Intra-operative Tumor Localization in Robot-assisted Minimally Invasive Surgery: A Review

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Abstract—Robot-assisted minimally invasive surgery has many advantages compared to conventional open surgery but also certain drawbacks: it causes less operative trauma and faster recovery times but does not allow for direct tumor palpation as is the case in open surgery. This article reviews state-of-the-art intra-operative tumour localization methods used in robot-assisted minimally invasive surgery and in particular methods that employ force-based sensing, tactile-based sensing, and medical imaging techniques. The limitations and challenges of these methods are discussed and future research directions are proposed.

Index Terms—haptic feedback, minimally invasive surgery, palpation, tumor localization

I. INTRODUCTION

MINIMALLY Invasive Surgery (MIS), also called laparoscopic, or keyhole surgery, was introduced in the mid-1980s and has since been widely performed worldwide increasingly replacing open surgery. MIS is performed through small incisions (Trocar ports) ranging from 3 to 12 mm in diameters [1] while open surgery is carried out using a single large incision. MIS has many advantages over open surgery, including improved therapeutic outcome, shortened postoperative recovery, lesser immunological stress response of the tissue, reduced tissue trauma, lower postoperative pain, and less scarring. However, MIS also carries some drawbacks: clinicians need to cope with motion constraints, limited vision of the operative site, reduction of intuitiveness, and the absence of direct tissue interaction. To solve the motion constraint problems, surgical robots have been developed in a master-slave configuration which separates the surgeons and the patient completely and augments the distal dexterity of the tool. The da Vinci system (Intuitive Surgical, Inc) is a successful example of this approach. Robot-assisted Minimally Invasive Surgery (RMIS) has enabled surgeons to achieve more successful outcomes and has been utilized in a variety of procedures from relatively routine ones such as prostatectomy [2], cholecystectomy [3], and cystectomy [4], to the more complex coronary artery revascularization and mitral valve repair [5], [6].

Limited vision of the operation site in MIS has been resolved with the application of high-definition 3D vision systems. The sense of touch however (kinesthetic force and tactile sensations) is still quite limited. In general, the use of the term "tactile" describes the mechanical stimulation of the skin [7]. The force exerted on soft tissue can only be estimated by observing the tissue deformation. Tactile information during tool-tissue contact is totally absent. During open procedures, surgeons can access affected organs directly which allows them to identify tumors and their boundaries through hand-soft tissue interaction, in other words through manual palpation, and to ensure that tumors have been removed in their entirety. Manual palpation can be conducted by non-prehensile motions, such as pushing and lifting, and prehensile motions, such as grasping and seizing [8]. Surgeons investigate the force-displacement response to acquire distributed tactile information. Tissue areas that are stiffer than the surrounding tissue can be recognized as abnormal tissue and, therefore, as possible tumors [9], [10].

Lack of direct palpation in RMIS may lead to insufficient tumor excising. Thus, it would be greatly beneficial to develop a real-time intra-operative tumor localization method which is safe, effective, precise, and user-friendly, whose components can be sterilized and which can be easily integrated within existing systems to conduct the palpation procedure at the master side of an RMIS device [11], [12]. Researchers have proposed methods that can obtain partial force and tactile information [13] to mimic the function of palpation during robotic-assisted surgical procedures. Intra-operative CT, MR, ultrasound imaging is also introduced.

Previous research survey articles have reviewed the applications of force and/or tactile sensing and/or feedback techniques in RMIS. However, intra-operative tumor localization in RMIS has not been reviewed in detail. The aim of this article is to present a comprehensive review of recent research achievements in intra-operative tumor localization methods for RMIS, address their limitations and propose future directions of research. In section II, force-based sensing is reviewed. Tactile-based sensing is discussed in section III. Section IV provides a review of medical imaging techniques. Challenges and future possible research directions are addressed in section V.

II. INTRA-OPERATIVE TUMOR LOCALIZATION USING FORCE-BASED SENSING

A. Direct force feedback architectures

At present tele-robotic systems [16] used in RMIS cannot provide direct force feedback to the surgeon. The clinician operating a master-slave surgical robotic system is not able to discern the material properties of soft tissue by using the surgical tool on the slave side. To achieve transparency, that is ,

a match between the indentation forces applied at the tool tip and the feedback as well as between the positions of master and slave [14], would require a total redesign of existing surgical systems, such as the da Vinci and Titan Medical Amadeus [15]. Given the absence of of direct force feedback in current tele-robotic systems [16], visual force feedback is considered as the only option [17]. However, research described in [18] shows a better performance of direct force feedback over visual force feedback using a color bar in tumor identification.

Bilateral control is the basic method used to integrate direct force feedback in robotic surgery [19], [20]. Instead of a simple two-port model, bilateral control has been extended to a four channel architecture, which considers not only the difference between the master and slave forces but also the positions. DLR (German Aerospace Center) developed a 7-DOF MiroSurge surgical robotic system providing bimanual force feedback based on a bilateral control scheme [21]. Manipulation and force feedback are provided by two input devices Sigma.7 (Force Dimension Inc., Nyon, Switzerland) on the master side. Using this system, the user can clearly distinguish between instrument collisions and tool-tissue interactions [21]. In other studies, Tavakoli et al. [20] developed and evaluated a force feedback method which helps users to distinguish tissue stiffness when probing them remotely. They used strain gauges and a load cell attached to the end of a surgical tool. Employing a PHANToM 1.5A force feedback device (Sensable Technologies Inc.) and implementing a bilateral tele-operation control scheme, the researchers provided direct force feedback of bending and torsional moments and the contact force between the tool and tissue. However, system instability is caused by uncontrollable jitters generated by small errors and delays when the transparency increases.

Surgery has a low tolerance for this type of inaccurate behaviors. The trade-off between force feedback transparency and system stability is a significant barrier of direct force feedback since it is not possible to successfully apply both position and force control using the aforementioned bilateral control scheme [22]. Instead, acceleration-based bilateral control achieves high transparency and maneuverability performing position and force control simultaneously and using the common variable between position and force – acceleration [19], [23]. This control type has been utilized in a 1-DOF master-slave forceps surgical robot [24] and in a multi-DOF haptic endoscopic surgery robot [19]. In order to distinguish between different tissue stiffness, further research regarding this application is needed.

B. Force sensing strategies

Currently, no commercially available, multiple DOF force sensor meets the dimensional constraints for potential use in MIS through Trocar ports (less than 12 mm in diameter) [1] [25]. Although the Nano-17 (ATI, Industrial Automation), a commercial 6-DOF sensor system with a diameter of 17 mm, can be sterilized, it cannot be used in standard MIS. However, this sensor is frequently utilized in MIS-related research studies [11], [26]–[28]. Other specialized force sensors include a 6-DOF force/torque sensor for the DLR telesurgery scenario MiroSurge, for instance. An additional 1-DOF gripping force sensor is integrated to the gripper, which has a annular cross section with a diameter of 10 mm. Sargeant et al. [29] developed an MR- compatible 6-DOF F/T sensor based on the Steward Platform that obtains intensity modulated light using linear polarizer materials and fiber optic guided light. This MR-compatible sensor has a height of 10 mm, diameter of 11 mm, and weight of 0.6 g which meets the MIS requirements.

If the sensor is positioned outside the patient, there would be no size restraints and sterilizability issues in regards to said sensor. However, the sensor measurement may be influenced by joint actuation or by the friction between the tool and the Trocar. Alternatively, by measuring contact forces without any force sensor issues related to MR-compatibility, size, sterilizability, and cost will not arise [30]. For snake-like robots, force sensing could be achieved by the kinematic analysis [31]. In another context, Mahvash et al. [18] estimated contact forces by using the current that is applied to the actuators of the slave robot during remote palpation experiment. However, the sensitivity of these methods is lower than force sensor implementations. Recently, Beccani et al. [33] proved the feasibility of a wireless uniaxial indentation palpation method using a 1-DOF magnetic device. This method eliminates direct physical connection through the Trocar port, and, thus, force data is not distorted by friction or joint actuation. Another choice is estimating forces and providing direct force feedback using a further developed bilateral teleportation controller, like acceleration-based bilateral control [32]. Force sensor is also not needed. Force sensing strategies for tumor localization are summarized in Table I.

C. Tissue property acquisition using uniaxial indentation

An alternative to direct force feedback is the acquisition of displacements and applied forces in real time and their combination with tissue models to estimate tissue property. The feasibility of conducting separate point uniaxial compression to acquire tissue stiffness distribution information and localize lung tumors utilizing a force-sensitive probe is discussed in [34]. Yamamoto et al. [26] supported surgeons with a graphical overlay to distinguish hard and soft tissues. Real-time tissue stiffness visualization was established using a Hue-Saturation-Luminance (HSL) representation on the image of tissue surface, where Hue value represents the stiffness at a contact point, while the Saturation value is calculated based on the distance from the palpated point (Fig. 1). Since the tumor tissue is typically stiffer than healthy tissue [17], [18], a surgeon can use the color information provided by the map to distinguish abnormal tissue regions from healthy areas. Later, this graphical overlay method was improved to an interoperable interface which provides augmented visual feedback using three-dimensional graphical material property overlays as well as virtual fixtures with haptic feedback [35].
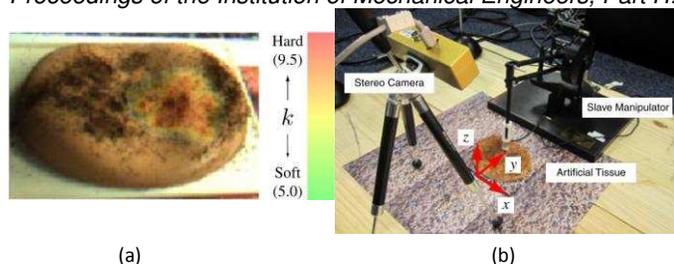
Fig. 1. A colored stiffness map displays the material property and a colour bar displays the stiffness range shown in (a). Slave-side hardware, including the artificial prostate tissue, the slave manipulator, and the stereo-camera shown in (b) [35].

Fig. 2 The rolling indentation experiment setup shown in (a) and the stiffness map produced by the rolling indentation probe shown in (b) [11].

D. Rolling indentation probes for continuous palpation

Individual discrete uniaxial indentation may be time intensive for rapid and efficient tumor localization in cases where the tissue area to be investigated is large [11]. Hence, lateral movement of finger tips or hands over the organ's surface is more beneficial for palpation [36]. In this case, if the indentation depths remain the same, reacting forces vary when moving over abnormal and normal tissue. The rolling indentation approach for tumor localization has been proposed by [11], [37], [38]. Instead of a discrete point uniaxial compression test, conducting a rolling indentation over a tissue surface using a force-sensitive wheeled probe can acquire the stiffness map rapidly along fixed trajectories continuously. A force distribution matrix can be obtained, which illustrates the tissue's elastic modulus at a given indentation depth assuming that the investigated tissue is linear elastic, isotropic, homogeneous, and incompressible [39]. The resultant forces f_r acquired by the force/torque sensor (f_x, f_y, and f_z) at each sampled point are used to generate the Rolling Mechanical Image (RMI), which depicts the geometrical tissue stiffness distribution as shown in Fig. 2. An air-cushion force sensitive indentation probe [40] - a concept similar to rolling indentation - was also designed to locate stiff tissue. In real applications, it is challenging to maintain a constant indentation depth during the scan. Hence, a stiffness probe, which is able to measure the reacting force and indentation depth at the same time, will be essential. Wanninayake et al. [41], [42] proposed an air-float stiffness probe, which meets these requirements.

Sangpradit et al. [28], [43], [44] developed an Inverse FE modeling method for the identification of the stiffness of a tumor at a known depth and the estimation of the depth of the tumor with known mechanical properties using rolling indentation. The FE model is established with an initial guess of the soft tissue parameters. The force-displace curve generated by the FE model is compared to real data. The Newton-Raphson method is applied to adjust tissue parameters and minimize the error. The results show that locations and depths of embedded nodules can be identified accurately. Ahn et al. [45] uses mechanical property characterization with FEM-based inverse estimation for a robotic sweeping palpation method. The comparatively long computational time is the main barrier of this method.
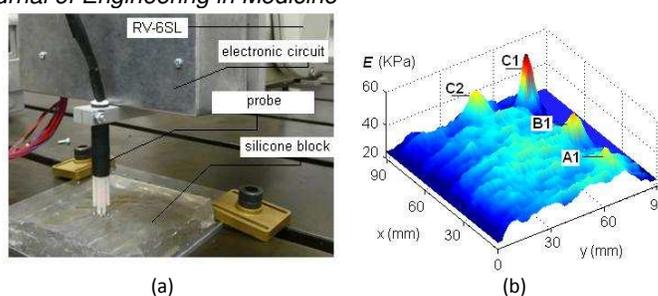
III. Intra-operative Tumor Localization using Tactile-based Sensing

Tactile information is significant in palpation in order to mechanically display properties of tissue regions [46]. It enables surgeons to investigate a tissue area rather than a specific point as is the case when using force sensors. Tactile sensors consist of an arrangement of force sensing elements which enable the surgeon to receive information of the internal structure of the tissue by determining pressure spatial distributions. Ideal tactile sensors are reliable, sensitive, firm, small, and low-cost. Tactile-based tumor localization is summarized in Table II.

A. Imitated tactile sensing palpation and visualization systems

A graphical representation of force or tactile data is a low-cost and effective method for intra-operative palpation and diagnosis applications. The commercialized tactile array systems Pressure Profile Systems, Inc. [47] and TekScan, Inc. [48] provide these graphical displays which are capable of showing the pressure distribution over a tissue surface. However, color-coded tissue stiffness maps only represent local relative stiffness differences and do not transfer absolute stiffness information to the surgeon. Hence, surgeons should rely on their expertise of haptic properties in order to correctly judge the corresponding tissue when using this system [49].

1) Grasping palpation

A common approach for tumor localization is to grab tissue with a grasper or hand (prehensile motions). Schostek et al. [49] developed a 10 mm disposable laparoscopic grasper with a mounted 32-element tactile sensor which conveys tactile information visually. The grasper is low-cost, entirely encapsulated in silicone rubber, and can withstand high grasping forces are the main benefits. Najarian et al. [50] and Dargahi et al. [51] equipped endoscopic graspers with miniaturized PVDF-sensing elements with a graphical visualization. The resulting data includes tissue stiffness and stress distribution on the tissue/grasper interface. An average discrepancy of about 10% was achieved between the evaluation experimental outputs and the known tactile properties [51]. However, the developed sensing array of 8 elements, which is limited by the size of the grasper, only covers a small tissue area. This is a problem when internal stiffness information of big organs is required.

2) Non-grasping palpation

Egorov et al. [52], [53] developed a mechanical imaging system for breast and transrectal prostate examination. The feedback provides a real time 2D pressure response pattern and a summary mode with a 3D reconstruction. The Breast Mechanical Imager (BMI) designed by Egorov et al. has a 16 ×12 array of pressure sensors (Pressure Profile Systems, Inc., Los Angeles, CA) covering a 40 mm×30 mm area of the scan head. Obviously, further miniaturization is needed in order to make it suitable for RMIS. Two pressure sensor arrays were integrated in a Prostate Mechanical Imaging (PMI) transrectal probe: probe head pressure sensor array for prostate imaging and probe shaft pressure sensor array for sphincter imaging. The probe head pressure sensor array consists of 16×8 sensors (Pressure Profile System) covering 40 mm $\times$ 16 mm. The shaft pressure array also has 16×8 sensors with a total slightly larger size of 60 mm $\times$ 20 mm. In 84% of studied cases, the system was able to reconstruct 2D cross-sectional and 3D images of the prostate. The PMI system was able to determine malignant nodules in 10 of 13 patients with biopsy-confirmed malignant inclusions. Trejos et al. [54] and Perri et al. [55], [56] developed and enhanced the Tactile Sensing Instrument (TSI) to a more advanced Tactile Sensing System (TSS) by adding a visualization interface (see Fig. 3). This system now visualizes a real-time updated pressure map of the contact surface between the tactile sensor (4×15 elements) and the organ surface. Both interaction force data and the color-coded pressure map (tactile data) are provided to the clinician. This study concludes that sustained applied forces exceeding 6 N would cause visible and irreversible bulk damage to the liver. Using a capacitive sensor array, Miller et al. [57] constructed a similar Tactile Imaging System (TIS) for the localization of tumors during MIS. The advantage is that a vision-based algorithm localizes the probe and a live video is overlaid with a registered pseudo-colour map of the measured pressure distribution (3×12 sensing elements) at the tracked probe location. The surgeon can locate tumors by scanning the surface of the organ using the probe and observing the change in pseudo-colors of the distribution map overlaid on the laparoscopic image.
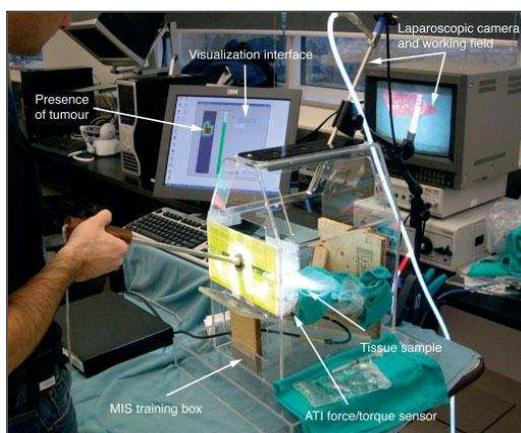

Fig. 3 The Tactile Sensing System (TSS) [55].

B. Palpation using tactile feedback devices

Using tactile feedback devices to interpret the stiffness distribution of the soft tissue may provide a more intuitive reception of tissue stiffness information [49]. However, tactile feedback devices are much less well developed than tactile sensing [17]. Limited understanding of human tactile receptors makes the development of tactile feedback devices a challenging task. Research of tactile interfaces is still in the early stages [58]. Currently, there are several types of tactile feedback display techniques including pins tactile display [46], vibrotactile [59], [60], pneumatic activated tactile display [61], microfluidic activated tactile display [62], surface acoustic waves [63], focused ultrasound [64], [65], electrorheology [66], [67], and magnetorheological fluid [68]. Most existing tactile technologies and devices are expensive, large, imprecise, and non-portable, and cannot be used in real haptic interaction, especially in MIS and in training procedures [1], [117], [118]. The lack of commercially available tactile devices also limits current research of intra-operative palpation in RMIS.

There are two main simulation types available for utilizing tactile feedback devices for tumor identification:

1) Tactile feedback using movable components

Ottermo et al. [69] presented a system capable of remote palpation equipped with a tactile sensor (total size: 24×8 mm^2, 2×2×0.5 mm^3×30 piezoelectric sensor elements in a 3×10 pattern) and a tactile display (with mounted 4×8 tactels (TACTil Element)). Force distribution is simulated by tactel height modification which creates skin deformation. A study comparing graspers with and without tactile feedback to each other proved that the grasper with tactile feedback can be helpful for hardness discrimination. Kim et al. [46] developed a planar distributed tactile display for organ palpation. It has a 5×6 pin array with a total size of 40×20×23 mm. The 30 stacked actuators are piezoelectric bimorphs. As is the case in Ottermo et al. [69], the height modification is used to simulate force distribution. The experimental results showed that the addition of tactile feedback display significantly improved precision of perception of the shape and stiffness of objects.

2) Tactile feedback using materials with variable stiffness

The use of rigid movable elements to simulate force distribution in palpation improves tumor identification results, but does not give the user a direct stiffness feeling. Hence researchers have investigated approaches to simulate stiffness directly. The viscosity of electrorheological (ER) fluid can be controlled by the application of an electric field. Similarly, the rheological properties of magnetorheological (MR) fluid will change when subjected to an external magnetic field. Khaled et al. [66] described a tactile actuator array using ER fluid. Liu et al. [68] proposed a single MR fluid-based tactile element: as the applied magnetic field changes, so does the sensed surface profile. Goto and Takemura [67] presented a tactile bump display which uses ER fluid. Although the original intention of this tactile feedback device is to improve the accuracy and precision of touch typing, it also has the potential to be modified and applied in tumor localization. Mansour et al. [120]

presented a device which can display both the stiffness distribution and surface shape of an object. It consists of an Elongation Spring (ES) for displaying shape and a Stiffness Spring (SS) for displaying stiffness. A finite element analysis of selected parameters proves and validates the design concept.

Pneumatic and micro fluidic activated tactile displays also illustrate shape and stiffness at the same time. Culjat et al. [61] developed a pneumatic balloon tactile display. Balloon deflections display the shape/height, while air pressures inside display the stiffness. This device can be easily attached to an existing commercial robot-assisted surgery system, such as the da Vinci. Here, commercial single-element piezoresistive force sensors (FlexiForce, Tekscan) were used for psychophysics experiments. The results revealed that their tactile feedback can reduce grasping force in robot-assisted surgery. Although it has not made inroads in tumor localization as yet, this application shows great potential.

Similar to pneumatic activated tactile displays, microfluidic activated displays also exert the force on the finger tip by using the inflation of a tactile layer. Tactus Technology, Inc. [62] developed a deformable tactile layer panel which can be integrated in a touch-screen device to provide transparent physical buttons. These buttons can be disabled and will recede into the screen where they become invisible. This has potential to be used in tactile feedback for palpation.

IV. MEDICAL IMAGING TECHNIQUES

A. Imaging Registration

Sophisticated pre-operative imaging techniques such as Computed Tomography (CT), Magnetic Resonance Imaging (MRI), and Ultrasound (US) imaging are often used for preoperative tumor identification. They provide accurate and highly detailed multidimensional images. However, sometimes they are not able to distinguish between tumor and edema fluid, especially in the case of small size formations [71]. Moreover, accurate rigid registration of the tumor's position is challenging as it is often different to the one recorded in the preoperative scan due to the movement of organs and the deformability of the soft tissue during surgery [72], [73]. Image registration is commonly used to transform preoperative images to the intra-operative tumor positions. Non-rigid transformations have a high degree of freedom and are capable of accommodating the local deformations that occur during surgery. This registration method, which can estimate the most likely deformations, has therefore been introduced as a way of mapping the pre-operative functional information into the intra-operative space. Deformable tissue models have been developed such as specialized non-linear finite element algorithms and solutions for real-time estimation of soft tissue deformation [74]. Compared to intra-operative palpation, the performance of pre-operative imaging techniques are moderate. Schipper et al. [75] compared the pulmonary nodule detection rates between intra-operative lung palpation and pre-operative CT imaging. The results show that a significant number of malignant pulmonary nodules that were detected intra-operatively were not identified on preoperative imaging.

Intra-operative imaging helps identify any residual tumor tissue and leads to a significant increase in the extent of tumor removal and survival rates. However, the quality of intra-operative images is often degraded compared to pre-operative images. Co-registration of pre- and intra-operative images could be a solution but is not straightforward due to tissue deformation, different acquisition parameters, resolutions, plane orientations, and computational time constraints [76]. Challenges include discontinuities and missing data in the registration algorithms due to retraction and resection, and time requirements of intra-operative registration. Rigid registration is more common because it is relatively faster compared to the non-rigid registration [76]. Non-rigid registration methods are still at an experimental stage and cannot be used as yet in practical applications. Registration uncertainty has also been considered [77]. By providing registration uncertainty information, the confidence level of surgeons in the registered image data can be increased, would be helpful in decision making.

B. Real-time elastography

Elastography, also known as elasticity imaging, is a technique to calculate and visualize various elastic parameters of soft tissue from different tissue stimuli, such as ultrasound, CT, MRI, or optics [78], [79]. Elastography involves mapping the strain of the soft tissue induced by applied stress is the concept of elastography [80]. Stiffer tissue experiences lower strains. In palpation, the Young's modulus (E), or shear modulus (μ) describe the elastic properties. In general, there is a simple linear relation between the Young's modulus and the shear modulus: $E = 3\mu$ for soft tissue. Ultrasound elastography can evaluate tissue stiffness in real-time, and has been applied to tumor identification in breast tissue [81], prostate [82], liver [83], and pancreas [80]. However, expertise of the surgeon is still essential to interpret the image properly. Combining real-time elastography with haptic actuators will allow remote palpation and solve this problem [66], [36]. Khaled et al. [66] developed an integrated haptic sensor/actuator system based on ultrasound real-time elastography and electro-rheological (ER) fluids. The results of elasticity images were combined to reconstruct virtual objects on the haptic actuator array, which allows users to palpate patient's organs while imaging. Hence, specialized personnel are not required to understand the images. However, disadvantages include high computational expenses [79], limited acquirable characteristics of linear elasticity such as Young's elasticity and Poisson's ratio [84]. Also, there is a limited depth for measurements of ultrasound.

V. DISCUSSIONS AND FUTURE DIRECTIONS

A. Tactile-based sensing

The force and tactile-based sensing methods and technologies reviewed above can be used to support surgeons during tumor removal procedures. However, sensing array sizes

are limited by the small mounting surface of surgical tools. This results in relative data variations over a large tissue area. Multiple discrete indentations need to be performed, a fact which increases the palpation time. The tumour detection result may be affected by the higher contact stress which appears at the edge of the sensor array when it is indented on the soft tissue. It is noted that this issue has been largely ignored in the research presented in the literature review. Graphical sensory substitution techniques are more common than other tactile actuators. One major disadvantage of these techniques is that tissue stiffness maps can only represent relative stiffness differences and pinpoint tumors on the tissue surface without providing depth information. Perception is not intuitive, so surgeons find it difficult to receive a sufficient impression of the actual stiffness. Hence, these techniques are no substitute for manual palpation.

B. Feedback modality combinations

Direct force feedback does not convey tactile information and thus is not useful for identification of exact tumor boundaries. Graphical material property overlays on the other hand could be beneficial for tumor identification. The combination of force feedback and tactile feedback could enhance the perception and improve the performance of tumor localization in future research.

Mahvash et al. [18] pointed out that force displays could be based on real-time intra-operative patient-specific tissue models rather than the current measured force. Tumor identification during RMIS can rely on intra-operative palpation of virtual tissue which is generated by rapid tissue property estimation based on in-vivo tests. Also, force displays based on such tissue models would enable the acquisition of quantitative information of abnormal tissue localization. Palpation with haptic feedback on a virtual tissue is superior to direct haptic feedback as it avoids the complex control between the master robot side and the slave robot side. Based on this virtual tissue real-time generation for intra-operative palpation, pseudo-haptic feedback can be used to enhance the perception of palpation on the virtual tissue.

Pseudo-haptic feedback has already been used in medical applications. Bibin et al. [85] introduced a medical simulator called SAILOR for training of Anaesthesia with neurostimulation in virtual environment. Pseudo-haptic feedback was utilized to give touch feedback of organs located under the skin. The implemented algorithm changes the speed of the cursor movement as function of the height of the picture pixels [86]. Further, the size of the cursor also varies to improve the pseudo-haptic sensation [87]. Li et al. [88] proposed the concept of pseudo-haptic feedback for soft tissue simulation and localization of abnormal tissue. Augmenting haptics with pseudo-haptics and its use for intra-operative palpation needs to be explored.

C. Multi-fingered palpation

Among clinicians, multi-fingered palpation is more common than single-fingered palpation. Some attempts have been made

at simulating multi-fingered palpation [89]–[93]. However, these multi-fingered palpation simulations used complex and expensive feedback systems. Moreover, no comparison study between single-fingered palpation and multi-fingered palpation has been conducted yet. Multi-fingered palpation feedback can be adapted to intra-operative palpation using real-time generated virtual tissue. Alternatively, a specialized multi-fingered probe and corresponding feedback actuator need to be developed to inspect the surface stiffness of tissues for direct force feedback.

D. Indentation depth measurement

Indentation depth measurement is crucial for stiffness calculation. For rolling indentation palpation, it is essential to maintain a constant indentation depth throughout the palpation activity. This could be achieved by pre-registration of the surface. However, it might be time consuming and the accuracy may be affected by errors introduced. Thus, a real-time indentation depth measurement is needed. Although some sensors with the capability of indentation depth measurement have been developed e.g. air-float palpation probe [42], some improvements should be undertaken to fulfill the requirements of RMIS with respect to miniaturization for instance.

Three-dimensional (3D) reconstruction techniques could be used in tissue surface contour acquisition for indentation depth measurement. In [94], a moving Microsoft Kinect is used for real-time 3D reconstruction and interaction. To make it more suitable for minimally invasive intra-operative purposes, endoscopic cameras should be used for 3D reconstruction. Once the original, unindented surface is reconstructed, the indentation depth can be calculated based on the distance between the current indenter position and the closest triangle planar on the mesh of the original reconstructed contour. To compensate any tissue shift or deformation, the surface reconstruction process can be repeated several times.

VI. CONCLUSION

This article reviewed current engineering solutions for intra-operative tumour localization. Overall, most existing engineering solutions for intra-operative tumour localization are still at an experimental stage and have not been tested in-vivo. Further research in this field needs to address the main problem of how to acquire accurate tissue stiffness data and convey useful information to the surgeon. So far, no fast and robust intra-operative solution has been established for clinical use. There are a number of approaches that need to be investigated further if we want to improve user experience and emulate manual palpation as much as possible: employment of multi-fingered actuators can be effective, and combination of tactile with kinesthetic feedback, of pseudo-haptic with real haptic feedback, and of graphical with haptic displays are all promising methods.

TABLE I.
SUMMARY OF FORCE SENSING STRATEGIES FOR TUMOR LOCALIZATION

Approach	Challenges	Example	Properties	Reference
Measuring contact forces with force sensors	Size, sterilizability, cost, and MR-compatibility. On the one hand, size limitations and sterilizability of the used sensor are negligible, if the sensor is positioned outside the patient. On the other hand, friction between the Trocar and the tool or by joint actuation affects the measurement.	Nano-17 (ATI, Industrial Automation)	Does not meet the dimensional constraints for potential use in MIS through Trocar ports (less than 12 mm in diameter) [1] [25]	[11], [26]–[28]
		A 6 DOF force/torque sensors for the DLR telesurgery scenario MiroSurge	An additional 1-DOF gripping force sensor is integrated in the gripper, which has a annular cross section with a diameter of 10 mm.	[21]
		An optical multi-axis F/T sensor	6-DOF force/torque MR-compatible sensor. Diameter: 11 mm, height: 10 mm weight:0.6 g	[95]
		A wireless indentation palpation approach using a magnetic device	Since a direct physical connection through the Trocar port is redundant, the force data is not distorted by friction or joint actuation.	[33]
Measuring contact forces without force sensor	Sensitivity and accuracy	An state observer is used to estimate environment force using the current applied to actuators	Not as accurate as force sensor	[18]
		Bilateral teleportation controllers	Transparency achieved is limited.	[32]
		Acceleration based bilateral control	High transparency and maneuverability Further research regarding distinguishing between different tissue stiffness is needed.	[24], [19]
		Kinematic analysis of a snake-like robot	The fexible continuum robot has intrinsic force sensing ability. Average force sensing errors: 0.34 g, standard deviation: 0.83 g.	[31]

TABLE II.
SUMMARY OF INTRA-OPERATIVE TUMOR LOCALIZATION USING TACTILE-BASED SENSING

Approach	Sensor	Feedback	Properties	In-vitro palpation experiments		In-vivo palpation experiments	Reference
				Phantom organ	Animal organ		
Disposable laparoscopic grasper with tactile sensing	10 mm disposable laparoscopic grasper with a 32-element tactile sensor	Graphical visualization	Main benefits: low-cost, entirely encapsulated in silicone rubber, and withstanding high grasping forces.	No	Yes	Yes	[49]
Endoscopic grasper with tactile sensing	Endoscopic graspers are equipped with miniaturized PVDF-sensing elements with a graphical visualization	Graphical visualization	The developed sensing array of 8 elements, which is limited by the size of the grasper, only covers a small tissue area.	Yes	No	No	[50], [51]
Breast Mechanical Imager (BMI)	A 16 ×12 array of pressure sensors (Pressure Profile Systems) covering 40 mm×30 mm	Graphical visualization	Further miniaturization is needed in order to make it suitable for RMIS	Yes	No	No	[49]
Prostate Mechanical Imaging (PMI) transrectal probe	Probe head pressure sensor array: 16×8 sensors (Pressure Profile System) covering 40 mm×16 mm. Shaft: 16× 8 sensors covering 60 mm× 20 mm.	Graphical visualization	Probe head pressure sensor array for prostate imaging and probe shaft pressure sensor array for sphincter imaging.	Yes	No	Yes	[50]
Tactile Sensing System (TSS)	Tactile sensor (4×15 elements)	Graphical visualization	Provides both contact force data and the color-coded tactile data.	No	Yes	No	[54], [55], [56]
Tactile Imaging System (TIS)	3×12 sensing elements (Pressure Profile System)	Graphical visualization	A live video overlaid with a registered pseudo-color map of the acquired pressure distribution.	No	Yes	No	[57]
A remote palpation	2×2×0.5 mm^3×30	A tactile display (a	Using rigid movable	Yes	No	No	[69]

instrument	piezoelectric sensor elements in a 3×10 pattern and a total size of 24×8 mm^2	tactile display with 4×8 tactels (TACTil Element)	elements to simulate force distribution in palpation.				
Area-based haptic palpation simulator	Null	A 5×6 pin array with a total size of 40×20×23 mm piezoelectric bimorphs	Designed for training residents how to perform diagnosis or surgery	Yes	No	No	[46]
HAptic Sensor Actuator System (HASASEM)	Ultrasound real-time elsatography	A tactile actuator array using electrorheological fluid	Simulates stiffness directly allows users to conduct palpation while imaging and conducting a biopsy	No	No	No	[66]
Magnetorheological fluid based tactile display	Null	A single magnetorheological fluid-based tactile element	Simulate stiffness directly. Miniaturization is needed.	No	No	No	[68]
A multi-modal tactile display device	Null	Two springs: the Elongation Spring and Stiffness Spring	Displays both surface shape and stiffness.	No	No	No	[70]
Pneumatic balloon actuators	Commercial single-element piezoresistive force sensors (FlexiForce, Tekscan)	A pneumatic balloon tactile display	Can be mounted directly onto the hand controls of the da Vinci surgical robotic system	No	No	No	[61]

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