pivot point leads to $F_j d = (F_m sin\alpha)((D - x)cos\alpha)$. From eq(1) and $\alpha = \alpha_0 + \theta$, the following force propagation model is obtained:

$$F_j = F_m \frac{Lcos(\alpha_0 + \theta)}{d} \tag{2}$$

The above eq (2) gives us the determination of F_j that is, the force exerted by the jaws on the tissue based on the linear compression F_m measurable by a single axis load cell [3].

Possible maneuvers of the instrument involve lateral and axial interactions at the distal end, occurring when push or pull forces are applied on the tissue, and torsional interactions that can happen, for example, during suturing. Assuming the instrument axis to be defined by z, the instrument endpoint forces (f_x, f_y, f_z) and the twist moment τ_z , can be determined from the measurements of all moments (τ_x, τ_y, τ_z) and the axial force f_z provided it is only the end point of the instrument where the interactions occur. Strain gauges are then used to non-invasively measure all of these interactions with the tissue. They are placed on opposite sides of the surface of the outer tube such that any lateral force at the endpoint causes tension in one strain gauge and compression in the other. These full-bridged gauges register the two bending moments τ_x and τ_y [3].

Compressional/tensional axial force f_z is registered by the full-bridged strain gauges placed on the opposite sides of the third link of the 2-dof wrist. This wrist is responsible for the spherical motions of the end-effector centered at the entry point through the skin.

The twist moment τ_z is measured by the torque gauge placed on the middle tube as the tip's outer body threads onto it [3]. It is to be noted that each of the strain gauges is in a transverse arrangement with respect to others and therefore, holds sensitivity only in the intended direction. The reason for having three tubes in the end-effector assembly is because this arrangement isolates the differential force that actuates the tip from the measurements in other directions. More specifically, the middle tube, which floats between the inner and outer tubes, prevents the differential inner tube/middle tube force from affecting the strain gauges mounted on the outer tube for measuring lateral forces

The strain gauges are calibrated by finding the relationship between the output voltages and the forces/torques applied at the tool end-point [3].

G. Remarks and Future Directions of Endoscopic end-effector

Every endoscopic operation requires degrees of freedom (pitch, yaw, roll, insertion, and grasping/cutting/dissecting). The endoscopic end effector's haptic system can measure tool-tissue interaction force in all 5 DOFs. This three-stage manipulator and its sensor assembly efficiently deal with the incision and size constraints and allow for remote actuation of a tip(disposable and replaceable) and the measurement of tip interactions with tissue (grasping forces, etc.) without using sensors on the jaws. There are still wires running from the strain gauges to the base of the end effector whose sterilization must be looked into before using the tool commercially. As a part of the same research, a robotic master-slave testbed has been developed to study haptics-based interaction in a minimally invasive environment and assess the performance to devise techniques that could bring down instability and communication latency.

XI. Haptics in Simulation for Surgical Training

Since the onset of laparoscopic surgery, there has been a need to develop and enhance the surgical skillset as surgeons had little to no experience with the new technology. Early years used animals for practical exercises which raised ethical issues. Finally came the virtual reality computer simulations that are still used for medical training to this day. Despite the success of such simulators, it is still believed that lack of haptic feedback in RMIS simulations is a disadvantage [1]. For medical learners, it would be best if the environment was as realistic as possible which can only be achieved once haptic feedback is added. This could lead to a faster learning curve. For example in needle insertion, bone cutting in middle ear surgery, and brachytherapy;poor techniques and handling can create troublesome and harmful consequences for the patient [1]. Haptic virtual environments for surgical simulations have been developed that will achieve two objectives. It will train novice clinicians to learn surgical procedures more efficiently. Secondly, for complex and critical procedures, expert surgeons could simulate and prepare themselves before actual operating procedures.

XII. Challenges of Deploying Haptic Technology in Surgical Robots

Haptic systems have several limitations and their severity increases especially with their application in the surgical field. All human environment sensing mechanism except for touch involve little to no interchange of energy. Touch and somatic senses on the other hand are the only sense that involves mechanical energy interchange [1]. This is termed as bidirectionality which is the cause of many challenges in haptic perception. Other than the design and manufacturing of these bidirectionally controlled robotic systems, there performance assessment and evaluation, stability, sensor placement and sterilization is challenging as well. We will explore these challenges below.

A. Stability

Closed Loop control is always affected by dynamic force interactions. Consequently, a force feedback-controlled robot capable of executing unconstrained motion stably is susceptible to increasing instability if interacted with rigid surfaces. This poses more challenge if instead of a single side control system, a bidirectional system is under consideration in which all three subsystems the human, robot operator, and the master robot interact dynamically [1]. The feedback loop will be destabilized by not only external factors and disturbances but also by neuromuscular delays and biomechanical impedance at the user's end [1]. Communication delays add to more instability. These nonlinear factors make it difficult to analyze the haptic system in terms of control variables and linear control theory. The same instability argument applies to virtual systems where the robot and the environment are replaced by computer simulations.

As discussed in the lectures, non linear control strategy is better suited for surgical robots to incorporate all external elements. Research is being carried out to improve stability in teleoperated haptic feedback robots by exploring non conservative methods. Until an ideal control strategy is not devised, the stability of haptic systems by improving the quality of the hardware [1]. We suggest that, nonetheless, the users of this technology need to be acquainted with all technical details and instability related issues so that they know what performance to expect from the devices.

B. Force and Tactile Sensing

Haptic Information for any system is acquired by the sensors installed on the master and the end-effector robot as well as the surgical instrument. Tactile and force sensors, used for this purpose, are constrained by the operating room environment which limits their size and robustness. Furthermore, the sensors used in the teleoperators must adhere to surgical device regulations such as those imposed by the European Medicines Agency (EMA) or the United States Food and Drug Administration (FDA) [1]. As expected, their cost is unreasonably high as well. A few other challenges related to sensing are explained below

1) Sensor Placement: Placement of the sensor is a concerning issue as it can detoriate the force data or rupture the tissue if placed at an incorrect location. For example the Minimal Invasive Surgery procedures involve inserting the surgical instrument in the patients body through a small incision where a trocar is placed. Sensor can be easily placed at the exterior of the instrument however that will affect forces from the abdominal wall, shaft contact with nearby tissues, friction, backlash, and instrument's weight and inertia [1]. An alternative is to place the sensor at instrument's tip which unfortunately places size and robustness constraints on the sensor [1]. Additionally we also think that attaching the sensor in immediate vicinity of the surgical site will be beneficial but its wiring and connections will be problematic for the manufacturer and can harm the patient as well.

2) Equipment Sterilization: In any medical procedure, non sterilized equipment is either disposed of or is sterilized before reused. Disposing is not feasible because of the high cost robotic equipment and sterilization is challenging as well. Sterilization is commonly carried out by applying saturated steam on the instruments for a duration of about 15 minutes [1].If this method is used, the sensors must stand heat, humidity and pressure. Conclusively, the sensors must be robustly tested for all mentioned conditions before being installed on the device.

3) Selection of Sensor:

1) *Force Sensors:* are single-point devices that are used for sensing. Their types include capacitive, piezoresistive, piezoelectric, and optical-based sensors [1]. Each sensor has their pros and cons and they need to be selected based on the application and the environment which it is exposed to. Optical based sensors do not require electricity and are convenient with not only sterilization procedure but procedures like MRI or CT scan as well. However, misalignment or tilting of optical cables cause sudden light changes and thus limits their use.
2) *Tactile Sensors:* measure quantities like pressure, vibration, stiffness, texture, shape, shear and normal forces through physical contact [1]. Tactile sensing point contain an array of sensors. This multiple-sensing point design can be a major cause of complication due to its size and difficulty in integration with surgical instruments as mentioned above. Here, we think that an additional concern could be that these tactile sensor array could be a single point of failure and can be extremely harmful if it happens during surgery.

C. Performance Assessment and Metrics

Somatic senses are to a certain degree vague. Evaluation is possible only if the objectives and benefits are quantifiable. One particular metric of interest is transparency - how transparent the intermediate interfaces are to the user. Transparency measures the extent to which a user feels as if they are directly interacting with the environment while performing a task in teleoperation mode [3]. Side effects of control strategy like vibrations, hot grip, etc worsen the transparency of a haptic system. Transparency is a good metric but not the only standard one. Moreover, transparency is not a suitable metric for teleoperators which superimpose extra guiding forces on top of interaction forces to encourage the user to move in a certain direction [1]. In these cases, performance is dependent on the task to be achieved instead of transparency. Therefore, we think it is much better to quantify performance based on each specific task the robot achieves. A convenient example is to measure the number of tissue breakage and suture with and without haptic feedback. For more complex and critical cases, in soft surgery or even in orthopedics, defining clear criteria is a serious problem.

1) Operator's Bias in Performance: Expertise of the user who is using the surgical robot plays an important role in performance. Similar to manual surgeries, it has been reported that expert surgeons obtain better performance scores than novice surgeons due to better hand-eye coordination and motor skills [1]. An option is to use it with people with no experience for preliminary evaluation but it seems unnatural to us because the device ultimately has to be used by practiced surgeons.

2) Subjective Evaluation: Alongside objective evaluation, which measures the robot's performance against quantifiable objective, subjective performance assessment is of the tool is of high importance too [1]. The subjective evaluation focuses on the operator's feelings and perception and is often performed by questionnaires asking the operator about her/his personal opinion and feelings. This might provide new insight into other problems and how to make the robot more suited to the surgical environment. We believe that this might be problematic too. The subjectivity of the subjective assessment responses varies a lot as well. Sometimes the incompetency of the user might be shown to be the issue with the robotic apparatus. The responses must be carefully considered before taking action upon.

XIII. Future Work in Haptics for Robot-Assisted Surgery

One promising area for future work is the use of the surgical system's visual channel for deformation and tissue property acquisition [3]. For example, camera images can be used to define virtual fixtures, designed using the sensed geometry of the workspace and a priori knowledge of the desired task. If inter-operative tissue models can be developed quickly, force display could be based on the model rather than the current estimated force. Such model-based teleoperation could also be effective in the presence of large time delays [3]. It would also be useful to examine the use of tactile information in surgery. The current drive for natural orifice surgery (surgery without external scarring) is an exciting opportunity and challenge for roboticists to develop new small, dexterous devices, as well as teleoperators and other mechanisms to control them. Haptic feedback will be important here for navigating a device to the surgical site and performing the surgery.

XIV. Conclusion

This paper presented a holistic overview of haptic technology and the benefits and challenges that come with it in surgical robotics applications. It explores the potential of RMIS systems, their implementations, design and technological and ethical challenges posed to its application in real world operation rooms. Three publications were reviewed as well as clinical studies which helped us conclude the benefits of haptic feedback in surgery. A specific case study of a haptic based surgical robot end-effector was reviewed in great detail to know practical aspects of design of this technology. Lastly the challenges faced in the arena of surgical robots with haptic capabilities was explored.

The cited literature sums everything up nicely, "Surgical robotics is still struggling to prove itself useful in the operating room" [1]. The inclusion of Haptic feedback in a surgical system is not only intuitive but a logical and beneficial decision. It has made robotic surgery more efficient, accurate, reliable, and natural for the surgeon. Despite the moral dilemma, robot assisted surgery is making its way through the skepticisms and controversies towards revolutionary applications that handle precision and details in the Operating Room. Future research in progress and areas that need improvement are also touched upon. Research now focuses on boosting haptic and robot hardware, and innovative solutions are being devised to change the future of robotics and the surgical arena that comes under it.

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