INVITED PAPER

# Haptic Feedback and Force-Based Teleoperation in Surgical Robotics

*This article examines key challenges associated with the application of haptic feedback and force-based teleoperation for surgical robots, such as instrumentation, fidelity, stability, and force-reflection modalities.*

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**ABSTRACT** | This article presents an overview of the current state of research and application of haptic (primarily kinesthetic) feedback and force-based teleoperation in the context of surgical robotics. Telerobotic surgery provides an approach for transferring the sensorimotor skills of a surgeon through a robotic platform to perform surgical intervention inside a patient's body. Integration of advanced sensing and haptic technologies in telerobotic surgery can help to enhance the sensory awareness and motor accuracy of the surgeon, thereby leading to improved surgical procedures and outcomes for patients. The primary mode of sensory feedback has been through 3-D visual observation using stereo endoscopes. However, until recently, the sense of touch, i.e., haptics, has been missing in the commercial telesurgery robots approved for use in the operating room despite over two decades of research and development in the field of haptics for teleoperated systems ("telehaptics"). Research has shown that high-fidelity force feedback can enhance the performance of telesurgery and potential outcomes by enabling the surgeon to have a more natural feel of interaction between surgical tools and tissue as normally experienced during open surgery. Interaction forces, such as those generated during palpation of tissue, insertion of a needle, unintentional (and potentially unsafe) exertion of force by a tool, suture breakage, needle slippage, or tool interaction, are replaced by indirect (virtual) sensations, termed visual haptics, which provides an alternative to sensory compensation. Although there is a significant amount of literature supporting this benefit, there are still several important technical challenges in introducing haptics in telesurgery, including instrumentation, fidelity (transparency), stability, and modalities for force reflection, e.g., direct or indirect. This article examines these challenges and discusses recent work on haptics-based teleoperated surgical robotic systems.

**KEYWORDS** | Haptics; human-centered robotics; kinesthetics; surgical robotics; telerobotics; telesurgery.

## I. INTRODUCTION

Any telerobotic system consists of a leader robot, a follower robot, and a communication network that connects the two. In the context of telerobotic surgery, the leader robot is the surgeon's console, and the follower robot is located at the patient's side. The leader robot registers and transfers (over the communication network) the surgeon's commands to control the patient-side surgical robot. The surgeon's commands could include instrument positions, orientations, velocities, camera motions, and so on. The patient-side robot replicates the motion generated by the leader robot and is generally composed of several manipulator arms carrying laparoscopic surgical tools and an endoscopic camera. The information gathered at the patient-side robot is transferred to the leader robot and the surgeon, mostly via visual feedback, for

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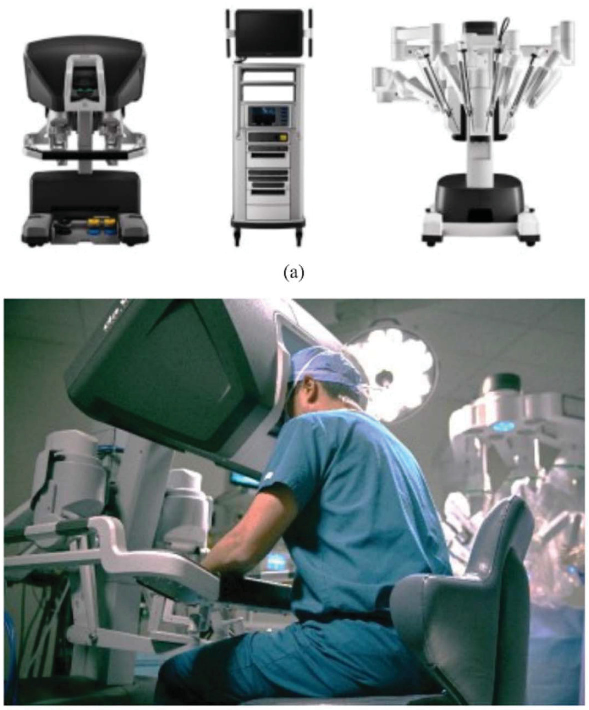

(a)

(b)

**Fig. 1.** *(a) da Vinci Xi Surgical System. (b) Surgeon's console of the da Vinci Xi System [5]. (© [2022] Intuitive Surgical Operations, Inc.)*

the needed situational awareness and actions. The current commercial teleoperated surgical robotic systems provide several features to enhance the sensorimotor abilities of surgeons [1]–[8], such as motion scaling to boost accuracy; 3-D vision (via stereo endoscopes) to provide 3-D depth perception; motion filters to exclude physiological tremors during operation; high-resolution manipulation, allowing surgeons to perform surgery in a more natural fashion and with greater dexterity; compensated hand-eye coordination to account for the mirroring effect, which is a challenge for manual minimally invasive surgery; and augmented imaging to allow surgeons to see beyond natural human visual bandwidth, such as using real-time high-resolution fluorescence imaging.

Among the existing systems, the da Vinci surgical system by Intuitive Surgical Inc. is the most successful commercial surgical robotic system. The latest model (the da Vinci Xi system) is shown in Fig. 1. Several new surgical robotic systems have been developed in recent years. One of these is the Senhance system (see Fig. 2) from Asensus [9] (formerly TransEnterix), which is haptics capable. The term "haptics" as used in the robotics literature covers a broad range of topics such as force feedback, tactile feedback, skin stretch, and vibration feedback [10]. Force feedback reflects the interaction forces that are sensed by the receptors in the muscles, joints, and tendons of the human operator. Force feedback is typically low in frequency but can be high in magnitude. Tactile feedback (or its subset cutaneous feedback) provides information about the texture and roughness of a surface, vibration, and skin stretch. It is sensed through stimulation of a variety of mechanoreceptors in the operator's skin [11]–[13]. In this article, the focus is on kinesthetics-based force feedback and the challenges that this type of haptic interaction creates for robotics-assisted surgery. Some aspects of tactile feedback are also discussed. It is important to note that interaction forces can not only change the response of the user due to the sensing-actuation loop but can also directly and mechanically affect the trajectory of motion generated by the operator. This feature closes an analog mechanical loop between the human operator and the robot, and is often studied under the topic of physical human–robot interaction.

Considering the cost, size, and needed infrastructure for a hospital to have multiple surgical robotic systems [14], the type of surgical procedures that can benefit from robotic surgery should be investigated in detail. Due to the different characteristics and properties of the parts of the human anatomy involved in various surgeries, often, there is a need to have a specialized robot for a specific type of surgery, rather than a generic surgical robotic system. In this regard, while there is acceptance of surgical robotics in such procedures as radical prostatectomy [15]–[17], there is some debate on the benefit of surgical robotic systems for some types of surgeries, such as thoracic surgery [14], [18]. The reason for such disparity may lie in the importance of features that are missing in current surgical robotic systems, such as haptic feedback. The absence of haptic feedback in the da Vinci system was highlighted in a report [19] by the FDA that summarized the responses to a survey of surgeons regarding their experience with the da Vinci surgical robot.

An important area of research is concerned with improving human–machine interaction through the incorporation of haptic feedback [20]. By augmenting the conventional audio–visual information transmitted to a human user through a communication medium, haptic information significantly enhances the realism of interaction with a remote environment by engaging the user's sense of touch. Notably, while audio–visual technologies have considerably matured over the past few decades, haptic technology has not quite reached a similar level. It is anticipated

**Fig. 2.** *Senhance Surgical System [9]. (© [2021] Asensus Surgical US, Inc. (www.asensus.com))*

that future advancements in terms of better capturing, manipulating, transmitting, and recreating haptic information, and the development of rigorous techniques and benchmarks for detailed validation of sensing technologies and haptic interfaces will enhance the future of human–machine interfaces for medical applications [21]. This has been discussed in the literature under the umbrella of tactile Internet [22]–[25], and several companies are investing in this area [26].

## II. HAPTICS AND SURGICAL ROBOTICS

Although, in general, existing surgical robotic systems enhance the quality of visual feedback for surgeons, most of them do not provide haptic feedback [27]–[29]. It is important to note that haptic feedback can incorporate critical information about stiffness, location, depth, size, and texture of areas of interest in tissue and organs, such as tumors. In addition, haptic feedback allows the surgeon to have an intrinsic awareness of the amount of force applied to tissue, which can be critical for guaranteeing safe tool–tissue interaction. Furthermore, with an appropriate choice of force sensing and haptic technology, the surgeon can use force feedback to quickly and accurately feel, react to, and, in some cases, avoid conditions such as suture breakage, needle slippage, loose knots, unintentional tissue cuts, and collision between tools, all of which are important during surgical procedures [27], [29]–[36]. Therefore, lack of haptic feedback can result in longer procedure times, inability to accurately palpate areas of interest, and the possibility of applying excessive or damaging forces on tissue and organs [27], [28], [35], [37]–[43]. Currently, surgeons who use these surgical robotic systems go through extensive training programs to develop not only the needed motor skills but also to learn how to operate without haptic feedback and possibly compensate for the lack of haptics using virtual compensatory sensation, such as visual haptics (the ability to judge the approximate amount of force based on visual cues, acquired through practice) [1], [2], [44], [45].

In order to address the abovementioned challenges and enable teleoperated surgical systems to also provide haptic feedback to the surgeon, extensive research and development have been conducted during the last three decades [46]. This article provides an in-depth analysis of the state of the art with regard to haptics-enabled robotics-assisted surgery. Although several fundamental challenges have been addressed to date, there still remain issues that need to be addressed for enabling surgical robotic systems to provide haptic feedback for a broad range of applications [38], [47]–[56].

In this regard, there are three fundamental challenges: transparency (fidelity), stability, and instrumentation. Transparency depends on a number of factors in a telesurgery system. The major parameters are: 1) the dynamics of the surgeon-side robot and the corresponding mechanism design; 2) the communication time delay; 3) the local controller at the surgeon's side to render the communicated force to the surgeon; and 4) the controller at the patient's side robot that follows the trajectory of motion to correspond to the motions specified by the surgeon. More details can be found in [57]. Challenges inherent in haptics-enabled systems exist due to the closed-loop nature of such telerobotic interactions. A system is stable if and when the trajectories of the system states converge to an equilibrium point or remain bounded. The magnitude or the energy (depending on the type of stability being considered) of the output of a stable system always remains bounded. This is not the case for unstable systems. Instability can result in a system that is susceptible to even the smallest delays, uncertainties that usually come from unmodeled dynamics of the system, and quantization [58]–[61]. The challenge with regard to instrumentation at the patient's side relates to the need for sterilizable, biocompatible, miniaturizable, disposable, and low-cost force sensors needed for enabling haptics. In some applications, it may be possible to obtain appropriate force feedback indirectly (without the use of specialized force sensors), e.g., via measurement of currents driving the arms of the surgical robot. However, there are certain concerns regarding dynamical artifacts, such as hysteresis effects in surgical tools [62], [63]. For greater accuracy and reliability, it may be possible to incorporate redundancy in measuring forces. In this article, these challenges and available solutions are discussed.

## III. HAPTIC INTERFACES

In order to achieve high-fidelity haptic feedback, which is critical to the success and safety of any interaction, the haptic interface must be designed and controlled appropriately. Here are some criteria that should be considered in selecting or designing haptic interfaces:

### A. Workspace

The extent of movement of a kinematic chain, be it a user interface or a surgical robot, defines its workspace. For performing a task in a teleoperation mode, the workspace of the user interface should be neither too large nor too small [28], [64]–[66]. A user interface with an excessively large workspace can be fatiguing for the user. For example, it is more comfortable for users if the small motions of a computer mouse are mapped to the larger motions of a cursor across a large monitor. On the other hand, too small a workspace for the user interface is also problematic as the users will be forced to frequently employ clutching (to move the user interface repeatedly to a new position and orientation without the surgical robot moving), thereby disrupting the fluidity and speed of the hand motions. Thus, the desirable workspace size is application-dependent.

A separate but related issue is the importance of scaling between the workspaces of the leader and follower robots, and the dependence of the accuracy of the teleoperated surgical systems on such scaling. For example, the accuracy can be improved by scaling down the motion of the follower robot relative to that of the leader robot. Motion scaling is beneficial when the surgical task needs to be done very precisely, such as in microsurgery [67], [68]. With motion downscaling from the leader to the follower robot, while the shape of the workspace is maintained, the workspace of the user interface and that of the surgical robot are scaled with respect to one another in a manner proportional to the scaling factor. Careful consideration should be given to motion scaling between the interface and the teleoperated robot when selecting a workspace for the haptic interface.

### B. Manipulability

The ability of a haptic interface to take any arbitrary pose and apply any arbitrary force or torque (wrench) across its workspace is measured by its manipulability. It is also important to consider the haptic interface's isotropy, which measures whether the interface can move and apply force equally well in all directions (i.e., directional uniformity). When a robot is isotropic, it is not singular within its workspace, which means that the manipulability would not become zero inside the workspace. It is critically important for haptic devices not to be singular within their workspace due to physical interaction with a human operator [66], [69], [70]. The other related topic that needs to be considered according to the type of medical intervention is the number of degrees of freedom (DoFs) of the end-effector of the haptic interface: a typical surgical application involves seven DoFs: three for positioning, three for orientation, and one for grasping. Some surgical applications may use fewer DoFs. An example is needle insertion, which typically involves five DoFs: three for positioning and two for orientation [71]. It should be noted that redundancy of the robotic system in terms of the active DoFs increases the manipulability of the system [72].

### C. Applicable Range of Force Feedback

A haptic interface should be able to emulate highly stiff environments, despite having a limited joint torque range, by applying large forces against the user's hand. Surgical tools are used to palpate, hold and stretch, lift organs (such as the liver), and insert tools inside the organs. All these tasks require high forces typically in the range of 0–5 N; however, forces as high as 40 N have also been reported [39], [73]–[75]. In addition, it should also be noted that, even though most tissues involved in the surgery are soft, there may exist compact and high stiffness tissue in the workspace, such as bony structures. Besides, the telerobotic system may also be in contact with stiff instruments, such as suturing needles or surgical probes and tools. Thus, the telerobotic system should be able to operate in a high stiffness environment. Otherwise, there would be an inaccurate perception of a stiff environment [76].

More importantly, the requirements of the medical intervention should be considered in order to determine the desired force feedback capability and resolution for the haptic interface. In other words, the characteristics and quality of haptic rendering should be connected to the interaction requirement of surgery or the corresponding surgical task. For example, for palpation-based tumor localization, the quality of haptic rendering should be high, while, for laser ablation, there is no need for haptic interaction. For surgical operations and tasks that have a high degree of interaction (such as gastrointestinal surgeries), ideally, haptic interfaces should have the ability to display a high range and resolution of force. As an example, during minimally invasive surgery, grasping instruments require a force range up to 10 N with a resolution of 0.2 N [77]. On the other hand, for applications that require interaction with solid objects (objects with a stiffness of above 2 N/mm [78]), such as bones, the haptic interface for telesurgery should be able to render high forces to accurately represent this hard contact for the remote surgeon.

### D. Sensing DoFs and Resolution

The number of DoFs for force and torque feedback should ideally match those of the end-effector. However, the number of DoFs for the haptic feedback is related to the complexity and cost of the interface and is dictated by the availability of measurements of interaction forces and torques at the end-effector of the teleoperated robot [31], [39]. In addition, the resolution of position sensing must be suitable for the surgical application under consideration. The haptic interface should be able to detect the position of the surgeon's hand with appropriately high resolution.

### E. Z-Width

The $Z$-width of a haptic interface refers to the dynamic range of the impedances that it can display while maintaining stability [79]–[83]. When the $Z$-width is large, the user is presented with richer haptic information. It should be large enough to permit natural motion by the surgeon and transitions between free space and stiff contact and between the different textures that surfaces may have. It can be difficult to tell different environments apart when a haptic interface with a small $Z$-width is used. When the teleoperated robot moves in free space, the haptic interface should not exert any force on the user's hand. Therefore, haptic interfaces should have a low apparent impedance (mainly inertia), as well as low friction, especially if high accelerations are involved. Inertia and friction are determined by the mechanical structure, actuators, and configuration of the haptic interface [84]. Poor performance of the system due to friction, high inertia, and lack of backdrivability limits the lower bound of the $Z$-width, leading to a smaller range of impedance that can be rendered by the telerobotic system. In addition to the mechanical limitation, the $Z$-width may be affected by signal digitization, the control system of the robot, and its filtering effect [81].

### F. Response Time (Bandwidth)

Sufficient bandwidth is required in telesurgery and for teleoperation, in general, to permit natural motion and operation by the surgeon [62], [63]. The system should be agile enough to render instrument contact with stiff tissue. A low-frequency system can affect the accuracy of the surgery and the perception of the surgeon. This issue is valid for any type of interaction, including haptic, auditory, and visual. Lightweight haptic interfaces, in general, have greater bandwidth [85]–[87].

In order to preserve and convey the surgeon's intuitive movements and replicate at the surgeon's console the feel of a tool's interactions with tissue at the surgical site, the haptic interface should offer sufficient workspace, manipulability, range of force feedback, and DoFs. It should also have sufficient dynamic ranges of impedances, and a low response time compared to what the surgeon would normally experience working directly on the tissue. In addition, for ease of integration in the operating room, the footprint of the haptic interface needs to be small.

It is possible to trade off certain desirable characteristics of haptic interfaces, such as high force feedback capability against low inertia or high stiffness against workspace size. Large actuators are necessary for high force feedback capability, adding inertia to the haptic interface. The stiffness of the haptic interface is reduced (and its inertia is increased) when the workspace is made large using long links. Therefore, for a haptic interface to perform optimally, it should be optimized for specific surgical applications. In order to design a haptic interface or to choose a commercially available haptic interface, the specific application should be taken into account because the application is the defining factor of the level of importance of each of the abovementioned items. It may be more straightforward and cost-effective to modify a commercially available haptic interface rather than to design and fabricate a new one. Nevertheless, all the desired properties of the haptic interface might not be achieved since only minor alterations can be made to a commercially available haptic interface.

It should be noted that, to determine the best haptic interface, not only surgery-driven hardware measures should be considered but also user-specific psychometric measures should be developed to validate the perception of the users.

1) Regarding hardware measures, the status of backdrivability, frictional force, and impedance bandwidth should be evaluated.
2) To determine user-based measures, the suitability of a haptic interface can be assessed through user studies and psychometric evaluation [84]. User-based measures are application-dependent and evaluate the haptic interface's perceptual rendering efficacy via psychophysical experiments. A user-based evaluation of haptic interfaces involves target acquisition, object manipulation, geometric perception, material perception, and environmental monitoring [88], [89]. Other factors, such as user ergonomics, fatigue, and discomfort, while using a haptic interface, can also be considered.

## IV. HAPTIC FIDELITY, PERCEPTION, AND STABILITY

Teleoperation fidelity of force feedback is also known as transparency of the corresponding telerobotic system. This characteristic refers to how accurately a remote interaction is perceived by the operator. In other words, how the remote impedance is reflected to the user and how much deviation the telerobotic medium causes in the reflected force field. An ideal telerobotic system will guarantee highly accurate reflection of the force field, thus ensuring high transparency. Implementing a transparent telerobotic system has been a challenge mainly due to the fact that, in order to realize transparent interactions, all the dynamics of the system and communication network should be compensated for in the presence of uncertainties and noise. This is a complex requirement that calls for in-depth investigation regarding the format of telerobotic architectures. In the context of telerobotic surgery, transparency is critical since inaccurate force reflection can result in misleading haptic cues and fatigue for the surgeon, which can have undesirable effects.

In order to ensure transparency, a four-channel telerobotic architecture was proposed in [58], which requires communication of force and motion data from both sides. Through a specific design of four-channel teleoperation, not only does the force provided to the operator at the leader side better follow the force measured at the follower side but the motion of the follower side also follows the force generated by the operator with less error leading to increased transparency. It should be noted that ideal transparency cannot be achieved in practice for several reasons, including actuator saturation, safety measures (such as a safe range of forces), noise in the measurements, unmodeled dynamics, and inaccurate kinematics (such as due to hysteresis in the cables) [79]. To reduce the complexity of the architecture, local force control loops were added to each side of the telerobotic architecture [90], using which one of the communication channels is dropped, and transparency is guaranteed using three communication channels. As the next step, it was shown that, using a particular local inverse dynamics approach, it is possible to achieve transparency by the minimum possible amount of communication, i.e., two channels for a haptics-enabled telerobotic system [91]–[95]. The specific design of the two-channel architecture removes several complications from the closed-loop dynamics of the system, thereby reducing the complexity of the closed-loop system and the susceptibility of the system performance to delay, noise, and uncertainties, including unmodeled dynamics (such as those due to flexibility in links or instruments). Also, the resulting system has enhanced and more robust stability [92], [96]. It should be noted that, due to technical challenges, more research effort is needed to realize high-quality and stable haptic feedback in telerobotic surgery. Early examples of realistic experimental work can be found in [97]–[100].

## A. Effect of Delay on Perception and Fidelity

Delay is an inherent component of any telerobotic system and has been one of the most critical factors that limit the wider utilization of haptic feedback in telerobotic surgical systems. Even in the case of direct line communication, delay can be caused by the digitization of signals or by the processing of transferred information. In the case of remote surgery, delays can be induced in the communication system due to the telecommunication network, which, in some cases (such as Internet-based teleoperation), includes several servers and protocols, causing variable network delays.

Several studies have been conducted to understand the tolerance of delays in unilateral telerobotic surgical systems (see [101]–[106]). In unilateral teleoperation, kinematic signals (motions) are transferred only from the leader to the follower without any haptic feedback; thus, there is no closed-loop force feedback. An example of a unilateral system is the da Vinci surgical system, which does not send force feedback to the surgeon's hands, as explained later. Studies around the effect of delay on unilateral teleoperation were conducted using the da Vinci surgical system [103] and an earlier system, the Zeus (which has been discontinued) [104]–[106]. The work examined the effect of delays caused when using a satellite network and also a virtual private network for performing telerobotically conducted surgical procedures on phantom tissue and animal models. The studies showed that an increase in time delay correlated strongly with degraded performance and fatigue. In these experiments, the time delay was in the range of 300–500 ms. At a higher amount of delay, it was determined that performing the surgical procedure was not feasible [101]–[103], [107]. When haptic feedback is included, the acceptable amount of latency drops by a factor of 10, which means that 50 ms of delay can significantly skew the perception of the environmental stiffness, which can play a critical role in haptics-enabled surgery, as demonstrated by the effect of delay on tumor characterization through palpation [107], [108]. It can be shown mathematically that the time delay directly affects the hybrid transfer matrix of a two-port telerobotic system. The elements of the hybrid matrix show the relationship between the sent and received forces and velocities of the two-port system (one port is on the leader side, and the other port is on the follower side). The hybrid matrix directly represents the transparency of the teleoperation system. It can also show the transfer function of the haptic echo in the system (which is a partial force felt by the user only due to their motion and without any correspondence to the forces measured at the follower side). Details can be found in [79], [90], [96], and [109]. By considering the frequency response of a time delay, a frequency-dependent phase lag between various variables in the network can be observed. This effect can also be seen in the hybrid matrix (since the elements of the matrix would include the transfer function of a time delay). Due to the generation of ultrafast and reliable Internet, such as mobile networks (5G, 6G, and beyond), it can be predicted that it should be feasible to conduct remote procedures by securing agile leader and follower communication.

## B. Effect of Delay on Safety of Telehaptics

Besides the effect of delay on fidelity and perception of telerobotic systems, one of the well-known challenges for any teleoperated robotic system is the possibility of instability caused by a delay in the network. In the context of surgical telerobotics, instability can directly affect the safety of patient–robot interaction and can result in dangerous situations. As a result, regardless of the perception and fidelity of the system, guaranteeing stability in the presence of time delay (and variation of time delay) is of practical importance and has been investigated extensively in the literature. The reason for the destabilizing effect of the time delay can be explained using the passivity control theory that determines the balance between energy dissipation and generation, and highlights the accumulation of energy due to the existence of a delay in networked telerobotic systems. This can also be explained using the absolute stability theory [110]–[113], using which it can be shown that a transparent haptics-enabled telerobotic system is only marginally stable. The sensitivity of the system to the time delay can be such that even a minimal amount of discretization delay due to digital implementation can result in instability [60], [114].

## C. Current Solution to Stabilize Delayed Telehaptics

In the last two decades, several algorithms have been proposed to stabilize telerobotic systems in the presence of communication delays. Among the proposed and commonly used algorithms are wave-variable control (WVC) techniques [59], [113], [115], [116] and the time-domain passivity approach (TDPA) [93], [117]–[120], both of which have been designed using the passivity control theory [121]–[123]. In this regard, WVC directly "passivates" the communication network by applying forward and inverse wave transformations preceding and following the communication channel. The transformations cancel out each other in the case of zero delays and modify the flow of energy in the presence of nonzero delays. In addition, TDPA directly observes the flow of energy and the validity of passivity-based stability conditions, and injects adaptive damping in case nonpassive energy is observed. Most of the earlier efforts were focused on stabilization in the presence of constant communication delays, which is a mathematically simpler problem to solve. However, advanced algorithms were proposed later to tackle the problem of variable time delays, which not only injects extra energy into the system but can also causes the spectrotemporal characteristics of the waveform [124]–[126] to deviate.

Besides the passivity control theory, the small-gain theory has also been used in the literature to generate novel stabilizers for guaranteeing the stability of teleoperated systems, which can be used for surgical applications [127]–[130]. The utilization of the small-gain theory is often motivated by relaxing conservative assumptions in passivity-based stabilizers, such as the passive behavior of the operator and the environment [92]–[94], [131]. Such assumptions cannot be made in the context of surgery due to physiological energy and activations, such as during beating heart surgeries or in the presence of respiratory motion. Using small gain control, the aforementioned assumptions are relaxed, and variable time delays are also considered to propose several new categories of stabilizers that guarantee system stability while reducing deterioration in transparency by decreasing the conservatism of the system [92]–[94], [127], [129], [130], [132]. Besides average latency, other challenging topics for designing stabilization algorithms are nonlinearity in the dynamics of the robots, uncertainty in the models, and high variability of time delay [133]–[137].

### D. Stability–Transparency Tradeoff

Stabilization algorithms, including the ones mentioned above, modify the flow of force-motion information in telerobotic systems to damp out the excess energy, thus directly affecting the transparency and performance of the system. In other words, existing approaches sacrifice transparency and performance to guarantee stability. Although this can be considered a reasonable tradeoff, it can make the use of haptic feedback impractical in a surgical robotic system since heavily skewed haptic feedback may not be informative or useful for surgeons or, in the extreme case, be misleading. More specifically, the degradation of motion tracking can directly induce surgical errors, and degradation of force feedback can cause inaccurate, disruptive, and misleading force information for the surgeon. This is, indeed, one of the main reasons that have slowed down the utilization of haptic feedback in practical leader–follower surgical applications.

There has been an extensive amount of research aimed at minimizing the error in force feedback and/or motion tracking resulting from stabilization, as well as the effect of the conservativeness of the passivity and small-gain sufficient conditions for stability. For example, due to the velocity modifications often needed for stabilization, a position drift is expected, which can result in major desynchronization of the leader and follower robots. As a result, new stabilization algorithms have been proposed to directly impose position tracking [51] and, in some cases, compensate for position drift [138]. Other examples of performance improvement are power-domain stabilizers that distribute the energy dissipation over time, avoiding sudden deployment of damping, in order to have a smoother haptic experience for the surgeon while guaranteeing stability [139]. In addition, some of the existing approaches, such as WVC, have been modified to improve transparency, taking into account the perceptual bandwidth of the users [140]. Using small-gain control, modulation of force feedback is also conducted while considering the directionality of the force to minimize the perceptual confusion using a projection-based force reflection algorithm [141]. Recently, to minimize the induced damping needed for stabilization and to take into account the complete capacity of the closed-loop system in absorbing nonpassive energy, the concept of biomechanical excess of passivity has been proposed. The aforementioned consideration allows accounting for the amount of energy that can be absorbed by the biomechanics of the user, which reduces the need for damping out the observed nonpassive energy, thereby eventually enhancing transparency. This approach significantly reduces the conservatism of the system and the need for modulating transparency compared with conventional counterparts that try to stabilize the system regardless of the dynamical behavior of the user's biomechanics [92]–[95], [142].

It should be noted that optimal force reflection requires the implementation of stabilizers that minimize the error in system transparency and performance. This is an active line of research, and recent developments have shown promising results for reducing transparency deterioration during the implementation of haptic feedback, especially for relatively large time delays in communication networks that connect the leader and follower robots.

### E. Sensory Substitution and Augmentation

In order to bypass the destabilizing effect of direct haptic feedback, indirect delivery of force feedback has been proposed in the literature. In this regard, the recorded force information can be provided to the user through various sensory modalities, such as visual, auditory, tactile (fingertip), and vibration feedback (see [143] and [144]). This can give the surgeon some degree of haptic awareness while reducing the abovementioned concerns in terms of stability and performance deterioration [35], [41]. Although sensory substitution may not be as natural/intuitive as direct feedback, it is stable, and so there is no concern about stability [13]. Using sensory substitution, a direct control loop is created, which eliminates the concern regarding stability, while an indirect sense of haptic awareness is provided to the surgeon. Thus, the surgeon can decide on actions to be taken in the conducted task based on the visualized force feedback (such as by color coding) or appropriate auditory notification. Some studies have demonstrated that haptic feedback and graphical cues are equally effective in improving performance and accuracy for certain tasks. In such cases, graphical cues can substitute for haptic feedback in a cost-effective and adequate manner [34], [49], [147]. This addresses the stability issue, but it does not eliminate the perceptual desynchronization caused by communication delays

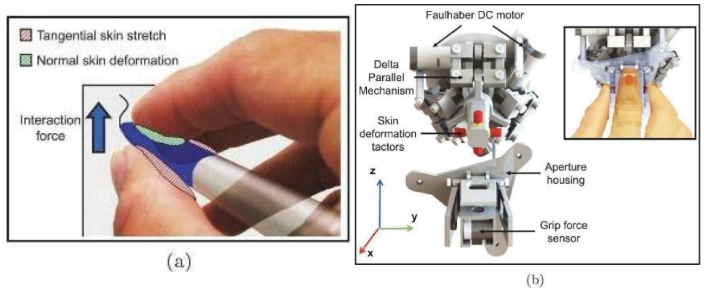


**Fig. 3.** *(a) Tangential and normal skin stretch. (b) 3-DOF actuator for skin stretch feedback [148]. (© [2015] IEEE)*

since a communication delay can affect the causality of the loop and, thus, the decision-making process of the surgeon. However, due to its inherent stability, it has been considered in the literature as a practical approach for providing force information to the surgeon to enhance sensory awareness during telerobotic surgery. In other words, a sensory substitution is an alternative approach to direct force feedback.

Several studies have been reported in the literature on the use of sensory substitution, and it has been shown that it has the capability to enhance the manipulation of surgical tools and can result in tool–tissue interaction forces close to ideal feedback. The studies showed that sensory substitution could result in high consistency of applied forces during procedures, which is an indicator of better control by surgeons over surgical tasks [35]. In this regard, the visual force feedback has been studied for suturing tasks, resulting in consistent force during knot tying and ultimately higher quality of sutures [34]. This concept is applied for sensorized da Vinci systems, and the results support the use of visual feedback to reduce suture breakage, the maximum force applied to tissue, and the standard deviation of force distribution during knot-tying tasks by novice surgeons [41]. The concept is also investigated for tumor localization using telerobotic surgical systems [56], and it has been shown that force feedback through visual cues, such as force distribution and stiffness maps, can directly assist the operator in finding lumps in tissues. Interestingly, the benefit of visualized force feedback has a lower degree of significance for expert surgeons who were able to conduct a task without relying on force feedback though they did show a tendency for effectively utilizing the provided information.

As a relatively new mode of sensory substitution, cutaneous feedback has also been studied in the literature using skin stretch actuators to provide proportional feedback to the fingertips of surgeons [11], [148]–[154]. The use of skin stretch is motivated by the corresponding intuitiveness and interpretability compared with direct contact (such as pushing tissue with a stylus, which would also result in a proportional stretch and deformation at the fingertip since the higher the normal force, the greater the stretch). Skin stretch is implemented using an actuator at the handle of the leader robot during telemanipulated tool–object interaction to provide intuitive indirect feedback for the normal force to the surgeon [149], [151], [153]. Taking into account both tangential and normal forces during tool-object interaction, a 3-DOF skin-stretch actuator was developed (see Fig. 3) [148]. This provides more precise and faster task performance. In addition, wearable haptic interfaces have shown great potential in rendering tactile feedback in robotic surgery [155]. The integration of these interfaces with commercial surgical systems needs further investigation.

In order to benefit from both direct and indirect force reflection, the concept of sensory augmentation has also been investigated. Using this concept, the loop gain of direct force feedback is reduced to guarantee stability, while indirect sensory addition (such as using skin stretch) is provided to balance the reduction of information due to loop-gain downscaling. In other words, the operator receives a combination of sensory feedback, including reduced-gain direct feedback and an additional sensory channel. Improved accuracy and performance have been reported in [148] and [151].

## V. INSTRUMENTATION FOR HAPTICS IN SURGERY

Success in realizing haptics in surgical robotics depends on the development and implementation of appropriate instrumentation. This includes the selection and deployment of sensors inside or on surgical tools to measure the multidimensional forces acting on the tools. Due to limited space in and on the tools and clinical restrictions, this is not a straightforward process. When surgery is being performed directly by a surgeon and without a robotic system, even for such common tasks as suturing, the surgeon would need to rely on the shear force during needle–tissue interaction to feel needle slippage and adjust for it appropriately. In addition, the surgeon needs to rely on skin stretch at the fingertip, and the sensed normal force to tune the gripping force of the needle. When the tool interacts with the environment, not only the sensors in the surgeon's muscles/tendons feel the interaction force but also the skin under the tip of their finger would stretch, and the combined information would be processed in the brain to provide tool-mediated perception [149], [151], [153]. Also, the surgeon needs to experience reaction forces to manipulate the knot, control the quality of the knot, ensure the needed tightness, and avoid breaking the suture while tightening the knot. As a result, just for suturing, there is a wide range, different types, and directions of forces that should be controlled for which sensors would be needed in a very small space and in direct contact with tissue. There is no single sensing technology so far that can provide all the abovementioned information during surgical tasks. This shows the complexity involved in instrumenting surgical tools for force sensing. An important technical challenge arises from the needs for biocompatibility, stabilizability, miniaturizability, disposability (considering the cost and limited use of surgical instruments), and multidirectionality of sensory data. During the last two decades, there has been considerable work aimed at developing sensors for this purpose. In this section, we discuss major existing efforts and challenges.

In order to develop sensorized tools, two strategies could be considered: 1) sensorizing existing surgical tools, such as those used in the da Vinci surgical robotic systems and 2) developing new tools that have an embedded sensor (such as using a flexure mechanism at the tip).

1) *Sensorizing Existing Surgical Tools:* This approach has been reported extensively in the literature, such as in [27] for sensorizing the da Vinci system to measure 1-DoF grip pressure. Besides pressure sensors, strain gauges [41], optical fiber Bragg grating (FBG) sensors [156], ultrathin nitinol strain sensors [157], and tactile sensors [146] have been utilized in the literature by attaching them to the shaft or distal end of the da Vinci surgical instruments, mainly to sense Cartesian interaction forces or contact deformation and vibrations at the tooltip. In addition to the body of the tool, sensors have also been attached to the tiny cables inside the shaft of the tool to measure the activation and reaction forces and estimate tool–tissue contact forces [158].
2) *Developing Sensorized Tools:* One fundamental approach to having a sensorized surgical tool is to change the design of the tool and fabricate it in a way that facilitates force sensing. For example, the DLR surgical system [159] has a fixture mechanism near the tip, which undergoes very small flexing during tool–tissue interaction that enables sensitive force recordings. In order to optimize the location of the sensors, finite element modeling has been used in the literature. In an early effort, using small conventional strain gauges, 6-DOF force recording has been achieved. Motivated by the same concept, a new sensorized platform has been designed [160] for the RAVEN-II surgical robotic system, which enables 3-DoF force sensing and grasping force. In this work, capacitance-based force sensing is used (to estimate the deflection of the part with flexure and thus the applied force) instead of strain gauges. Torque sensors are also added to the pulleys of the tool to enhance the estimation of the force. Besides designing surgical tools with force sensing capability, there are some specific tools designed only for determining force as the primary function, mainly for palpation. One example is the work that utilizes a matrix of capacitive pressure sensors to provide the force distribution map for palpation of soft tissue (such as for liver, kidney, and lung). The resulting technology was extended to a dual-modality (tactile and ultrasound) instrument for the da Vinci surgical system, as shown in Figs. 4 and 5. Another example of using capacitive and piezoelectric sensing can be found in [32], where specific attention has been paid to develop a system that is custom-made, low-cost, and disposable. Wireless palpation is proposed in [161]

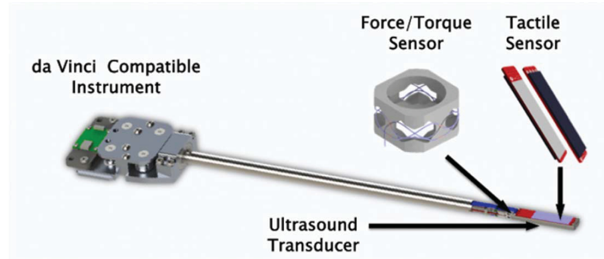


**Fig. 4.** ***Dual-modality palpation instrument for the da Vinci Classic surgical system [171]. (© 2017 IEEE)***

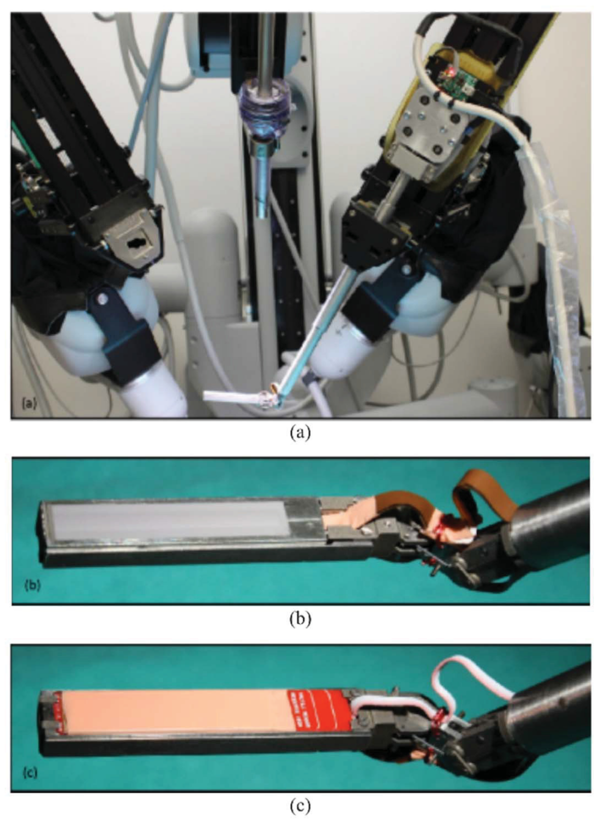

**Fig. 5.** ***Details of the dual-modality palpation instrument shown in Fig. 4. (a) Instrument mounted on the da Vinci Classic. (b) Instrument's ultrasound transducer. (c) Instrument's tactile sensor [171]. (© 2017 IEEE)***

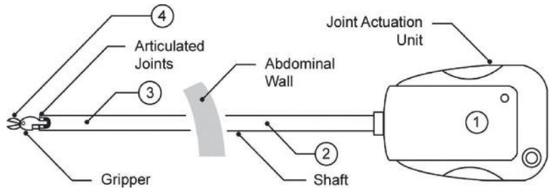


**Fig. 6.** *Options for locations of force sensors [162]. (© 2008 IEEE)*

using a wireless capsule that can be deployed inside the patient's body and manipulated by a secondary tool to generate force and stiffness distribution maps. Further examples can be found in [162].

Besides explicit force sensing, implicit force estimation has also been considered in the literature, such as: 1) vision-based interaction force estimation using a deep learning algorithm from camera outputs [163]–[165]; 2) estimating instrument force using external force sensors [63], [160], [166]–[168], e.g., underneath the patient or in the cannula; and 3) using kinematic data such as the vibration due to instrument–tissue contact [169]. These indirect force estimation methods are at a relatively early stage in tackling challenges for force sensing that makes them less accurate than direct force sensing. This reduced accuracy increases uncertainty that could affect control accuracy. These indirect methods use advanced models that can account for nonlinearity, uncertainty, temperature dependence, hysteresis, and backlash in the mechanical structures of a system [170]. This is an active field of research that can significantly reduce the cost of introducing haptic feedback in surgical robotics.

### A. Technological Challenges for Sensorizing Tools

As mentioned earlier, there are critical technical challenges with the implementation of force sensing, most of which arise due to the location of the sensors [37], [162]. Possible locations for sensors in a laparoscopic instrument for a surgical robot are shown in Fig. 6. Research has shown that only locations 3 and 4 would result in reliable force measurements [37], [162], [172]–[175]. This corresponds to attaching the sensor on the shaft that is inserted in the patient's body or attaching the sensor at the tip of the surgical tool. This selection is desired because of extraneous forces, such as friction effects at the trocar, and friction, backlash, and hysteresis inside the tool and at the actuator outside the patient's body. These forces make tool–tissue interaction force measurements unreliable [37], [162], [176]. Although some effort has been made to model and compensates for such forces in order to enable sensors to be located outside the patient's body, the results so far indicate superior sensing accuracy corresponding to a location near the tip and inside the patient's body. As a result, significant effort has been made to identify and resolve the challenges associated with locating sensors near the instrument tip to measure forces inside the patient's body. The current challenges include: 1) cost-effectiveness (since many of the tools should be disposed of after a certain number of uses); 2) miniaturization (to allow the force sensors to pass through the trocar during surgery); 3) fluid resistance (to operate effectively in the presence of various body fluids); 4) sterilizability (which is a major challenge due to the need for withstanding one of the standard sterilization processes after every use); and 5) biocompatibility (which would limit the choice of material to be used in the sensor).

In order to address the abovementioned challenges, considerable research has focused on the use of optical force sensing [52], [156], [177]–[181]. In optical force-sensing technology, optical fibers play a role equivalent to that of the strain gauge. Optical force sensors function based on the changes in the property of light (wavelength and intensity) due to the strain created in the sensorized tool. Most of the optical fibers are biocompatible and sterilizable, and they are very thin in size, making them the perfect choice for force sensing. Optical fiber-based sensors can be attached to the body of the tool or to a reflective flexure mechanism to detect the deformation and translate that into force sensor readings. Earlier efforts, such as those described in [52], required embedding a reflective surface inside the flexure mechanism using which the applied forces are translated into changes in the intensity of the reflected light, which can be measured using light processing equipment placed outside the patient's body. More advanced technology, such as FBG, also requires a flexure mechanism and reflecting surfaces. This can significantly reduce the size of force sensing equipment and has been used to make 6-DOF optical force sensors for surgical robots, such as the DLR system [177], [182]. More examples can be found in [183]–[185] and have also been implemented on the da Vinci system [156], [186]. It should be mentioned that FBGs have significant benefits for force sensing in the surgical domain due to their high biocompatibility, sterilizability, low cost (the fibers are not expensive), and small size while providing highly accurate force measurements [187]. The design of a novel ultra-small optical fiber-based sensor that meets size constraints in minimally invasive surgical applications has been proposed in [178].

## VI. RECENT SURGICAL ROBOTIC SYSTEMS WITH HAPTIC CAPABILITIES

The challenges and considerations in designing a haptics-enabled surgical robotic system are summarized in Fig. 7. In this figure, "sensory substitution" could consist of one or more tactile, visual, and auditory information. The "direct feedback" could also be in the form of tactile feedback. As mentioned earlier, the most commonly used surgical robotic system, the da Vinci (from Intuitive Surgical Inc.), does not provide direct force/haptic feedback to the surgeon's console [57]. Although it has redundant sensors to measure joint kinematic values, it would be very challenging to provide redundant sensors for force

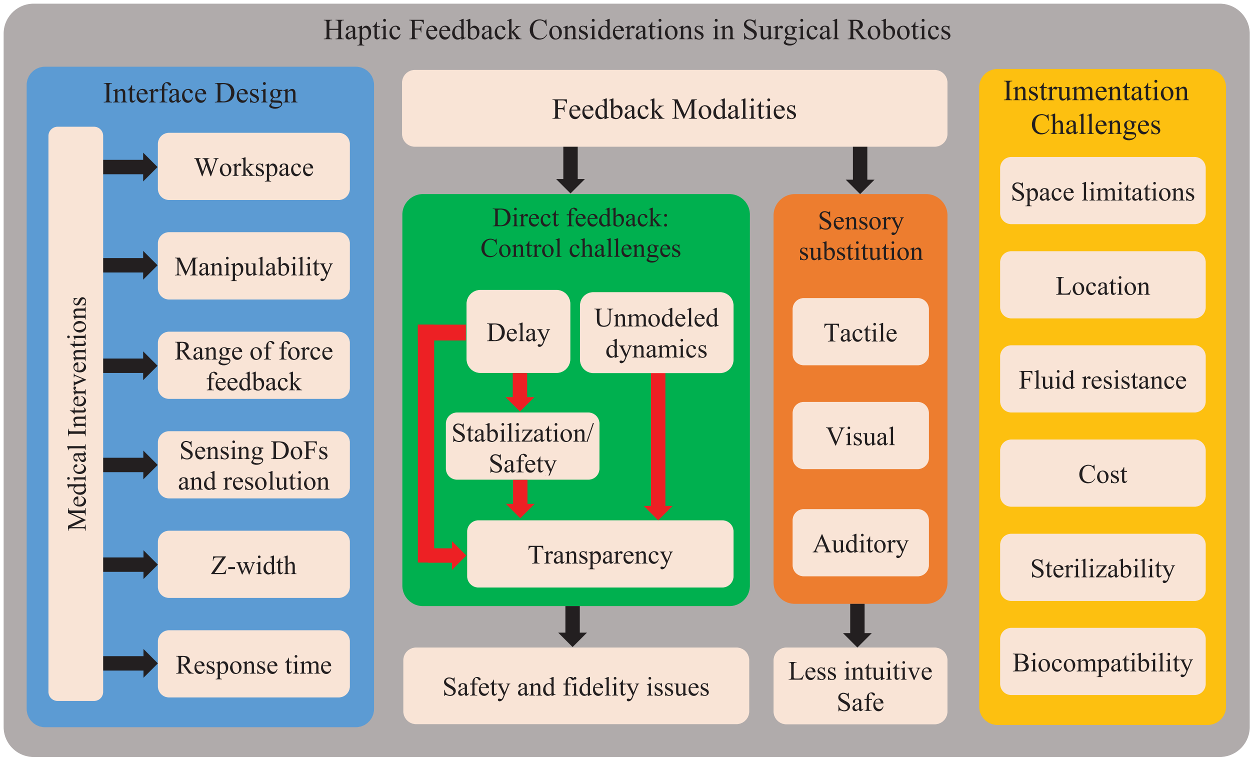


**Fig. 7.** *Summary of the design considerations and challenges for haptics-enabled surgical robotic systems with regard to interface design, feedback modalities, and instrumentation.*

measurements due to the very limited space, especially since the force information required would primarily be that of tool–tissue interaction. However, several research groups have reported work on introducing haptic or force feedback in the classic da Vinci (using the dVRK platform) (e.g., see [57] and [188]–[190] and references therein). This shows the feasibility of introducing haptic feedback in a leader–follower surgical system. A more recent surgical robotic platform with a similar leader–follower architecture as the da Vinci, the Senhance system from Asensus Surgical Inc. (formerly, TransEnterix), is capable of providing haptic feedback that reflects the forces generated during tool–tissue interaction by the patient-side robot arms. Some clinical experience with the use of the Senhance system has been reported in the literature [191]–[193]. In addition, the Senhance system enables the utilization of reusable forceps. However, in comparison to the da Vinci system, Senhance lacks in terms of accessories and instruments, such as articulated cutting, vessel sealer, integrated intraoperative ultrasonography, and infrared imaging [194]. The Senhance has recently been approved by FDA for laparoscopic gynecological and colorectal procedures. A discussion on other recent surgical robotic systems is given in [195]. The available information about the Senhance surgical system is limited in comparison to that of the da Vinci.

There are other examples of surgical robotic systems that have integrated off-the-shelf haptic devices as the surgeon's user interface. For instance, the Force Dimension Omega 7 haptic devices are used in the second generation of the NeuroArm surgical system [196]. Two haptic devices transfer the sense of touch to the two hands of a surgeon. This particular haptic device is from a series of devices from Force Dimension [197] that employs a small-footprint, parallel kinematic design enabling high levels of force feedback to the user if needed. Some of the Force Dimension devices, such as Sigma 7 and Omega 7, also provide large grasping force feedback, which can be useful in some surgical applications.

There are several other surgical robotic systems for specific applications that are or have been on the market and have been designed to provide some form of haptic feedback, e.g., the Versius system from CMR Surgical (Cambridge, U.K.), designed for upper GI, gynecological, colorectal, and renal surgeries and currently undergoing trials in Europe using a nonhaptic version of the system. The Mirosurge system [198], [199] from DLR has been designed to provide accurate haptic feedback during surgery, but the system has not yet received FDA approval.

## VII. CONCLUSION

This article discussed the history, current state, and technological issues with regard to the implementation of haptics in the robotics-assisted surgery. The possibility of enabling telerobotic surgical systems with force feedback to the surgeon was discussed. For this purpose, the current status of the available technology and the corresponding challenges were reviewed. Several major issues were identified, including stability of force-enabled telerobotic surgical systems, and instrumentation challenges, such as miniaturization, biocompatibility, sterilizability, and cost. Future research to address some of these challenges could benefit from the current intensive effort aimed at the design and development of intelligent algorithms, autonomous modules, and smart surgical tools. ■

## REFERENCES


[1] K. Moorthy *et al.*, "Dexterity enhancement with robotic surgery," *Surg. Endosc. Intervent. Techn.*, vol. 18, no. 5, pp. 790–795, 2004.

[2] J. C. Byrn *et al.*, "Three-dimensional imaging improves surgical performance for both novice and experienced operators using the da Vinci robot system," *Amer. J. Surg.*, vol. 193, no. 4, pp. 519–522, Apr. 2007.

[3] G. Spinoglio *et al.*, "Real-time near-infrared (NIR) fluorescent cholangiography in single-site robotic cholecystectomy (SSRC): A single-institutional prospective study," *Surgical Endoscopy*, vol. 27, no. 6, pp. 2156–2162, Jun. 2013.

[4] G.-P. Haber *et al.*, "Novel robotic da Vinci instruments for laparoendoscopic single-site surgery," *Urology*, vol. 76, no. 6, pp. 1279–1282, Dec. 2010.

[5] *Da Vinci*. Accessed: Sep. 12, 2021. [Online]. Available: https://www.intuitive.com/en-us/products-and-services/da-vinci

[6] J. Huang, Y. Li, and L. Huang, "Spine surgical robotics: Review of the current application and disadvantages for future perspectives," *J. Robotic Surg.*, vol. 14, no. 1, pp. 11–16, Feb. 2020.

[7] A. Attanasio, B. Scaglioni, E. D. Momi, P. Fiorini, and P. Valdastri, "Autonomy in surgical robotics," *Annu. Rev. Control, Robot., Auto. Syst.*, vol. 4, no. 1, pp. 651–679, May 2021.

[8] O. Khanna, R. Beasley, D. Franco, and S. DiMaio, "The path to surgical robotics in neurosurgery," *Operative Neurosurg.*, vol. 20, no. 6, pp. 514–520, Jun. 2021.

[9] *The First in Digital Laparoscopy*. Accessed: Oct. 3, 2021. [Online]. Available: https://www.senhance.com/us/digital-laparoscopy

[10] B. Hannaford and A. M. Okamura, "Haptics," in *Springer Handbook of Robotics*, 2nd ed., B. Siciliano and O. Khatib, Eds. Cham, Switzerland: Springer, 2016, pp. 1063–1084.

[11] D. Prattichizzo, C. Pacchierotti, and G. Rosati, "Cutaneous force feedback as a sensory subtraction technique in haptics," *IEEE Trans. Haptics*, vol. 5, no. 4, pp. 289–300, Apr. 2012.

[12] S.-C. Lim, H.-K. Lee, and J. Park, "Role of combined tactile and kinesthetic feedback in minimally invasive surgery," *Int. J. Med. Robot. Comput. Assist. Surg.*, vol. 11, no. 3, pp. 360–374, 2015.

[13] I. El Rassi and J.-M. El Rassi, "A review of haptic feedback in tele-operated robotic surgery," *J. Med. Eng. Technol.*, vol. 44, no. 5, pp. 247–254, Jul. 2020.

[14] G. Turchetti, I. Palla, F. Pierotti, and A. Cuschieri, "Economic evaluation of da Vinci-assisted robotic surgery: A systematic review," *Surgical Endoscopy*, vol. 26, no. 3, pp. 598–606, Mar. 2012.

[15] W. T. Lowrance *et al.*, "Contemporary open and robotic radical prostatectomy practice patterns among urologists in the United States," *J. Urol.*, vol. 187, no. 6, pp. 2087–2092, Jun. 2012.

[16] G. Gandaglia *et al.*, "Is robot-assisted radical prostatectomy safe in men with high-risk prostate cancer? Assessment of perioperative outcomes, positive surgical margins, and use of additional cancer treatments," *J. Endourol.*, vol. 28, no. 7, pp. 784–791, Jul. 2014.

[17] V. Trudeau *et al.*, "Robot-assisted versus laparoscopic nephroureterectomy for uppertract urothelial cancer: A population-based assessment of costs and perioperative outcomes," *Can. Urolog. Assoc. J.*, vol. 8, nos. 9–10, p. 695, Oct. 2014.

[18] S. J. Swanson *et al.*, "Comparing robot-assisted thoracic surgical lobectomy with conventional video-assisted thoracic surgical lobectomy and wedge resection: Results from a multihospital database (Premier)," *J. Thoracic Cardiovascular Surg.*, vol. 147, no. 3, pp. 929–937, Mar. 2014.

[19] *Center for Devices and Radiological Health (CDRH) Office of Surveillance and Biometrics (OSB) Medical Product Safety Network (MedSun) Small Sample Survey Final Report Topic: Da Vinci Surgical System*, U.S. Food and Administration, Silver Spring, MD, USA, Nov. 2013.

[20] J. K. Koehn and K. J. Kuchenbecker, "Surgeons and non-surgeons prefer haptic feedback of instrument vibrations during robotic surgery," *Surg. Endoscopy*, vol. 29, no. 10, pp. 2970–2983, 2015.

[21] E. Abdi, D. Kuli, and E. Croft, "Haptics in teleoperated medical interventions: Force measurement, haptic interfaces and their influence on user's performance," *IEEE Trans. Biomed. Eng.*, vol. 67, no. 12, pp. 3438–3451, Dec. 2020.

[22] G. P. Fettweis, "The tactile internet: Applications and challenges," *IEEE Veh. Technol. Mag.*, vol. 9, no. 1, pp. 64–70, Mar. 2014.

[23] D. A. Meshram and D. D. Patil, "5G enabled tactile internet for tele-robotic surgery," *Proc. Comput. Sci.*, vol. 171, pp. 2618–2625, Jan. 2020.

[24] Y. Miao, Y. Jiang, L. Peng, M. S. Hossain, and G. Muhammad, "Telesurgery robot based on 5G tactile internet," *Mobile Netw. Appl.*, vol. 23, no. 6, pp. 1645–1654, Dec. 2018.

[25] R. Gupta, S. Tanwar, S. Tyagi, and N. Kumar, "Tactile-internet-based telesurgery system for healthcare 4.0: An architecture, research challenges, and future directions," *IEEE Netw.*, vol. 33, no. 6, pp. 22–29, Nov. 2019.

[26] R. K. Kochhar. *The 5G Tactile Internet is Here. What Next*. Ericsson. Accessed: Jan. 2020. [Online]. Available: https://www.ericsson.com/en/blog/2019/4/5g-tactile-internet

[27] C. R. Wottawa *et al.*, "Evaluating tactile feedback in robotic surgery for potential clinical application using an animal model," *Surg. Endoscopy*, vol. 30, no. 8, pp. 3198–3209, 2016.

[28] C. Freschi, V. Ferrari, F. Melfi, M. Ferrari, F. Mosca, and A. Cuschieri, "Technical review of the da Vinci surgical telemanipulator," *Int. J. Med. Robot. Comput. Assist. Surg.*, vol. 9, no. 4, pp. 396–406, 2013.

[29] O. A. J. van der Meijden and M. P. Schijven, "The value of haptic feedback in conventional and robot-assisted minimal invasive surgery and virtual reality training: A current review," *Surgical Endosc.*, vol. 23, no. 6, pp. 1180–1190, 2009.

[30] M. Kitagawa, A. M. Okamura, B. T. Bethea, V. L. Gott, and W. A. Baumgartner, "Analysis of suture manipulation forces for teleoperation with force feedback," in *Medical Image Computing and Computer-Assisted Intervention (MICCAI)* (Lecture Notes in Computer Science), vol. 2488. Berlin, Germany: Springer, 2002, pp. 155–162.

[31] A. Talasaz, A. L. Trejos, and R. V. Patel, "Effect of force feedback on performance of robotics-assisted suturing," in *Proc. 4th IEEE RAS EMBS Int. Conf. Biomed. Robot. Biomechtron. (BioRob)*, Jun. 2012, pp. 823–828.

[32] A. S. Naidu, R. V. Patel, and M. D. Naish, "Low-cost disposable tactile sensors for palpation in minimally invasive surgery," *IEEE/ASME Trans. Mechatronics*, vol. 22, no. 1, pp. 127–137, Feb. 2017.

[33] C. R. Wagner, N. Stylopoulos, and R. D. Howe, "The role of force feedback in surgery: Analysis of blunt dissection," in *Proc. 10th Symp. Haptic Interface Virtual Environ. Teleoperator Syst. HAPTICS*, Mar. 2002, p. 73.

[34] A. Talasaz, A. L. Trejos, and R. V. Patel, "The role of direct and visual force feedback in suturing using a 7-DOF dual-arm teleoperated system," *IEEE Trans. Haptics*, vol. 10, no. 2, pp. 276–287, Apr. 2017.

[35] M. Kitagawa, D. Dokko, A. M. Okamura, and D. D. Yuh, "Effect of sensory substitution on suture-manipulation forces for robotic surgical systems," *J. Thoracic Cardiovascular Surg.*, vol. 129, no. 1, pp. 151–158, Jan. 2005.

[36] S. F. Atashzar, M. Naish, and R. V. Patel, "Active sensorimotor augmentation in robotics-assisted surgical systems," in *Mixed and Augmented Reality in Medicine*. Boca Raton, FL, USA: CRC Press, 2018, pp. 61–81.

[37] A. Trejos, R. Patel, and M. Naish, "Force sensing and its application in minimally invasive surgery and therapy: A survey," *Proc. Inst. Mech. Eng. C, J. Mech. Eng. Sci.*, vol. 224, no. 7, pp. 1435–1454, 2010.

[38] E. Westebring-Van-Der-Putten, R. Goossens, J. J. Jakimowicz, and J. Dankelman, "Haptics in minimally invasive surgery–A review," *Minimally Invasive Therapy*, vol. 17, no. 1, pp. 3–16, 2008.

[39] A. M. Okamura, "Methods for haptic feedback in teleoperated robot-assisted surgery," *Ind. Robot, Int. J.*, vol. 31, no. 6, pp. 499–508, 2004.

[40] L. Toledo, D. Gossot, S. Fritsch, Y. Revillon, and C. Reboulet, "Study of sustained forces and the working space of endoscopic surgery instruments," *Ann. Chir.*, vol. 53, no. 7, pp. 587–597, 1999.

[41] C. E. Reiley, T. Akinbiyi, D. Burschka, D. C. Chang, A. M. Okamura, and D. D. Yuh, "Effects of visual force feedback on robot-assisted surgical task performance," *J. Thoracic Cardiovascular Surg.*, vol. 135, no. 1, pp. 196–202, Jan. 2008.

[42] D. Ricchiuti, J. Cerone, S. Shie, A. Jetley, D. Noe, and M. Kovacik, "Diminished suture strength after robotic needle driver manipulation," *J. Endourol.*, vol. 24, no. 9, pp. 1509–1513, Sep. 2010.

[43] B. Weber and S. Schneider, "The effects of force feedback on surgical task performance: A meta-analytical integration," in *Haptics: Neuroscience, Devices, Modeling, and Applications*. Berlin, Germany: Springer, 2014, pp. 150–157.

[44] S. Kaul, N. L. Shah, and M. Menon, "Learning curve using robotic surgery," *Current Urol. Rep.*, vol. 7, no. 2, pp. 125–129, Apr. 2006.

[45] M. E. Hagen, J. J. Meehan, I. Inan, and P. Morel, "Visual clues act as a substitute for haptic feedback in robotic surgery," *Surgical Endoscopy*, vol. 22, no. 6, pp. 1505–1508, Jun. 2008.

[46] A. M. Sabatini, M. Bergamasco, and P. Dario, "Force feedback-based telemicromanipulation for robot surgery on soft tissues," in *Proc. Images 21st Century. Proc. Annu. Int. Eng. Med. Biol. Soc.*, Nov. 2003, pp. 890–891.

[47] A. M. Okamura, L. N. Verner, C. E. Reiley, and M. Mahvash, "Haptics for robot-assisted minimally invasive surgery," in *Springer Tracts in Advanced Robotics*. Berlin, Germany: Springer, 2010, pp. 361–372.

[48] M. Tavakoli, R. V. Patel, and M. Moallem, "Haptic interaction in robot-assisted endoscopic surgery: A sensorized end-effector," *Int. J. Med. Robot. Comput. Assist. Surg.*, vol. 1, no. 2, pp. 53–63, 2005.

[49] M. Tavakoli, A. Aziminejad, R. V. Patel, and

M. Moallem, "High-fidelity bilateral teleoperation systems and the effect of multimodal haptics," *IEEE Trans. Syst., Man, Cybern. B. Cybern.*, vol. 37, no. 6, pp. 1512–1528, Dec. 2007.

[50] A. Simorov, R. S. Otte, C. M. Kopietz, and D. Oleynikov, "Review of surgical robotics user interface: What is the best way to control robotic surgery?" *Surgical Endoscopy*, vol. 26, no. 8, pp. 2117–2125, Aug. 2012.

[51] V. Chawda and M. K. O'Malley, "Position synchronization in bilateral teleoperation under time-varying communication delays," *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 1, pp. 245–253, Feb. 2015.

[52] J. Peirs *et al.*, "A micro optical force sensor for force feedback during minimally invasive robotic surgery," *Sens. Actuators A, Phys.*, vol. 115, no. 2, pp. 447–455, 2004.

[53] C. R. Wagner and R. D. Howe, "Force feedback benefit depends on experience in multiple degree of freedom robotic surgery task," *IEEE Trans. Robot.*, vol. 23, no. 6, pp. 1235–1240, Dec. 2007.

[54] M. M. Dalvand, B. Shirinzadeh, S. Nahavandi, and J. Smith, "Effects of realistic force feedback in a robotic assisted minimally invasive surgery system," *Minimally Invasive Therapy Allied Technol.*, vol. 23, no. 3, pp. 127–135, 2014.

[55] B. T. Bethea *et al.*, "Application of haptic feedback to robotic surgery," *J. Laparoendoscopic Adv. Surgical Techn.*, vol. 14, no. 3, pp. 191–195, Jan. 2004.

[56] A. Talasaz and R. V. Patel, "Integration of force reflection with tactile sensing for minimally invasive robotics-assisted tumor localization," *IEEE Trans. Haptics*, vol. 6, no. 2, pp. 217–228, Apr. 2013.

[57] S. Mehrdad, F. Liu, M. T. Pham, A. Lelevé, and S. F. Atashzar, "Review of advanced medical telerobots," *Appl. Sci.*, vol. 11, no. 1, p. 209, Dec. 2020.

[58] D. A. Lawrence, "Stability and transparency in bilateral teleoperation," *IEEE Trans. Robot. Autom.*, vol. 9, no. 5, pp. 624–637, Oct. 1993.

[59] A. Aziminejad, M. Tavakoli, R. V. Patel, and M. Moallem, "Stability and performance in delayed bilateral teleoperation: Theory and experiments," *Control Eng. Pract.*, vol. 16, no. 11, pp. 1329–1343, Nov. 2008.

[60] M. Tavakoli, A. Aziminejad, R. V. Patel, and M. Moallem, "Discrete-time bilateral teleoperation: Modelling and stability analysis," *IET Control Theory Appl.*, vol. 2, no. 6, pp. 496–512, Jun. 2008.

[61] H. K. Khalil, *Nonlinear Systems*, 3rd ed. Upper Saddle River, NJ, USA: Prentice-Hall, 2002.

[62] F. Anooshahpour, I. G. Polushin, and R. V. Patel, "Classical Preisach model of hysteretic behavior in a da Vinci instrument," in *Proc. IEEE Int. Conf. Adv. Intell. Mechatronics (AIM)*, Jul. 2016, pp. 1392–1397.

[63] F. Anooshahpour, P. Yadmellat, I. G. Polushin, and R. V. Patel, "A motion transmission model for a class of tendon-based mechanisms with application to position tracking of the da Vinci instrument," *IEEE/ASME Trans. Mechatronics*, vol. 24, no. 2, pp. 538–548, Apr. 2019.

[64] M. C. Cavusoglu, I. Villanueva, and F. Tendick, "Workspace analysis of robotic manipulators for a teleoperated suturing task," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. Expanding Societal Role Robot. Next Millennium*, Nov. 2001, pp. 2234–2239.

[65] A. A. Thakre, Y. Bailly, L. W. Sun, F. Van Meer, and C. K. Yeung, "Is smaller workspace a limitation for robot performance in laparoscopy?" *J. Urol.*, vol. 179, no. 3, pp. 1138–1142, Mar. 2008.

[66] A. Torabi, M. Khadem, K. Zareinia, G. R. Sutherland, and M. Tavakoli, "Using a redundant user interface in teleoperated surgical systems for task performance enhancement," *Robotica*, vol. 38, no. 10, pp. 1880–1894, Oct. 2020.

[67] S. M. Prasad, S. M. Prasad, H. S. Maniar, C. Chu, R. B. Schuessler, and R. J. Damiano, "Surgical robotics: Impact of motion scaling on task performance," *J. Amer. College Surgeons*, vol. 199, no. 6, pp. 863–868, Dec. 2004.

[68] S. E. Salcudean and J. Yan, "Towards a force-reflecting motion-scale system for microsurgery," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 1994, pp. 2296–2301.

[69] T. Yoshikawa, "Manipulability of robotic mechanisms," *Int. J. Robot. Res.*, vol. 4, no. 2, pp. 3–9, 1985.

[70] A. Torabi, M. Khadem, K. Zareinia, G. R. Sutherland, and M. Tavakoli, "Manipulability of teleoperated surgical robots with application in design of master/slave manipulators," in *Proc. Int. Symp. Med. Robot. (ISMR)*, Mar. 2018, pp. 1–6.

[71] H. S. Bassan, R. V. Patel, and M. Moallem, "A novel manipulator for percutaneous needle insertion: Design and experimentation," *IEEE/ASME Trans. Mechatronics*, vol. 14, no. 6, pp. 746–761, Dec. 2009.

[72] A. Torabi, M. Khadem, K. Zareinia, G. R. Sutherland, and M. Tavakoli, "Application of a redundant haptic interface in enhancing soft-tissue stiffness discrimination," *IEEE Robot. Autom. Lett.*, vol. 4, no. 2, pp. 1037–1044, Apr. 2019.

[73] M. O. Culjat *et al.*, "A tactile feedback system for robotic surgery," in *Proc. 30th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Aug. 2008, pp. 1930–1934.

[74] U. Kim, D.-H. Lee, W. J. Yoon, B. Hannaford, and H. R. Choi, "Force sensor integrated surgical forceps for minimally invasive robotic surgery," *IEEE Trans. Robot.*, vol. 31, no. 5, pp. 1214–1224, Oct. 2015.

[75] J. Rosen, J. D. Brown, S. De, M. Sinanan, and B. Hannaford, "Biomechanical properties of abdominal organs *in vivo* and postmortem under compression loads," *J. Biomech. Eng.*, vol. 130, no. 2, Apr. 2008, Art. no. 021020.

[76] H. Kolbari, S. Sadeghnejad, M. Bahrami, and K. E. Ali, "Adaptive control of a robot-assisted tele-surgery in interaction with hybrid tissues," *J. Dyn. Syst., Meas., Control*, vol. 140, no. 12, Dec. 2018, Art. no. 121012.

[77] M. Lazeroms, G. Villavicencio, W. Jongkind, and G. Honderd, "Optical fibre force sensor for minimal-invasive-surgery grasping instruments," in *Proc. 18th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Nov. 2002, pp. 234–235.

[78] T. H. Massie, J. K. Salisbury, and Others, "The phantom haptic interface: A device for probing virtual objects," in *Proc. ASME Winter Annu. Meeting, Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst.*, vol. 55, 1994, pp. 295–300.

[79] K. Hashtrudi-Zaad and S. E. Salcudean, "Analysis of control architectures for teleoperation systems with impedance/admittance master and slave manipulators," *Int. J. Robot. Res.*, vol. 20, no. 6, pp. 419–445, 2001.

[80] B. Khademian and K. Hashtrudi-Zaad, "A four-channel multilateral shared control architecture for dual-user teleoperation systems," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Oct. 2007, pp. 2660–2666.

[81] J. E. Colgate and J. M. Brown, "Factors affecting the Z-width of a haptic display," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 2002, pp. 3205–3210.

[82] B. Khademian and K. Hashtrudi-Zaad, "Dual-user teleoperation systems: New multilateral shared control architecture and kinesthetic performance measures," *IEEE/ASME Trans. Mechatronics*, vol. 17, no. 5, pp. 895–906, Oct. 2012.

[83] G. A. V. Christiansson, R. Q. V. D. Linde, and F. C. T. V. D. Helm, "The influence of teleoperator stiffness and damping on object discrimination," *IEEE Trans. Robot.*, vol. 24, no. 5, pp. 1252–1256, Oct. 2008.

[84] N. Najmaei, A. Asadian, M. R. Kermani, and R. V. Patel, "Design and performance evaluation of a prototype MRF-based haptic interface for medical applications," *IEEE/ASME Trans. Mechatronics*, vol. 21, no. 1, pp. 110–121, Feb. 2016.

[85] M. C. Çavuşoğlu, W. Williams, F. Tendick, and S. S. Sastry, "Robotics for telesurgery: Second generation Berkeley/UCSF laparoscopic telesurgical workstation and looking towards the future applications," *Ind. Robot, Int. J.*, vol. 30, no. 1, pp. 22–29, 2003.

[86] S. Shimmyo, Y. Saito, T. Nozaki, and K. Ohnishi, "Bandwidth expansion of bilateral teleoperation based on synergy of observer gain and velocity feedback gain," in *Proc. IECON 45th Annu. Conf. IEEE Ind. Electron. Soc.*, Oct. 2019, pp. 3597–3602.

[87] H. Singh, A. Jafari, A. Peer, and J.-H. Ryu, "Enhancing the command-following bandwidth for transparent bilateral teleoperation," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Oct. 2018, pp. 4972–4979.

[88] A. E. Kirkpatrick and S. A. Douglas, "Application-based evaluation of haptic interfaces," in *Proc. 10th Symp. Haptic Interface Virtual Environ. Teleoperator Syst. HAPTICS*, Mar. 2002, pp. 32–39.

[89] A. Abiri *et al.*, "Multi-modal haptic feedback for grip force reduction in robotic surgery," *Sci. Rep.*, vol. 9, no. 1, p. 5016, Mar. 2019.

[90] K. Hashtrudi-Zaad and S. E. Salcudean, "Transparency in time-delayed systems and the effect of local force feedback for transparent teleoperation," *IEEE Trans. Robot. Autom.*, vol. 18, no. 1, pp. 108–114, Feb. 2002.

[91] E. Naerum and B. Hannaford, "Global transparency analysis of the Lawrence teleoperator architecture," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 2009, pp. 4344–4349.

[92] S. F. Atashzar, I. G. Polushin, and R. V. Patel, "A small-gain approach for nonpassive bilateral telerobotic rehabilitation: Stability analysis and controller synthesis," *IEEE Trans. Robot.*, vol. 33, no. 1, pp. 49–66, Feb. 2017.

[93] S. F. Atashzar, M. Shahbazi, M. Tavakoli, and R. V. Patel, "A passivity-based approach for stable patient–robot interaction in haptics-enabled rehabilitation systems: Modulated time-domain passivity control," *IEEE Trans. Control Syst. Technol.*, vol. 25, no. 3, pp. 991–1006, May 2017.

[94] S. F. Atashzar, M. Shahbazi, M. Tavakoli, and R. V. Patel, "A grasp-based passivity signature for haptics-enabled human-robot interaction: Application to design of a new safety mechanism for robotic rehabilitation," *Int. J. Robot. Res.*, vol. 36, nos. 5–7, pp. 778–799, Jun. 2017.

[95] S. Thudi and S. F. Atashzar, "Discrete windowed-energy variable structure passivity signature control for physical human-(Tele)Robot interaction," *IEEE Robot. Autom. Lett.*, vol. 6, no. 2, pp. 3647–3654, Apr. 2021.

[96] S. F. Atashzar, M. Shahbazi, H. A. Talebi, and R. V. Patel, "Control of time-delayed telerobotic systems with flexible-link slave manipulators," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Oct. 2012, pp. 3035–3040.

[97] G. R. Sutherland, P. B. McBeth, and D. F. Louw, "NeuroArm: An MR compatible robot for microsurgery," *Int. Congr. Ser.*, vol. 1256, pp. 504–508, Jun. 2003.

[98] M. Tavakoli, R. V. Patel, M. Moallen, and A. Aziminejad, *Haptics For Teleoperated Surgical Robotic Systems*. Singapore: World Scientific, 2008.

[99] A. Milstein, T. Ganel, S. Berman, and I. Nisky, "Human-centered transparency of grasping via a robot-assisted minimally invasive surgery system," *IEEE Trans. Human-Mach. Syst.*, vol. 48, no. 4, pp. 349–358, Aug. 2018.

[100] Z. Chua and A. M. Okamura, "Characterization of real-time haptic feedback from multimodal neural network-based force estimates during teleoperation," 2021, *arXiv:2109.11488*.

[101] R. Rayman *et al.*, "Effects of latency on telesurgery: An experimental study," *Med. Image Comput. Comput. Assist. Interv.*, vol. 8, no. 2, pp. 57–64, 2005.

[102] R. Rayman *et al.*, "Robotic telesurgery: A real-world comparison of ground- and satellite-based internet performance," *Int. J. Med. Robot. Comput. Assist. Surg.*, vol. 3, no. 2, pp. 111–116, Jun. 2007.

[103] C. Nguan, B. Miller, R. Patel, P. P. Luke, and C. M. Schlachta, "Pre-clinical remote telesurgery trial of a da Vinci telesurgery prototype," *Int. J. Med. Robot. Comput. Assist. Surg.*, vol. 4, no. 4, pp. 304–309, Dec. 2008.

[104] J. Marescaux *et al.*, "Transcontinental robot-assisted remote telesurgery: Feasibility and potential applications," *Ann. Surg.*, vol. 235, no. 4, pp. 487–492, 2002.

[105] R. Rayman *et al.*, "Long-distance robotic telesurgery: A feasibility study for care in remote environments," *Int. J. Med. Robot. Comput. Assist. Surg.*, vol. 2, no. 3, pp. 216–224, Sep. 2006.

[106] M. Anvari, C. McKinley, and H. Stein, "Establishment of the world's first telerobotic remote surgical service: For provision of advanced laparoscopic surgery in a rural community," *Ann. Surg.*, vol. 241, no. 3, pp. 460–464, Mar. 2005.

[107] I. Nisky, F. A. Mussa-Ivaldi, and A. Karniel, "A regression and boundary-crossing-based model for the perception of delayed stiffness," *IEEE Trans. Haptics*, vol. 1, no. 2, pp. 73–82, Jul. 2008.

[108] A. Pressman, L. J. Welty, A. Karniel, and F. A. Mussa-Ivaldi, "Perception of delayed stiffness," *Int. J. Robot. Res.*, vol. 26, nos. 11–12, pp. 1191–1203, Nov. 2007.

[109] S. E. Salcudean, M. Zhu, M.-H. Zhu, and K. Hashtrudi-Zaad, "Teleoperation under position and rate," *Int. J. Rob. Res.*, vol. 19, no. 12, pp. 1185–1202, 2000.

[110] A. Haddadi and K. Hashtrudi-Zaad, "Bounded-impedance absolute stability of bilateral teleoperation control systems," *IEEE Trans. Haptics*, vol. 3, no. 1, pp. 15–27, Jan. 2010.

[111] H. C. Cho and J. H. Park, "Stable bilateral teleoperation under a time delay using a robust impedance control," *Mechatronics*, vol. 15, no. 5, pp. 611–625, Jun. 2005.

[112] A. Jazayeri and M. Tavakoli, "Absolute stability analysis of sampled-data scaled bilateral teleoperation systems," *Control Eng. Pract.*, vol. 21, no. 8, pp. 1053–1064, Aug. 2013.

[113] A. Aziminejad, M. Tavakoli, R. V. Patel, and M. Moallem, "Transparent time-delayed bilateral teleoperation using wave variables," *IEEE Trans. Control Syst. Technol.*, vol. 16, no. 3, pp. 548–555, May 2008.

[114] J. J. Abbott and A. M. Okamura, "Effects of position quantization and sampling rate on virtual-wall passivity," *IEEE Trans. Robot.*, vol. 21, no. 5, pp. 952–964, Oct. 2005.

[115] Y. Ye and P. X. Liu, "Improving trajectory tracking in wave-variable-based teleoperation," *IEEE/ASME Trans. Mechatronics*, vol. 15, no. 2, pp. 321–326, Apr. 2010.

[116] D. Sun, F. Naghdy, and H. Du, "Application of wave-variable control to bilateral teleoperation systems: A survey," *Annu. Rev. Control*, vol. 38, no. 1, pp. 12–31, 2014.

[117] J.-H. Ryu, D.-S. Kwon, and B. Hannaford, "Stable teleoperation with time-domain passivity control," *IEEE Trans. Robot. Autom.*, vol. 20, no. 2, pp. 365–373, Apr. 2004.

[118] J.-H. Ryu, C. Preusche, B. Hannaford, and G. Hirzinger, "Time domain passivity control with reference energy following," *IEEE Trans. Control Syst. Technol.*, vol. 13, no. 5, pp. 737–742, Sep. 2005.

[119] H. Li and K. Kawashima, "Bilateral teleoperation with delayed force feedback using time domain passivity controller," *Robot. Comput.-Integr. Manuf.*, vol. 37, pp. 188–196, Feb. 2016.

[120] J. Rebelo and A. Schiele, "Time domain passivity controller for 4-channel time-delay bilateral teleoperation," *IEEE Trans. Haptics*, vol. 8, no. 1, pp. 79–89, Jan. 2015.

[121] F. M. Callier, "Dissipative systems analysis and control: Theory and applications (2nd edition)-[book review; B. Brogliato, R. Lozano, B. Maschke]," *IEEE Trans. Autom. Control*, vol. 52, no. 7, pp. 1357–1358, Jul. 2007.

[122] P. F. Hokayem and M. W. Spong, "Bilateral teleoperation: An historical survey," *Automatica*, vol. 42, no. 12, pp. 2035–2057, Dec. 2006.

[123] H. K. Khalil and J. Grizzle, *Nonlinear Systems*, vol. 3. Upper Saddle River, NJ, USA: Prentice-Hall, 1996.

[124] D. Lee and M. W. Spong, "Passive bilateral teleoperation with constant time delay," *IEEE Trans. Robot.*, vol. 22, no. 2, pp. 269–281, Apr. 2006.

[125] S. Munir and W. J. Book, "Internet-based teleoperation using wave variables with prediction," *IEEE/ASME Trans. Mechatronics*, vol. 7, no. 2, pp. 124–133, Jun. 2002.

[126] J.-H. Ryu, J. Artigas, and C. Preusche, "A passive bilateral control scheme for a teleoperator with time-varying communication delay," *Mechatronics*, vol. 20, no. 7, pp. 812–823, 2010.

[127] I. G. Polushin, X. P. Liu, and C.-H. Lung, "Stability of bilateral teleoperators with generalized projection-based force reflection algorithms," *Automatica*, vol. 48, no. 6, pp. 1005–1016, Jun. 2012.

[128] I. Polushin, H. J. Marquez, A. Tayebi, and P. X. Liu, "A multichannel IOS small gain theorem for systems with multiple time-varying communication delays," *IEEE Trans. Autom. Control*, vol. 54, no. 2, pp. 404–409, Feb. 2009.

[129] I. G. Polushin, S. N. Dashkovskiy, A. Takhmar, and R. V. Patel, "A small gain framework for networked cooperative force-reflecting teleoperation," *Automatica*, vol. 49, no. 2, pp. 338–348, 2013.

[130] I. G. Polushin, "A generalization of the scattering transformation for conic systems," *IEEE Trans. Autom. Control*, vol. 59, no. 7, pp. 1989–1995, Jul. 2014.

[131] A. Jazayeri and M. Tavakoli, "Bilateral teleoperation system stability with non-passive and strictly passive operator or environment," *Control Eng. Pract.*, vol. 40, pp. 45–60, Jul. 2015.

[132] I. G. Polushin, A. Takhmar, and R. V. Patel, "Projection-based force-reflection algorithms with frequency separation for bilateral teleoperation," *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 1, pp. 143–154, Feb. 2015.

[133] N. Chopra, M. W. Spong, and R. Lozano, "Synchronization of bilateral teleoperators with time delay," *Automatica*, vol. 44, no. 8, pp. 2142–2148, 2008.

[134] E. Nuño, L. Basañez, and R. Ortega, "Passivity-based control for bilateral teleoperation: A tutorial," *Automatica*, vol. 47, no. 3, pp. 485–495, Mar. 2011.

[135] F. Hashemzadeh, I. Hassanzadeh, M. Tavakoli, and G. Alizadeh, "Adaptive control for state synchronization of nonlinear haptic telerobotic systems with asymmetric varying time delays," *J. Intell. Robotic Syst.*, vol. 68, nos. 3–4, pp. 245–259, Dec. 2012.

[136] S. Islam, P. X. Liu, A. El Saddik, and Y. B. Yang, "Bilateral control of teleoperation systems with time delay," *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 1, pp. 1–12, Feb. 2015.

[137] C. Hua, Y. Yang, and P. X. Liu, "Output-feedback adaptive control of networked teleoperation system with time-varying delay and bounded inputs," *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 5, pp. 2009–2020, Oct. 2015.

[138] J. Artigas, J.-H. Ryu, and C. Preusche, "Position drift compensation in time domain passivity based teleoperation," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Oct. 2010, pp. 4250–4256.

[139] Y. Ye, Y.-J. Pan, and T. Hilliard, "Bilateral teleoperation with time-varying delay: A communication channel passification approach," *IEEE/ASME Trans. Mechatronics*, vol. 18, no. 4, pp. 1431–1434, Aug. 2013.

[140] N. A. Tanner and G. Niemeyer, "Improving perception in time-delayed telerobotics," *Int. J. Robot. Res.*, vol. 24, no. 8, pp. 631–644, 2005.

[141] I. G. Polushin, P. X. Liu, and C.-H. Lung, "A force-reflection algorithm for improved transparency in bilateral teleoperation with communication delay," *IEEE/ASME Trans. Mechatronics*, vol. 12, no. 3, pp. 361–374, Jun. 2007.

[142] A. Haddadi, K. Razi, and K. Hashtrudi-Zaad, "Operator dynamics consideration for less conservative coupled stability condition in bilateral teleoperation," *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 5, pp. 2463–2475, Oct. 2015.

[143] R. Sigrist, G. Rauter, R. Riener, and P. Wolf, "Augmented visual, auditory, haptic, and multimodal feedback in motor learning: A review," *Psychon. Bull. Rev.*, vol. 20, no. 1, pp. 21–53, Feb. 2013.

[144] F. Sanfilippo and C. Pacchierotti, "A low-cost multi-modal auditory-visual-tactile framework for remote touch," in *Proc. 3rd Int. Conf. Inf. Comput. Technol. (ICICT)*, Mar. 2020, pp. 213–218.

[145] J. D. Brown, J. N. Fernandez, S. P. Cohen, and K. J. Kuchenbecker, "A wrist-squeezing force-feedback system for robotic surgery training," in *Proc. IEEE World Haptics Conf. (WHC)*, Jun. 2017, pp. 107–112.

[146] C. Pacchierotti, D. Prattichizzo, and K. J. Kuchenbecker, "Cutaneous feedback of fingertip deformation and vibration for palpation in robotic surgery," *IEEE Trans. Biomed. Eng.*, vol. 63, no. 2, pp. 278–287, Feb. 2016.

[147] M. E. Currie *et al.*, "The role of visual and direct force feedback in robotics-assisted mitral valve annuloplasty," *Int. J. Med. Robot. Comput. Assist. Surg.*, vol. 13, no. 3, Sep. 2017, Art. no. e1787.

[148] Z. F. Quek, S. B. Schorr, I. Nisky, W. R. Provancher, and A. M. Okamura, "Sensory substitution and augmentation using 3-degree-of-freedom skin deformation feedback," *IEEE Trans. Haptics*, vol. 8, no. 2, pp. 209–221, Apr. 2015.

[149] S. B. Schorr, Z. F. Quek, I. Nisky, W. R. Provancher, and A. M. Okamura, "Tactor-induced skin stretch as a sensory substitution method in teleoperated palpation," *IEEE Trans. Human-Mach. Syst.*, vol. 45, no. 6, pp. 714–726, Dec. 2015.

[150] S. M. Sketch, D. R. Deo, J. P. Menon, and A. M. Okamura, "Design and experimental evaluation of a skin-stretch haptic device for improved control of brain-computer interfaces," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2015, pp. 272–277.

[151] Z. F. Quek, S. B. Schorr, I. Nisky, A. M. Okamura, and W. R. Provancher, "Augmentation of stiffness perception with a 1-degree-of-freedom skin stretch device," *IEEE Trans. Human-Mach. Syst.*, vol. 44, no. 6, pp. 731–742, Dec. 2014.

[152] Z. F. Quek, S. B. Schorr, I. Nisky, A. M. Okamura, and W. R. Provancher, "Sensory augmentation of stiffness using fingerpad skin stretch," in *Proc. World Haptics Conf. (WHC)*, Apr. 2013, pp. 467–472.

[153] S. B. Schorr, Z. F. Quek, R. Y. Romano, I. Nisky, W. R. Provancher, and A. M. Okamura, "Sensory substitution via cutaneous skin stretch feedback," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 2013, pp. 2341–2346.

[154] L. Meli, C. Pacchierotti, and D. Prattichizzo, "Sensory subtraction in robot-assisted surgery: Fingertip skin deformation feedback to ensure safety and improve transparency in bimanual haptic interaction," *IEEE Trans. Biomed. Eng.*, vol. 61, no. 4, pp. 1318–1327, Apr. 2014.

[155] A. Giannini *et al.*, "Wearable haptic interfaces for applications in gynecologic robotic surgery: A proof of concept in robotic myomectomy," *J. Robot. Surg.*, vol. 13, no. 4, pp. 585–588, 2019.

[156] K. S. Shahzada, A. Yurkewich, R. Xu, and R. V. Patel, "Sensorization of a surgical robotic instrument for force sensing," *Proc. SPIE*, vol. 9702, pp. 153–162, Mar. 2016.

[157] A. Srivastava, R. Xu, A. Escoto, C. Ward, and R. V. Patel, "Design of an ultra thin strain sensor using superelastic nitinol for applications in

minimally invasive surgery," in *Proc. IEEE Int. Conf. Adv. Intell. Mechatronics (AIM)*, Jul. 2016, pp. 794–799.

[158] A. Talasaz, A. L. Trejos, S. Perreault, H. Bassan, and R. V. Patel, "A dual-arm 7-degrees-of-freedom haptics-enabled teleoperation test bed for minimally invasive surgery," *J. Med. Devices*, vol. 8, no. 4, Dec. 2014, Art. no. 041004.

[159] U. Seibold, B. Kubler, and G. Hirzinger, "Prototype of instrument for minimally invasive surgery with 6-axis force sensing capability," in *Proc. IEEE Int. Conf. Robot. Autom.*, Apr. 2006, pp. 496–501.

[160] H.-R. Choi, D.-H. Lee, U. Kim, T. Gulrez, W. J. Yoon, and B. Hannaford, "A laparoscopic grasping tool with force sensing capability," *IEEE/ASME Trans. Mechatronics*, vol. 21, no. 1, pp. 130–141, Feb. 2015.

[161] M. Beccani, C. Di Natali, L. J. Sliker, J. A. Schoen, M. E. Rentschler, and P. Valdastri, "Wireless tissue palpation for intraoperative detection of lumps in the soft tissue," *IEEE Trans. Biomed. Eng.*, vol. 61, no. 2, pp. 353–361, Feb. 2014.

[162] P. Puangmali, K. Althoefer, L. D. Seneviratne, D. Murphy, and P. Dasgupta, "State-of-the-art in force and tactile sensing for minimally invasive surgery," *IEEE Sensors J.*, vol. 8, no. 4, pp. 371–381, Apr. 2008.

[163] A. Marban, V. Srinivasan, W. Samek, J. Fernández, and A. Casals, "A recurrent convolutional neural network approach for sensorless force estimation in robotic surgery," *Biomed. Signal Process. Control*, vol. 50, pp. 134–150, Apr. 2019.

[164] W.-J. Jung, K.-S. Kwak, and S.-C. Lim, "Vision-based suture tensile force estimation in robotic surgery," *Sensors*, vol. 21, no. 1, p. 110, Dec. 2020.

[165] Z. Chua, A. M. Jarc, and A. M. Okamura, "Toward force estimation in robot-assisted surgery using deep learning with vision and robot state," 2020, *arXiv:2011.02112*.

[166] H. Sang, J. Yun, R. Monfaredi, E. Wilson, H. Fooladi, and K. Cleary, "External force estimation and implementation in robotically assisted minimally invasive surgery," *Int. J. Med. Robot. Comput. Assist. Surg.*, vol. 13, no. 2, Jun. 2017, Art. no. e1824.

[167] M. Haghighipanah, M. Miyasaka, and B. Hannaford, "Utilizing elasticity of cable-driven surgical robot to estimate cable tension and external force," *IEEE Robot. Autom. Lett.*, vol. 2, no. 3, pp. 1593–1600, Jul. 2017.

[168] Y. Li and B. Hannaford, "Gaussian process regression for sensorless grip force estimation of cable-driven elongated surgical instruments," *IEEE Robot. Autom. Lett.*, vol. 2, no. 3, pp. 1312–1319, Jul. 2017.

[169] K. J. Kuchenbecker *et al.*, "VerroTouch: High-frequency acceleration feedback for telerobotic surgery," in *Haptics: Generating and Perceiving Tangible Sensations* (Lecture Notes in Computer Science), vol. 6191. Berlin, Germany: Springer, 2010, pp. 189–196.

[170] A. Mohammadi, H. J. Marquez, and M. Tavakoli, "Nonlinear disturbance observers: Design and applications to Euler–Lagrange systems," *IEEE Control Syst. Mag.*, vol. 37, no. 4, pp. 50–72, Aug. 2017.

[171] A. S. Naidu, M. D. Naish, and R. V. Patel, "A breakthrough in tumor localization: Combining tactile sensing and ultrasound to improve tumor localization in robotics-assisted minimally invasive surgery," *IEEE Robot. Autom. Mag.*, vol. 24, no. 2, pp. 54–62, Jun. 2017.

[172] W. Sjoerdsma, J. L. Herder, M. J. Horward, A. Jansen, J. J. G. Bannenberg, and C. A. Grimbergen, "Force transmission of laparoscopic grasping instruments," *Minimally Invasive Therapy Allied Technol.*, vol. 6, no. 4, pp. 274–278, Jan. 1997.

[173] G. Picod, A. C. Jambon, D. Vinatier, and P. Dubois, "What can the operator actually feel when performing a laparoscopy?" *Surgical Endoscopy*, vol. 19, no. 1, pp. 95–100, Jan. 2005.

[174] V. Gupta, N. P. Reddy, and P. Batur, "Forces in surgical tools: Comparison between laparoscopic and surgical forceps," in *Proc. 18th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Oct. 1996, pp. 223–224.

[175] J. J. van den Dobbelsteen, A. Schooleman, and J. Dankelman, "Friction dynamics of trocars," *Surgical Endoscopy*, vol. 21, no. 8, pp. 1338–1343, Aug. 2007.

[176] A. L. Trejos, R. V. Patel, R. A. Malthaner, and C. M. Schlachta, "Development of force-based metrics for skills assessment in minimally invasive surgery," *Surgical Endoscopy*, vol. 28, no. 7, pp. 2106–2119, Jul. 2014.

[177] R. Haslinger, P. Leyendecker, and U. Seibold, "A fiberoptic force-torque-sensor for minimally invasive robotic surgery," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 2013, pp. 4390–4395.

[178] R. Xu, A. Yurkewich, and R. V. Patel, "Curvature, torsion, and force sensing in continuum robots using helically wrapped FBG sensors," *IEEE Robot. Autom. Lett.*, vol. 1, no. 2, pp. 1052–1059, Jul. 2016.

[179] H. Seok Song, J. W. Jeong, and J. J. Lee, "Optical fiber Bragg grating (FBG) force reflection sensing system of surgical tool for minimally invasive surgery," in *Proc. 9th IEEE Conf. Ind. Electron. Appl.*, Jun. 2014, pp. 478–482.

[180] P. Puangmali, H. Liu, L. D. Seneviratne, P. Dasgupta, and K. Althoefer, "Miniature 3-axis distal force sensor for minimally invasive surgical palpation," *IEEE/ASME Trans. Mechatronics*, vol. 17, no. 4, pp. 646–656, Mar. 2012.

[181] J. B. Gafford, R. J. Wood, and C. J. Walsh, "Self-assembling, low-cost, and modular mm-scale force sensor," *IEEE Sensors J.*, vol. 16, no. 1, pp. 69–76, Jan. 2016.

[182] M. S. Müller, L. Hoffmann, T. Christopher Buck, and A. Walter Koch, "Fiber-Bragg grating-based force-torque sensor with six degrees of freedom," *Int. J. Optomechtron.*, vol. 3, no. 3, pp. 201–214, Sep. 2009.

[183] S. J. Blumenkranz *et al.*, "Force and torque sensing in a surgical robot setup arm," U.S. Patent 9 895 813, Feb. 20, 2018.

[184] S. J. Blumenkranz and D. Q. Larkin, "Force sensing for surgical instruments," U.S. Patent 8 375 808, Feb. 19, 2013.

[185] A. H. H. Hosseinabadi and S. E. Salcudean, "UltraLow noise, high bandwidth, low latency, no overload 6-axis optical force sensor," *IEEE/ASME Trans. Mechatronics*, vol. 26, no. 5, pp. 2581–2592, Oct. 2021.

[186] A. H. H. Hosseinabadi, M. Honarvar, and S. E. Salcudean, "Optical force sensing in minimally invasive robotic surgery," in *Proc. Int. Conf. Robot. Autom. (ICRA)*, May 2019, pp. 4033–4039.

[187] S. C. Ryu and P. E. Dupont, "FBG-based shape sensing tubes for continuum robots," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2014, pp. 3531–3537.

[188] M. Selvaggio, A. M. G. E, R. Moccia, F. Ficuciello, and B. Siciliano, "Haptic-guided shared control for needle grasping optimization in minimally invasive robotic surgery," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Nov. 2019, pp. 3617–3623.

[189] L. Wang *et al.*, "Force-controlled exploration for updating virtual fixture geometry in model-mediated telemanipulation," *J. Mech. Robot.*, vol. 9, no. 2, Apr. 2017, Art. no. 021010.

[190] Z. Chen *et al.*, "Virtual fixture assistance for needle passing and knot tying," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Oct. 2016, pp. 2343–2350.

[191] N. E. Samalavicius *et al.*, "Robotic surgery using Senhance Robotic platform: Single center experience with first 100 cases," *J. Robot. Surg.*, vol. 14, no. 2, pp. 371–376, Apr. 2020.

[192] A. Spinelli *et al.*, "First experience in colorectal surgery with a new robotic platform with haptic feedback," *Colorectal Disease*, vol. 20, no. 3, pp. 228–235, 2018.

[193] H. Sugita *et al.*, "First experience using the senhance surgical system in laparoscopic local gastrectomy for gastrointestinal stromal tumor," *Asian J. Endoscopic Surg.*, vol. 14, no. 4, pp. 790–793, Oct. 2021.

[194] P. P. Rao, "Robotic surgery: New robots and finally some real competition!" *World J. Urol.*, vol. 36, no. 4, pp. 537–541, Apr. 2018.

[195] B. S. Peters, P. R. Armijo, C. Krause, S. A. Choudhury, and D. Oleynikov, "Review of emerging surgical robotic technology," *Surgical Endoscopy*, vol. 32, no. 4, pp. 1636–1655, Apr. 2018.

[196] G. R. Sutherland, S. Wolfsberger, S. Lama, and K. Zareinia, "The evolution of NeuroArm," *Neurosurgery*, vol. 72, no. 1, pp. 27–32, Jan. 2013.

[197] Forcedimension. *NeuroArm*. Forcedimension. Accessed: Feb. 2022. [Online]. Available: https://www.forcedimension.com/products

[198] U. Hagn *et al.*, "DLR MiroSurge: A versatile system for research in endoscopic telesurgery," *Int. J. Comput. Assist. Radiol. Surg.*, vol. 5, no. 2, pp. 183–193, Mar. 2010.

[199] Institute of Robotics and Mechatronics, Analysis and Control of Advanced Robotic Systems. *MiroSurge*. DLR. Accessed: Feb. 2022. [Online]. Available: https://www.dlr.de/rm/en/desktopdefault.aspx/tabid-11674#gallery/28728


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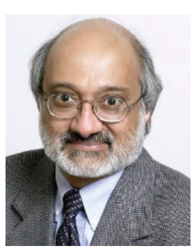

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