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Application of tactile sensing in human-computer interaction in robot-assisted surgery and medical fields

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Abstract. Robot-assisted Minimally Invasive Surgery (RMIS) is a revolutionary breakthrough in the field of surgery in 21st-century clinical medicine, and in recent years it has become the standard of care in Western medicine. It makes highly accurate medical operations possible based on the advantages of traditional minimally invasive surgery, such as reducing patient trauma and accelerating post-operative healing. However, the most advanced robotic-assisted surgical systems available on the market, as exemplified by the da Vinci system, are still not equipped with tactile receptors. In recent years, scientists and engineers have come up with different techniques and ideas, including various forms of tactile sensors, to improve the quality of the process. In this paper, the sensor devices that can be used for RMIS are classified into six different types based on their structural characteristics, and typical examples of them are listed. For some of the sensing structures that are only in the theoretical stage, inferences and explanations are given based on references. And the application directions are summarized as ‘tactile diagnosis’ and ‘operator sensing’. Research in the last decade in both areas of sensing technology is summarized and outlined respectively.

Keywords: Tactile Sensor, Robot-Assisted, Minimally Invasive Surgery, Human-Computer Interaction.

1. Introduction

Advances in medicine have spawned a revolution in surgical techniques. Minimally invasive surgery involves making a small incision of 0.5-3cm on the patient’s body surface, and laparoscopic instruments are passed through the small incision to perform the surgery, with visual feedback provided by the endoscope. It has the advantages of small incisions, less bleeding, and faster recovery. Also, the risk of infection is much lower with this procedure than with open surgery. However, it also restricts the surgeon’s range of motion, presenting new challenges such as the need for cumbersome body posture. As mechanical engineering continues to integrate with the medical field, the advent of robot-assisted minimally invasive surgery (RMIS) appears to be another major breakthrough in surgery. During RMIS, the surgeon only needs to operate the main control panel from a console 2 meters away from the patient, and the robotic arm can manipulate the instruments to perform the operation instead [1]. The surgeon can remain comfortably seated throughout the process. This technology eliminates the inconvenience of changing the surgeon’s position so often, as is the case in minimally invasive surgery. What’s more, the robotic arm tends to have a higher degree of precision

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than the surgeon. Moreover, robotic arms avoid the trembling in large and complex surgeries due to muscle fatigue that occurs in the human body over time, ensuring safe surgery. The da Vinci system is the most advanced and famous of these [2].

In traditional open surgery, the surgeon obtains physical information about deeper tissues, such as tumors, by touching the tissue with his or her hands, as most diseased tissues are harder than their surroundings. On the other hand, haptic feedback facilitates the surgeon's judgment of the force to be applied during tissue manipulation to support decision-making, thus preventing damage to sensitive tissue. Because the robotic arm replaces direct contact between the surgeon and the tissue, haptic feedback to the surgeon via a haptic sensing system is required. Unfortunately, until now, no haptic sensing technology has been available for commercial surgical robots.

In order to reconstruct realistic haptics in robotic applications, a variety of sensing devices and complex behavioral control systems are required to sense and interpret different types of stimuli. Haptic sensors have seen an active development in the early 21st century, among which are also applications in the medical field [3]. Chi et al. and Bandari et al. provided detailed reviews of the development of tactile sensors and their application in minimally invasive surgery [4,5]. However, the haptic sensors used in RMIS must fulfill higher requirements. Haptic information needs to be collected sent and presented at the operating end. Force feedback and haptic feedback are the two modes to be implemented in haptic sensors and they have different effects on the system. Therefore finding the best trade-off between the two modes is one of the important research directions at this stage. This paper presents emerging cases of the technology in two application areas in recent years from an application point of view, respectively, with several of the most recent studies using sensing systems combining the two modalities.

2. Type of tactile sensor structure

Tactile sensors directly contact soft tissues in vivo, making their structural characteristics and sensing principles particularly important. Various tactile sensors are categorized and outlined in this section based on these two criteria.

Many researchers have worked on providing efficient solutions to this problem in recent years. Existing solutions can be broadly classified into contact devices based on indentation, suction-based devices, fiber-optic devices, and non-contact devices, as well as laminar structures and sensing arrays that combine several sensing elements. Some of these structures have been developed as specific sensing devices, and some still do not have concrete technical examples due to technical limitations or theoretical inappropriateness.

2.1. Indentation-based contact devices (Palpation)

The contact probe is the most often used haptic device design in surgical applications, a construction principle usually used for manual tactile probing or palpation, as shown in figure 1. A force is applied to the target tissue thereby creating strain. The sensor equipment then measures the stiffness of soft tissue which was contacted. In order to obtain a high degree of accuracy, the cross-sectional area of the probe should be as small as possible without damaging the tissue. The most common are force and torque-based sensors, a typical application is the use of strain gauges to form multidimensional sensors, researchers have designed a new triple-torque sensor that accurately reflects the values of force and torque between the tissue and the arthroscope during surgical procedures that are applied to the joint cavity through an endoscope [6]. Another indentation contact device works based on fiber optics, where light intensity indicates force feedback from the tissue. In a study by Knoop et al, a dual-mode sensing scheme was utilized to actualize fast ringing and more accurate force measurements for palpation [7]. In addition to this, resonant frequency is the third method, where the probe undergoes a phase shift in vibrational frequency when in contact with the tissue, with different elastic tissues resulting in different magnitudes of phase shifts.

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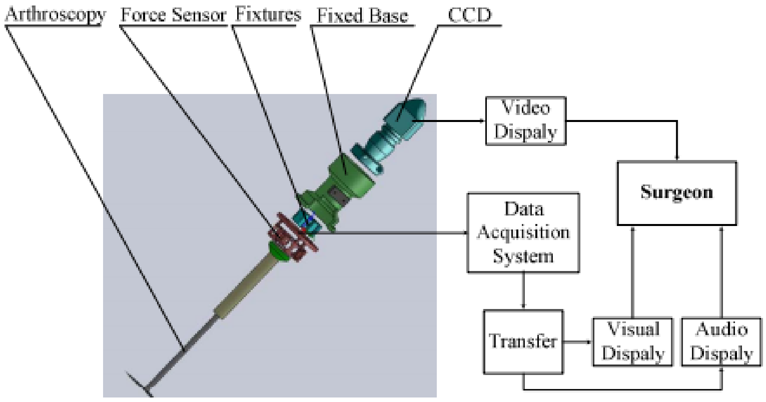

Figure 1. Typical structure of the probe based on indentation principle [6].

2.2. Suction device (Palpation).

Another structure used for palpation is the inhalation or aspiration of the target tissue using a pipette device, which is used for tumor detection. However, the time consumption is greater because the target area must be aspirated and then released. And the pipette should be positioned very accurately in order to collect information from the entire organ. Probably this is the reason why this method is only in the envisioning stage.

2.3. Catheters with tactile sensing elements (Palpation)

Catheter structures are widely used for minimally invasive cardiac surgery. During the introduction of the catheter into the body, the force feedback of the tissue needs to be detected to avoid damage. This process is usually performed under MRI monitoring, making fiber optic sensing a suitable technique. Alternatively, a combination of multiple sensing may be an optimized solution. a multifunctional balloon material studied by Kim et al was used to can provide sensors for measuring temperature, flow, haptic, optical and electrophysiological data, and experimental data acquisition was accomplished in vivo in animals [8]. Figure 2 demonstrates the acquisition of tactile signals in the right ventricular vessels of a rabbit.

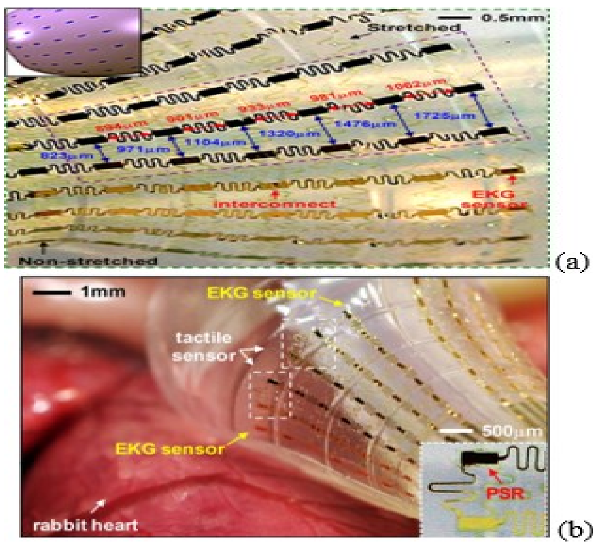

Figure 2. (a) Enlarged view of the non-coplanar interconnection on the balloon under expansion. (b) An instrument balloon catheter in a dilated state, a sensor array in direct contact with the surface of the right ventricle. The tactile sensor is inside the dotted white box, with a larger view in the lower right corner [8].

2.4. Layered structures (Both)

Strictly speaking, laminar structure is not a new sensing principle. It is simply a structure formed by combining and arranging sensors and materials with different functions, thus combining various advantages. Piezoresistive, piezoelectric, and capacitive sensing materials can all be designed to achieve specific combinations. Because of better stability during static single-point measurements, this structure is more suitable for gripping force feedback on the device surface.

2.5. Array sensors (Both)

Sensing arrays hold great potential for RMIS applications as circuit integration technology improves. Similar to the above one, the array structure also allows multiple tactile receptors to be used for sensing and comparison. The number of sensors determines the sensitivity of the sensing array, but also affects the size. Sensing elements made with Micro-electro Mechanical Systems are easy to fabricate and small in size, so they can be integrated into the gripper at the end of the robotic arm. Another advantage is that the output can be used directly for tactile displays.

2.6. Non-Contact Devices (Tactile)

The basic working principle of this method is based on the measurement of applied deformations. The most convenient method is to apply airflow to the target tissue and estimate the resulting indentation effect through the visual feedback image obtained by the endoscope. Visual feedback system combined with a deep learning model can optimize the estimating result. Its main advantages are continuity and the possibility of detecting soft tissues in real time. In addition, because there is no more direct contact, interference from tool-tissue interaction is ruled out. However, achieving a fixed camera position in surgery is difficult. The computational speed of the model determines the time required.

The information presented above indicates that most haptic sensing technologies detect and localize soft tissues, which we call ‘palpation’. It is also true that the majority of studies in the survey of technologies based on the application of haptic sensing technologies in robotic-assisted surgery have been directed toward palpation. The next section summarizes and presents various tactile sensing technologies based on different principles targeted for research in the last decade with two main types of RMIS applications.

3. Two kinds of applications in RMIS

The application of haptic sensors in RMIS can be broadly categorized into two directions: detecting and localizing lesion areas in tissues and detecting the contact force of surgical instruments on the end of robotic arms with tissues. Surgeons must remove diseased tissue and preserve healthy tissue as accurately as possible when performing surgery, reducing surgical trauma and shortening postoperative healing time. Knowing the tumor’s exact location allows the surgeon to achieve this goal. Since the mechanical properties of the vast majority of healthy tissues differ dramatically from those of diseased tissues - the modulus of elasticity of tumor tissue is about ten times higher. This makes artificial haptic transmission possible, i.e., applying tactile sensors in detecting diseased areas. Haptic feedback during surgery and visualization of the surgical site can help enhance the dexterity and controllability of surgical instruments, thereby improving the quality of tool-tissue interactions and helping to reduce unnecessary trauma. More importantly, surgeons need force feedback to determine whether the force they apply to the tissue is appropriate. Thus, the lack of haptic feedback during RMIS could lead to serious accidents, making the surgery more difficult. Table 1. summarizes the structure and sensing principles of the six different haptic sensors presented below.

Table 1. Tactile Sensor Classification for Surgical Application.

Construction principle	Application
Contact Device Based on Indentation Principle	Palpation
Aspiration Devices	Palpation

Table 1. (continued).

Catheters with Tactile Sensing Elements	Palpation
Layered Structure	Vigorous feedback & Palpation
Array Sensors	Vigorous feedback & Palpation
Non-contact Devices	Palpation

3.1. Palpation

Traditionally, one of the most important steps in surgery is to identify the position and area to be performed, and during RMIS as well, by touching the soft tissues in order to detect abnormal areas. A sensing system can only achieve this goal since the robotic arm replaces the direct contact between the surgeons and the tissue. However, because of the relative simplicity of achieving this goal, it is considered the most promising aspect of implementing haptic feedback in RMIS. An important point in sensing systems for tactile diagnosis is how to quantify the amount of force applied. Currently available techniques are categorized as direct force perception, indirect force perception, and force judgment with the aid of vision.

3.1.1. Direct force sensing. The most common approach to direct force sensing is based on elastic deformation, combining strain gauges into specific structures and incorporating a film of flexible material to enable tissue-specific detection. The first to propose this technique was Yamamoto et al., who selected the Hunt-Crossley model to estimate the acting forces through self-validation and 25 cross-validations [9]. The model yielded mean and standard deviation in self-validation and cross-validation of 0.245, 0.235, 0.431, and 0.271, respectively, in the experiments of force estimation of target tissues in phantom. This study used least squares to calculate the missing parameters, combined with interpolation and successfully obtained colour maps expressing the stiffness of hard tissues within the soft material in the model in terms of hue-saturation-luminance (HSL). In a study, McKinley et al. designed a device that could be mounted on the da Vinci system for probing the location of subcutaneous blood vessels using a Hall effect sensor to measure the deflection of the probe tip [10]. The results showed that the probe could be used in sliding or rolling mode for stable detection of structures up to 5 mm below the tissue surface with a diameter of 2.25 mm.

The advantages of this method are its ease of implementation and low cost. However, it needs to be placed inside the body, so sterilization and size requirements and stability for operation in sliding and vibration environments must be considered.

3.1.2. Indirect force sensing. Indirect force sensing techniques include acoustic reflection, probe media pressure, and piezoelectric material sensing. Figure 3 illustrates the basic structure of a piezoelectric sensor and a schematic diagram of its operating state. For example, Ju et al. proposed a small-diameter miniature tactile sensor suitable for hardness palpation of catheterized robotic tissue, which can operate in the frequency range of 675-978 Hz [11]. By extracting the resonant frequency of the sensor, the hardness of the load can be detected based on the electrical impedance of the sensor. Combined with the k-means algorithms, the shape and position of the mass can be detected. The system has a stiffness measurement error of less than 2.5% when dealing with soft tissues with stiffness up to 2000 $N \cdot m^{-1}$. Although the accuracy and sensitivity of the system is strongly influenced by the load stiffness. Another example is the study by Zhang et al [12]. A miniature piezoelectric tactile sensor was proposed to detect tissue hardness by measuring the electrical impedance spectrum, which is able to measure in both transverse and longitudinal directions, possesses high deflection and is less limited by the contact angle, and has high sensitivity and accuracy in non-vertical conditions.

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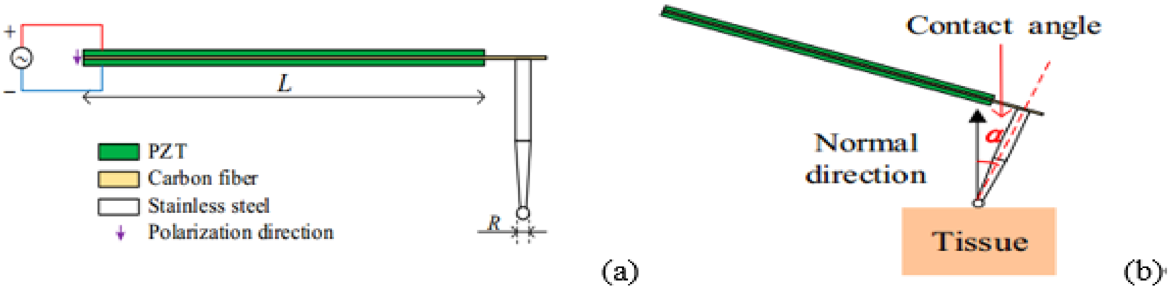

Figure 3. (a) The basic structure of a piezoelectric sensor. (b) In application, α refers to the angle between the tip of the probe and the normal direction of the tissue surface [13].

In addition, Fiber Bragg Grating (FBG) force sensors are considered as one of the most suitable materials for palpation probes due to their small size, high-temperature resistance, and immunity to electromagnetic interference. Lai et al. proposed a triaxial force sensor based on FBG, which can be integrated into an endoscopic endo-wrist to display real-time tool-tissue interactions [14].

3.1.3. Palpation with vision-based force estimation. Another method is estimating the force based on endoscopic imaging, which is the most used method. Its main advantage is that it does not require the addition of additional equipment. However, this method is often accompanied by a large number of operations. With the development of artificial intelligence technology, neural networks are increasingly applied to imaging algorithms. A new force estimation method was proposed in a study by Aviles et al., combining a vision-based solution with deep learning to find a mapping between the force exerted by the instrument and the tissue deformation to estimate the applied force [15].

3.2. Operator sensing

Surgeons rely on tactile and force feedback to feel the tension of the thread during suturing and to perceive the grip force when operating. More importantly, the surgeon needs to sense the pressure exerted by the instrument to avoid damaging tissues and blood vessels during the operation. In RMIS, achieving all these goals is based on sensors of various modalities.

Sense of touch is a combination of two feedback forms, kinesthetic and tactile, as can be learnt in detail in [16]. Tactile receptors are sensitive to higher frequencies; conversely, kinesthetic receptors are sensitive to lower frequencies. Therefore, a sophisticated haptic sensor should have both force and tactile feedback mechanisms, corresponding to kinesthetic and haptic sensations respectively, in order to perceive it without direct contact, which is called “Transparency”.

The purpose of force feedback is to allow the surgeon to feel the position of the instruments in relation to each other inside the body, ensuring better control of the force the surgeon applies to the tissue. However, this feedback is detrimental to stability. A classical approach to simulate force feedback through vibration was proposed in [17].

Haptic feedback is used to sense the physical properties of an object. Although this is more important in palpation, it still influences the surgeon’s judgment on applying force. In other words, haptic feedback increases the transparency of the system. Haptic feedback is measured in the force or torque at the main end. In their study, Kanjanapas et al. received the signal at the main end, directly in contact with the surgeon’s finger, producing a more realistic stimulus [18]. Although this feedback is not harmful to the stability, haptic feedback is less efficient than force feedback. Therefore, a combination of both modalities is often used in recent studies. An example is, in a research Li et al. proposed a surgical state sensing utilizing a sensing system mounted on the end of a robotic arm with a combination of acceleration and force sensors [19]. A one-dimensional CNN based on the Sinc-convolutional layer is proposed with which the intraoperative signals obtained are analyzed. In the state analysis for blockage, the accuracy of the bimodal signal source model is 96.8%, relative to

94.7% for a single vibration signal and 64.3% for a single force signal. The result demonstrated the positive impact of the combination of bimodal signals on improving the accuracy of the system.

Rehan's study proposed a multiaxial soft magnetic tactile sensor [20]. The applied force can be calculated based on the voltage change due to the displacement of a neodymium magnet embedded in the sensor. The sensing range in the normal, tangential, and torque directions is 20 N, 3 N, and 1.5 N, respectively, corresponding to resolutions of 16 mV/N, 30 mV/N, and 81 mV/N. In addition, the sensor has a resolution of up to 5 mN, while having only 8.4% hysteresis. Hooshiar et al. also proposed a novel force feedback mode based on magnetostriction [21]. In addition, Ehrampoosh et al. proposed a novel force-sensing device based on indirect force estimation based on a data model for suturing in RMIS [22]. In which the operator obtains information about the needle-tissue interaction force simulation through an impedance-controlled sensing system.

4. Conclusion

The diagnosis of lesion location and many operations during surgery rely on haptic feedback combined with the surgeon's experience. The absence of physical contact in robot-assisted surgical techniques has eliminated direct haptic feedback during surgery. In almost all RMIS, only visual feedback can be relied upon to determine the force applied to the tissue. This is a great challenge to the operating precision of the practitioner and the inexperienced surgeon. Therefore there has been an objective need for tactile sensors in the industry. Accuracy, stability, sensitivity, cost, resistance to high temperature and humidity, and non-magnetic materials must be considered in developing tactile sensors for use in RMIS instruments. After more than ten years of research, there are more results in the research of sensor application technology in tactile diagnosis. There have been relatively well-established setups with high accuracy and stability in single-point static measurements. However, practical applications require dynamic scanning to detect organs' mechanical parameter information. It is still not possible to achieve the required sensitivity, and prolonged operation is not acceptable during surgery. In addition, relative to the many technological studies in haptic diagnostics, there are still fewer research reports and results obtained for haptic sensing techniques used to sense contact forces between the end of the instrument and the tissue, due to the impact of system stability and transparency.

Given that the medical field is much more careful about implementing any new system. This aspect of the application still requires further research, and the existing results are still far from the reliability needed to be put into clinical use. Due to the extremely important impact of this technology on surgical procedures and the use of RMIS in an increasing number of different types of surgical procedures, if information related to haptics can be fed back, it will greatly contribute to the improvement of healthcare and the spread of applications to meet the growing demand.

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