Tactile Sensing Systems for Tumor Characterization: A Review

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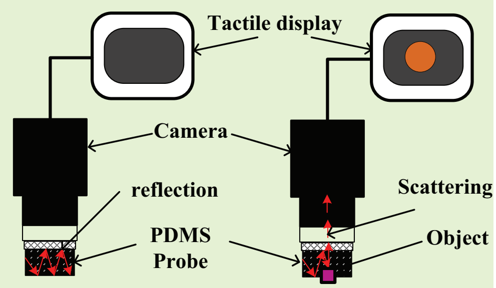
***Abstract*—This paper presents a review of Tactile Sensing Systems, with an emphasis on their application to the non-invasive characterization of tumors. Emulating the perceptual mechanism of the human skin, the Tactile Sensing Systems characterize tumors using touch sensors by quantifying the mechanical properties such as size and elasticity. The authors survey several tactile transduction methods: capacitive, piezoresistive, piezoelectric, magnetic, and optical. The advantages and disadvantages of different tactile sensors are discussed. The complex human sense of touch is emulated using tactile sensor data, novel data processing algorithms, and near real-time interpretation in a human-readable format. Tactile Sensing Systems utilize tactile sensors and other subsystems to come up with accurate mechanical properties of the touched objects. We review Elasticity Determination Systems, which are a special case of Tactile Sensing Systems. These systems are based on capacitive sensors, piezoelectric sensors, elastography, and optical tactile sensors. Then the optical Tactile Sensing System is discussed in detail; architecture, sensing principle, and algorithms to compute a risk score. Moreover, a survey of multimodal Tactile Sensing Systems, which broaden the capabilities of existing tactile sensing systems, is presented. The paper concludes with discussions and future research directions.**



***Index Terms*—tactile sensors, elasticity, multiple-sensor systems, imaging sensors, integrated optics sensors, tactile sensing, touch sensors, mechanical imaging, Young's modulus**

I. Introduction

THIS paper reviews research in the area of tactile sensing systems. Tactile sensors are a special type of sensors which obtain information through physical touch. A tactile sensor may measure hardness, temperature, vibration, wetness, shape, pressure, and/or vibration. Tactile sensors have been in development for over 40 years and an excellent review of the tactile sensors is given in [1], [2]. The main differences among various tactile sensors are the transduction methods. There are capacitive, piezoresistive, piezoelectric, magnetic, and optical transduction methods. We review these methods in the next section. Tactile sensing systems are based on touch sensors. Harmon first studied tactile sensing systems for robotic applications over 30 years ago [3]. Lee published a review of tactile sensors in 2000 [4]. Here, we review different tactile transduction methods. In 2003, Eltaib and Hewit studied tactile sensing for minimally invasive surgery [5]. Wettels demonstrated how sensors can mimic human skin [6], with a special focus on robotic applications. Recently, other applications of tactile sensor have emerged. Capacitive tactile sensors are used for clinical breast examination [7] and the small tactile sensor was used in oral cancer screening in [8].

In 2009, Najarian and Dargahi [9] published a comprehensive book about tactile sensing for biomedical applications. More recently, researchers published a comprehensive review of tactile sensors with applications in biomedical engineering [1], [2]. However, they focused on touch sensors. In this review, we focus on the system concept, where we utilize tactile sensors and processors to develop a system with more functions.

Tactile sensing systems allow the measurement of one or more of aforementioned touch sensations. This is a complicated mechanism that requires a multiple sensors and processors. Tactile sensing systems are known in the literature as mechanical imaging [10], [11], elasticity imaging [12], [5], or tactile sensation imaging [13]. In biomedical applications, tactile sensing systems measure embedded tumor properties such as size, depth, and elastic modulus. In the last three decades, various groups from Harvard University [14]–[16], Artann Laboratory [10], and Temple University [13], [17], [18] have been working on the development of tactile sensing systems.

Harvard University researchers developed a handheld scanner consisting of a distributed pressure sensor and magnetic tracker for documenting the mechanical properties of the palpable lumps [15], [16]. Artann laboratories developed a breast mechanical imaging system consisting of a probe with a pressure sensor array, an electronic unit, and a laptop [10],

Submitted July 2020, "This work was supported in part by the U.S. Department of Defense, CDMRP W81XWH-16-1-0035."
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[11]. Temple University researchers have been utilizing high-resolution charge-coupled-device (CCD) sensors to capture the tactile information [17]–[19]. Here, we review various different tactile sensing systems with focus on biomedical applications.

This paper reviews the tactile sensing transduction methods and their applications in Section II. Then the authors review the tactile sensing system for hardness or elasticity determination. In Section IV, multimodal tactile sensing systems are discussed. Finally, we discuss various tactile sensing technologies and future research directions.

II. Tactile Transduction Methods

Many artificial tactile sensors have been developed over the past decade to mimic the tactile spatial resolution of the human finger [20]. Tactile sensors are an integral part of the Tactile Sensing System. This section provides a review of tactile transducers. Artificial tactile sensors can be categorized using different sensing principles. Sensing mechanism, defined as the conversion of one form of energy into another, occurs when human mechanoreceptors receive stimuli and transduce physical energy into a nervous signal. Several types of artificial tactile sensors exist which emulate the different sensing mechanisms. In this section, some examples of artificial tactile sensors are presented.

A. Capacitive Sensors

The capacitive type of tactile sensor transforms the applied force into capacitance variation [21], [22], [23]. The basic principle behind capacitive sensors is that they monitor changes in capacitance resulting from contact. A single tactile sensor consists of three layers with parallel-plate capacitors and dielectric materials between the plates. The dielectric layer is usually made up of air or silicone. If force is applied to one plate, the distance between two of the conductive plates decreases, resulting in increased capacitance [24], [25]. By measuring the increased capacitance, the tactile data can be perceived. A diagram of a typical capacitive sensor is shown in Fig. 1. Let A be the area of the plates and d be the distance between the top and bottom plates, with d being much smaller than the plate area. The capacitance of the cell can be expressed by

$$C = \varepsilon_0 \varepsilon_r (A/d), \tag{1}$$

where $\varepsilon_0 = 8.85 \times 10^{-12} F \cdot m^{-1}$ is the permittivity and ε_r is the dielectric constant of the dielectric layer [26].

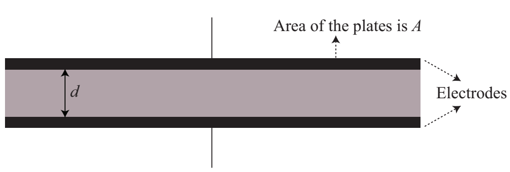

Fig. 1. The schematic of capacitive sensor [26].

The main advantage of capacitive sensors is their high density due to the small size of the sensor [27], [28]. Some researchers have reported capacitive sensor arrays within a 1 mm spatial resolution; which is compatible spatial resolution to that of human mechanoreceptors [29]. The disadvantages of this type of sensor include significant hysteresis and temperature sensitivity [27].

Capacitive tactile sensors have seen significant progress in recent years. Low-cost tactile sensors for minimally invasive surgery have been developed [30], which are purely sensors and not a complete system. Mechanical imaging method of [31] is similar to our optical tactile system, but uses different technology. This is based on pressure sensors similar to [14]–[16].

B. Piezoresistive Sensors

The tactile sensing method for piezoresistive sensors is to monitor the resistance change in a conductive material under the applied force [32]. The resistance value is maximum when there is no force, and it decreases as the applied force increases. The conductive layer is typically made from carbon [25]. Fig. 2 shows a schematic of the cylinder-shaped piezoresistive sensor [26]. The advantages of these types of sensors are their high sensitivity, low cost, and wide dynamic range [25]. However, they can measure only a single touch point, not a simultaneous multiple touch points. Also, these types of sensors typically consume a great deal of power. Their limited tactile spatial resolution is another disadvantage [33]. Miniature portable tactile sensors can generate the softness information but do not sense the elastic modulus [34].

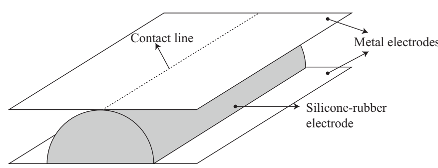

Fig. 2. The schematic of piezoresistive sensor [26].

C. Piezoelectric Sensors

Piezoelectric sensors use the piezoelectric effect in which voltage is generated across a piezoelectric material when the force is applied [35]. Fig. 3(a) and Fig. 3(b) show the general concept of the piezoelectric mechanism [26]. In a piezoelectric material, the dipoles are randomly spread out if no voltage is applied. Once electricity is applied, the dipoles are aligned along the direction of the applied electric field. Under this condition, when the sensors are pressed by an external force, the dipoles shift from the axis causing the charges to become unbalanced and the voltage to be induced [36]. The applied force is measured by the generated voltage due to the imbalance in charge. Many tactile sensors have been developed based on the piezoelectric mechanism [27], [37]. These types of sensors have a wide dynamic range and durability. They are also simple, inexpensive, and easy to fabricate; however, they are sensitive to temperature [38]. Furthermore, as with piezoresistive tactile sensor, limited tactile spatial resolution and hysteresis are disadvantages [36]. More recently, a variable-impedance piezoelectric tactile sensor has been developed for roughness sensing [39], [40].

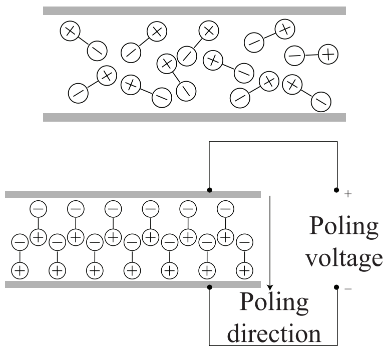

Fig. 3. A schematic of a piezoelectric sensor. (a) Randomly directed dipoles in ceramic structure [26]. (b) Alignment of dipoles in the direction of applied electric field [26].

D. Magnetic-Based Sensors

Magnetic-based sensors measure the movement of a small magnet by an applied force-generating flux density. This phenomenon is known as the Villari effect [41]. The sensor uses magnetoelastic material, which deforms under force, causing changes in its magnetic characteristics [42]. A micro-machined, magnetic-based sensor is introduced in [43], demonstrating that the sensor is very small, sensitive, and requires little power. The general advantages of the magnetic-based sensor include good dynamic range, lack of mechanical hysteresis, high sensitivity, and linear response. However, this type of sensor can be used only in non-magnetic objects, which is a major drawback. Magnetic tactile sensors using the hall effects are developed [44]. These types of sensors cannot be used with metallic materials nearby.

E. Optical Sensors

An optical sensor is also commonly used in artificial tactile sensors. This type of sensor uses the optical tactile sensing mechanism called “phenomenon of photoelasticity” [45]. When pressure is applied to the photoelastic sensing probe of optical sensors, teh change in intensity of the injected light can be measured. Various research groups have explored optical sensors for tactile sensing, primarily because these sensors are immune to electromagnetic noise, and have the ability to process tactile data using a charged-coupled device (CCD) without complex wiring [46]. In [47], optical sensors are developed using an elastic sheet and a transparent board parallel to the sheet. The applied force makes the protrusion contact the sheet, and the amount of force is measured by the contact area. In [48], an optical sensor which uses markers inside an elastic body and a fiberscope is introduced. The sensor is formed as a miniaturized fingertip shape, which measures a relatively small amount of force. An optical-based three axial tactile sensor capable of measuring the normal and shear forces is also reported in [49], [50], [51], [52]. The general advantages of this type of sensor include its high resolution, flexibility, sensitivity, and electromagnetic interference immunity. Common disadvantages are loss of light by chirping and bending, difficulty in calibration, as well as bulkiness [51], [53]. Recent MEMS technologies allow the sensor unit to be tightly integrated into the system, so the limitations of spatial resolutions is improved [40]. Moreover, in optical sensors, the compact CCD cameras are integrated into robotic fingers so that the transmission loss of light minimized [54].

F. Discussions

Different tactile sensors have different characteristics based on the transduction methods. The advantages and disadvantages of different tactile sensors are summarized in Table I. Capacitive (high sensitivity) and piezoresistive (good spatial resolution) tactile sensors are widely used in robotic applications. However, piezoelectric (poor spatial resolution), inductive (poor reliability), and optical (bulky in size) tactile sensors are not widely used for robotic applications. These sensors need to be re-evaluated in tactile sensing systems, where processors and other hardware/software are incorporated for a specific application. This section introduces various tactile sensing systems such as an elasticity determination system.

Although various tactile sensors are widely used in robotics, these sensors have limitations in emulating the human sense of touch because human touch sensation has many different modalities. Human touch sensation can detect softness versus hardness, wetness versus dryness, heat versus cold, smoothness versus roughness etc. To emulate the human sense of touch, we need to make the sensor into a system. Thus, we are extending the tactile sensors into a tactile sensing system.

III. Tactile Sensing Systems for Elasticity Determination

Over the past two decades, various methods have been devised for measuring or estimating soft tissue stiffness [74], [75]. Generally, this is called “elasticity determination system.” In this section, we review Tactile Sensing Systems for elasticity determination.

A. Tactile Sensing with Elastography

Elastography is a non-invasive method in which tissue elasticity is used to detect or classify tumors [76], [77]. When a compression or vibration is applied to the tissue, the included tumor deforms less than the surrounding tissue. Under this observation, elastography records the distribution of tissue elasticity [78]. Elastography has been successfully applied to tumor characterization to improve diagnostic accuracy and surgical guidance.

Ultrasonic elastography is the most intensely investigated area of elastography [79]. There are three types of ultrasonic elastography: compressive elastography, transient elastography, and sonoelastography. In compressive elastography, controlled compression of the transducer probe is loaded to the tissue, and signals of pre- and post-compression are compared to calculate the tissue stiffness distribution map [80]. Compression is applied by the operator or the external compressor attached to the transducer probe. Transient elastography uses a

TABLE I
DIFFERENT TRANSDUCTION METHODS FOR TACTILE SENSING.

Transduction Methods	Advantages	Disadvantages	Applications, references
Capacitive (change in capacitance)	Highly sensitive Excellent spatial resolution Wide dynamic range Insensitive to temp. variation	Affected by stray capacitance Susceptive to noise Need complex electronics Cross-talk Nonlinear Hysteresis	Robotic hands Medicine Biomedical [55]–[58]
Piezoresistive (change in resistance)	Excellent spatial resolution High scanning rate Simple construction Low cost	Low repeatability Nonlinear Hysteresis High power consumption	Robotics Hardness detection Knee prosthesis [59]–[61]
Piezoelectric (change in strain polarization)	Good accuracy Highly sensitive High frequency response Wide dynamic range	Poor spatial resolution Only dynamic sensing Charge leakages	Telemanipulator Minimally invasive surgery [62]–[65]
Inductive LVDT (change in magnetic coupling)	Linear output Highly sensitive Wide dynamic range High power output	Low spatial resolution Bulky in size Low frequency response Poor reliability High power consumption Moving parts	Biomimetic Artificial mechanoreceptor [66]–[68]
Optical (light intensity)	Wide sensing range High reliability High repeatability High spatial resolution Immunity from EMI	Bulky in size Non-conformable Susceptible to temp. variation Susceptible to misalignment	Underwater robot Robotic finger Humanoid robot Roughness measurement [19], [69]–[73]

transient vibration, produced by the transient probe, to create tissue deformation. The transient probe consists of a transducer probe that is located at the end of a vibrating piston. The piston produces a vibration of low amplitude and frequency, which generates a shear wave that passes through the tissue. The quantity of tissue deformation is then detected by pulse-echo ultrasound.

Sonoelastography uses a real-time ultrasound Doppler technique to record the propagation pattern through the tissue with low-frequency shear waves. The linear array broad-band transducer probe with a frequency range of 6 to 14 MHz is used to produce the low-frequency shear waves.

Ultrasonic elastography in three different groups is carried out with the same equipment except for the transducer probe. The software algorithm embedded in the module is different for each group. Ultrasonic elastography is a well-developed method and can be used in a wide range of medical applications [81], [82]. However, compared to the Tactile Sensing System of this paper, ultrasonic elastography is computationally expensive, making it challenging to display data in real-time. Another disadvantage is that ultrasonic elastography is very expensive. Fig. 4(a) shows a conventional ultrasonic elastography modality and Fig. 4(b) shows the breast elastogram.

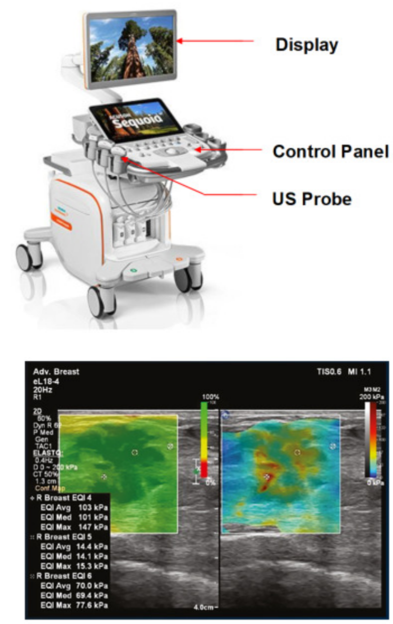

Fig. 4. The ultrasonic elastography system and its image sample. (a) The conventional ultrasonic elastography modality [83], (b) The breast elastogram [84]

B. Elasticity Imaging with Capacitive Sensors

A technological method entitled "elasticity imaging using tactile sensor" has been explored [12], [5]. This type of technology calculates and visualizes tissue elasticity by sensing mechanical stresses on the surface of tissues using tactile sensors. Elasticity imaging using tactile sensors is also called mechanical imaging, tactile imaging, elastic modulus imaging, or biomechanical imaging [12], [5], [85], [86].

The medical device named "SureTouch Visual Mapping System" produced by Medical Tactile Inc. is an elasticity imaging system using capacitive tactile sensors [87]. The device consists of a probe with capacitive pressure sensor arrays and electronic units to transmit tactile data to the computer. Using a 32×32 capacitive tactile sensor array, the device obtains the stress distribution on the tissue surface [88], [89]. The device is capable of computing and visualizing the pressure pattern of the tissue. One advantage is that it is small and portable, thus it is easy to use. Also, it utilizes no ionizing radiation and magnetic fields, unlike CT or MRI. A disadvantage is that the tactile spatial resolution of the device is not as good as the optically based tactile sensing method. Thus, obtaining precise tissue stiffness map through this device is difficult and requires extensive calibration. Moreover, the device is expensive as it requires extra sensors to detect the applied force.

To estimate tissue inclusion parameters using tactile data obtained from capacitive tactile sensors, different approaches have been explored. In [88], the finite element modeling (FEM) based forward algorithm and Gaussian fitting model-based inversion algorithm are devised. This work was extended to attempt to find a more complete set of tissue inclusions. They showed that the estimation results are more accurate in determining the size of a tissue inclusion than manual palpation. Nevertheless, the results are limited to tissue inclusions at least 100 times stiffer than the surrounding tissues. In addition, other tissue inclusion parameters such as depth and hardness are not available. In [89], the FEM based forward algorithm and transformation matrix based inversion algorithm is proposed to estimate the size, depth, and hardness of the tissue inclusion. However, the relative error in estimating the tissue inclusion modulus was still large (over 90%). Fig. 5 shows the SureTouch Visual Mapping System using capacitive tactile sensors [87].

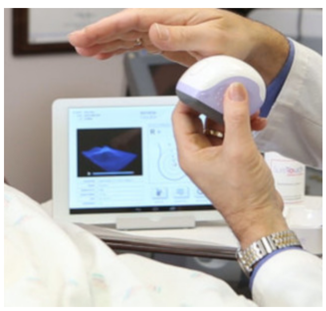

Fig. 5. The SureTouch Visual Mapping System of Medical Tactile Inc., [87]

C. Elasticity Imaging Using Piezoelectric and Piezoresistive Sensors

Another type of elasticity imaging system using tactile sensors is the "piezoelectric finger (PEF)" [90]. Here, the micro-machined artificial finger using a piezoelectric tactile sensing mechanism is introduced. The PEF is a type of cantilever system. For driving, a top layer consists of piezoelectric zirconate titanate (PZT); for sensing, a bottom layer consists of PZT [91]. In the initial condition, an electric field is induced to the top layer for driving, causing the PEF to bend. Under this condition, if an external force is applied to the sensing layer, the sensing layer bends more and the voltage is induced across it. By measuring this voltage, the PEF measures the elasticity of the target. The PEF has several advantages, such as low cost, small form factor, and large dynamic range. However, it is sensitive to temperature variation and, thus requires somewhat extensive calibration. Furthermore, limited spatial resolution and hysteresis are disadvantages. Fig. 6 shows the PEF using PZT [91], [92].

The elasticity imaging system using a piezoelectric polyvinylidene fluoride (PVDF) tactile sensor is also investigated in [93]. The PVDF sensor structure consists of three layers. The top layer is a tooth-like protrusion using a silicon wafer. The middle layer is a patterned PVDF film and works as a transducer. These two layers are sustained by a plexiglass

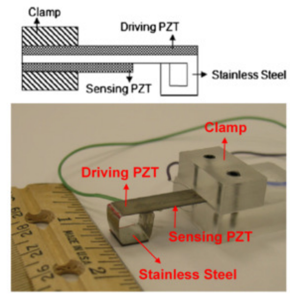

Fig. 6. The piezoelectric finger using piezoelectric zirconate titanate (PZT) [91], [92].

bottom layer. Although PVDF is capable of measuring tissue property such as hardness, the calculation of other important parameters such as size, depth, and shape is still unavailable. To estimate tissue inclusion parameters using PVDF, the FEM based forward algorithm and artificial neural network (ANN) based inversion algorithm is investigated in [93]. For the ANN training algorithm, they used the resilient back-propagation algorithm. In their work, a small number of forward algorithm data used to train an inversion algorithm also makes the parameter estimation results less accurate. Also, the calculation of inclusion parameters such as size, depth, and shape is still not available. In addition, the performance of the proposed method was validated using only simulated data without phantom experimental data or clinical data.

The piezoresistive tactile sensor for tissue elasticity measurement is also investigated in [94]. In their work, an array of force-sensing resistors (FSRs) is integrated into the polymer sheet to get a tactile distribution of a target. The obtained low-resolution tactile image is improved by the super-resolution image processing algorithm. The study shows that the elasticity imaging system using FSRs can distinguish between a hard and a soft object. However, the absolute tissue inclusion parameter estimation is still impossible through this device and algorithms.

D. Tactile Sensing System with Optical Sensors

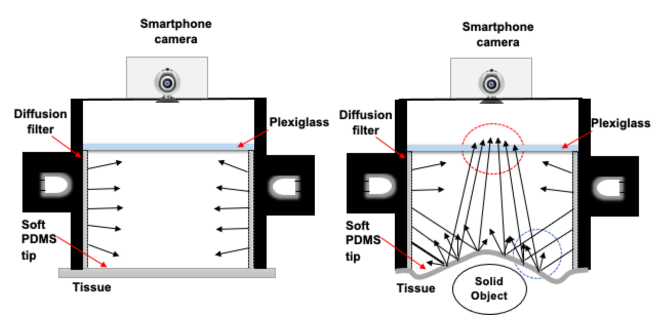

Fig. 7. Tactile Sensing Principle

1) Architecture of Tactile Sensing System: Tactile imaging is possible through two different principles. The first principle is the total internal reflection principle of the transparent elastomer. Light is injected into the elastomer at a certain angle and is totally and internally reflected within the elastomer.

When the contour of the elastomer changes, the light escapes. An image of the escaped light is captured by a camera. The second method is based on light diffusion. Light is injected into the elastomer through a diffusion filter and the diffused light generates multilayered intensity levels within the elastomer. The light gathers near the elastomer surface until the contour is disturbed, at which point the light escapes. This scattered light is captured by the camera. Initial Tactile Imaging Systems used the first method [17]. The second method is used in the current version of the Tactile Sensing System, which is discussed in [19], see Fig. 7. These images are processed by an algorithm to estimate the mechanical properties of the touched object.

The overall functional block diagram of the Tactile Sensing System is given in Fig. 8. The probe part consists of transparent, flexible elastomer (e.g. polydimethylsiloxane), light source (light-emitting diode), and constant current driver. The other part of Tactile Sensing System consists of a power unit, force sensor, processing unit, imaging unit (camera), and communication (WiFi) unit.

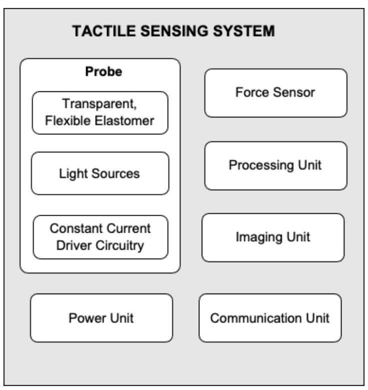

Fig. 8. Tactile Sensing System Functional Block Diagram.

2) Size Estimation Algorithm: Multiple tactile images are obtained from the imaging unit. The system then processes these images to come up with the mechanical properties of the compressed object. The object can be embedded such as tumors inside the tissue. The Tactile Sensing System estimates the size and elasticity of the touched object from tactile images. Here, we summarize the size estimation algorithm and the deformation index estimation algorithm. Deformation index is closely related to the elasticity. Tactile sensing requires robust data processing algorithms.

During clinical breast examination, doctors roughly estimate the size and depth of the tumors. This information is utilized to accurately determine tumor size using the three-dimensional (3D) interpolation method. The 3D interpolation models are developed to estimate the size of tumors from tactile images. The 3D interpolation method relates applied normal force, F, the sum of pixel intensities on the compression-induced image, I_p, and the diameter of the imaged inclusion, D. The multiple surfaces for different depth and sizes of inclusions are modeled based on these three parameters. Once the models are obtained, the force, F, is recorded from a force sensor, tactile image from Tactile Sensing System, and approximate depth from the user. Then, these modeled surfaces are used to estimate the size of the tumors using the following equation,

$$D(F, I_p) = \sum_{i=0}^{i=n} \sum_{j=0}^{j=m} p_{ij} F^i I_p^j. \tag{2}$$

The 3D model coefficients, p_{ij}, define the modeled surface. Indices n and m in the above equation denote the order of the polynomial for the size estimation. In this case, a third-order polynomial surface is developed for the 3D interpolation (i.e. $n = 3, m = 1$). The values of the developed 3D interpolation surface parameters reflect the inclusions' depth and size variations within the tissue. Four interpolation surfaces were built: large and deep inclusions, large and shallow inclusions, small and deep inclusions, and small and shallow inclusions. Depending on the application, the size and depth thresholds should be determined. For the human experiments, the threshold of 12 mm for size and 10 mm for the depth of inclusions were used.

3) Deformation Index (DI) Algorithm: The amount at which the probe tip gets deformed by applying a force is called the deformation index (DI). The experiments were performed with a custom-made silicone tissue phantom with embedded spherical inclusions. To determine the deformation index of the Tactile Sensing System, the probe tip, which is made up of polydimethylsiloxane (PDMS) is pressed against the spherical inclusions (tumor phantoms) placed inside the silicone tissue phantoms. The tumor phantoms could be soft or stiff and can be small or big. When the probe is pressed, the PDMS probe tip will deform. The amount of deformation depends upon the properties of the phantom. Under the condition that the applied force, depth of the tumor, and size of the tumor phantom are kept constant, the softer inclusion makes the probe tip deform less than the stiffer inclusion. Hence the deformation index for stiffer inclusion will be higher than for softer inclusions. Every image is defined as a multiple of 8-bit gray-scale numbers (0 to 255) with a size of 492×768 pixels. The reference force F_{ref} is applied to the contact region (phantom), which produces a reference image M_{ref} which is a 492×768 matrix. The ith tactile image, M_i is obtained after applying a force F_i. The change in the pixel intensities can be represented as

$$\Delta M_i = M_i - M_{ref}, \tag{3}$$

where $i = 1, 2, 3, \cdots$. The change in the force values corresponding to change in pixel intensity can be calculated as:

$$\Delta F_i = F_i - F_{ref}, \tag{4}$$

where $i = 1, 2, 3, \cdots$. The deformation index, DI, is the slope of the graph plotted with the sum of the pixel intensities ΔM_i vs. the change in the applied force ΔF_i, which is calculated using

$$DI_i = \frac{\sum_{l=1}^{m} \sum_{k=1}^{n} \Delta M_i^{l,k}}{\Delta F_i}, \tag{5}$$

where the $i-$th tactile image has l rows and m columns.

4) Risk Score Calculation: Risk Score is a unitless numerical value, which can be used as a scale to classify the tumor as malignant or benign. Based on the calculated size of the tumor and measured deformation index, the breast tumors are classified as benign or malignant using the scoring method. The Risk Score ranges from 0 to 5, where 0 represents the benign, and 5 represents the malignant tumor. A marginal threshold value was set, where any risk score below the threshold is considered benign. The calculated Risk Score is based on the below equation,

$$\text{Risk Score} = \left(\frac{W_1 \times S}{S_{max}} - \frac{W_2 \times DI}{DI_{max}} \right) R, \tag{6}$$

where W_1 and W_2 are the two weights used for size and deformation index respectively, S represents the estimated size value, S_{max} is the maximum estimated size value, DI is the calculated deformation index, DI_{max} is the maximum calculated deformation index. R is the highest value of Risk Score used.

IV. Multimodal Tactile Sensing System

Quantitative multimodality imaging can achieve a more complete characterization of a tumor and its surrounding environment. Combining two or more complementary imaging techniques provides more data and helps overcome some of the disadvantages of one modality imaging. Two examples of quantitative multimodality imaging are Positron Emission Tomography-Computed Tomography (PET-CT) and Positron Emission Tomography-Magnetic Resonance Imaging (PET-MRI) [95]–[97]. A comprehensive review is available in [98].

The diffuse optical tomography researchers found two advantages with regards to multimodal imaging. First, using prior anatomical information from various imaging techniques, such as magnetic resonance imaging, ultrasound, and X-ray, they enhanced the image reconstruction performance [99]–[103]. Brooksby demonstrated 32% reduction in error for the diffuse optical image reconstruction using prior information from MRI [101].

Second, multimodal imaging also improves the sensitivity and specificity for differentiating benign and malignant tumors. With the ultrasound-guided diffuse optical tomography, Zhi *et al.* showed an increase in sensitivity from 96.3% to 100% compared to the independent diffuse optical tomography. At the same time, the specificity showed an increase from 65.9% to 93.9% [103].

Motivated by the advantages of multimodal systems, the authors review a new class of tactile sensing system called, “Multimodal Tactile Sensing System (MTSS),” which may have the following characteristics:

- MTSS uses more than one modality for data acquisition. The data acquisition for multi modalities can be sequential or simultaneous.
- MTSS estimates elastic modulus and/or stiffness map of the targeted object and/or region. It may estimate other mechanical properties of the probed object such as size, depth, and mobility.
- MTSS may provide additional information other than the mechanical properties of the probed object.

In the following sections, we discuss two systems that can be categorized as a multimodal tactile sensing system: a bimodal dynamic imaging system and a digital breast tomosynthesis combined with mechanical imaging.

A. Bimodal Dynamic Imaging (BDI) System

The bimodal dynamic imaging (BDI) system uses tactile and diffuse optical modalities for a better mechanical and spectral characterization of a tumor [73]. BDI also uses dynamic positioning of the illuminator and detector for data acquisition and the positioning information for data analysis. The tactile and diffuse optics modalities in the BDI system complement each other by providing mechanical and spectral information on a tumor. In the tactile mode, it estimates the mechanical properties such as size, depth, and elastic modulus of tumors.

In the diffuse optics mode, absorption and reduced scattering coefficients of the probed region are derived. Using these coefficients, BDI can provide physiological information such as chromophore concentrations of biological tissues [104]. The total hemoglobin concentration and blood oxygen saturation, determined from the chromophore concentrations can be used for distinguishing benign and malignant tumors. Hence, the combination of tactile and diffuse optics modalities may achieve a superior tumor characterization performance.

Previously, the researchers from Temple University developed a tactile imaging sensor to estimate the mechanical properties of tumors [17]. This tactile sensor exhibited relatively low sensitivity (67%) for differentiating malignant and benign tumors [18]. To enhance this sensitivity level, a dynamic positioning system and multispectral light sources have been combined with this tactile sensor. Preliminary results on developing BDI were published with a brief explanation of the method in [105], [106]. A detailed analysis of the BDI system and method can be found in [73]. To be more specific, this paper also discusses in detail the numerical analysis of the tactile mode, the derivation of spectral properties estimation, and the bimodal imaging method for determining size, depth, elastic modulus, absorption coefficient, chromophore concentrations of the embedded target.

One research avenue is the trajectory optimization in three-dimensional space for sources and detectors during scanning for BDI.

B. Digital Breast Tomosynthesis Combined with Mechanical Imaging

Digital breast tomosynthesis (DBT) combined with mechanical imaging (DBT-MI) can be categorized as a multimodal tactile sensing system. This type of MTSS stems from digital breast tomosynthesis. DBT is a limited angle tomographic breast imaging technique. Over the past decades, DBT, often called three-dimensional mammography, emerged as a tool for breast cancer screening. In DBT, an x-ray tube moves along a pre-specified trajectory, typically an arc spanning an angular range of 60 degrees or less. While the x-ray tube is in motion, multiple low-radiation dose projections of the breast are captured at different angles. The collected projection views can then be reconstructed using various algorithms. A compact review can be found here [107]. A recent study showed that

DBT is better in cancer detection rate and reducing recall rate when compared against digital mammography [108].

Motivated by the observation that the relative stiffness can differentiate malignant structure from healthy tissue, researchers from Sweden started investigating how the pressure is distributed over breasts with malignant tumor masses as a result of breast compression in mammography [109]–[111]. They built a prototype of DBT-MI by attaching a thin force-sensing resistor (FSR) beneath the compression plate of mammography. Their study suggested a strong correlation between mean tumor pressure and mean breast pressure, where the mean breast pressure refers to the area of the full sensor which gives nonzero output. However, the sensors were radiopaque, which means that these sensors block radiation from x-ray. Therefore, this would be a design consideration for this system to be used for clinical application. Another limitation is that these sensor elements may be bent and gives rise to invalid pressure output and mismatching of sensor elements with pressure data. Also, the size of the sensor elements may introduce partial area effects and difficulties when matching sensor elements with tumor area [111]. Later, Dustler *et al.* improved the DBT-MI method by affixing two FSRs to the inferior side of the compression paddle of a mammography device [112]. The mechanical imaging and mammography were performed sequentially. They investigated the effect of adding adjunct mechanical imaging to mammography and found that it substantially lowered recall and biopsy rates.

It is imperative that for maximum benefit, DBT and MI data should be acquired simultaneously. However, the radiopaque MI sensor arrangement produces visible artifacts in DBT images. Bakic *et al.* proposed an artifact reduction method during the DBT image reconstruction [113]. In the previous prototype of DBT-MI, the sensor array was attached to the breast compression paddle. As a consequence, the projection of the sensor array on the detector has a variable geometric magnification, which depends on the thickness of the compressed breast. To overcome this dependency, Bakic *et al.* placed the sensor array on the breast support above the detector. This placement ensured a fixed geometric magnification and position in the sensor projection. Eventually, this design simplified the DBT reconstruction, and the methods used to suppress sensor-related artifacts efficiently. Afterward, Bakic *et al.* proposed a pre-processing method based on flat fielding to reduce artifacts [114]. A phantom study was conducted to evaluate this flat field-based DBT-MI system. The preliminary results demonstrated a substantial reduction of artifacts by flat fielding (on average 83%) [115]. The system still requires quantitative validation, noise stabilization, and method optimization in virtual clinical trials and subsequent patient studies.

V. Conclusions: Discussions and Future Directions

Various tactile transduction modalities such as capacitance, piezoelectric, magnetic, or optical means are discussed. The authors focused on utilizing optical tactile sensors for elasticity imaging. This is a tactile sensing system built on optical sensors. Then elastography and other elasticity determination systems are reviewed. We concluded that optical Tactile Sensing Systems are more compact, easier to use, and do not require a dedicated operator. As an application, Tactile Sensing Systems have been used to classify the tumor as benign or malignant based on the proposed Risk Score. Moreover, we reviewed the multimodal tactile sensing systems. Multimodal tactile sensing system improved the characterization accuracy. The tactile Sensing System technology is well-positioned to be applied to various applications such as medicine, robotics, sports, and agriculture.

Tactile sensor technology is maturing with many technological advances. The U.S. patents with the words tactile and sensor increased from 84 in 1970-79 to 11,772 in 2000-2009 [2]. A query in Google Patent searching website (patents.google.com) returned 43,341 U.S. patents with the words tactile and sensor in 2010-2020. Commercialization is being pursued with these intellectual properties. This is an important metric because a large social impact occurs through commercialization. The researchers should keep commercialization in mind when they are developing tactile sensing technologies.

Sensing systems have many limitations. One of the main obstacles is a barrier to entering the commercial space. Even though sensing technologies have been researched for many years, not many technologies are widely used in the world. Sensing technologies failed to gain prominence in the world because researchers and business people have yet to find a critical application. Both researchers and business people should re-evaluate the sensing system being researched and find an application that will have a high impact on society.

With the advancement of data processing and artificial intelligence, more sensing systems are being developed. These systems are moving towards multi-point sensing as well as multimodality sensing. Moreover, advanced artificial intelligence and machine learning technologies are used to come up with better classification and identification algorithms. Furthermore, there are significant advances with respect to the hardware. There are flexible electronics, wearable sensors, and implantable sensors. These advances will introduce sensing systems with more functions and higher performance. One sensing system that is being developed is based on smartphones. An optical tactile system is developed on a smartphone platform for elasticity determination. The ubiquitous nature of smartphones allows an excellent platform for various sensors.

Robotics and biomedical applications are accelerating tactile sensing technology. For robots to grasp objects properly, tactile sensors are critical. Tactile sensing systems are providing many necessary technologies for the robots as well. Moreover, biomedical applications such as tumor characterization and ovarian cancer detection are being investigated with tactile sensing systems. Touch sensation is being quantified for tumor classification. There are other important advances in minimally invasive surgery and prostheses that are being investigated for sensing systems.

Single point sensors have reached maturity. As future research direction, multiple-point, mesh-base, multimodal sensors need to be developed.

To develop a tactile sensing system, there must be standards. The anatomical structure and characteristics of human skin can be used as the gold standard. Human skin has a spatial resolution of 1.25mm and frequency response of at least 32Hz for force estimation and 250Hz for vibration [2]. These can be the target gold standards for tactile sensing systems.

Tactile sensing systems have a wide range of applications. Naturally, robotics is a huge application area for tactile sensors. Biomedical applications such as telerobotics, diagnostic tools, dentistry, and gait analysis are other areas that tactile sensing systems will contribute. There are also sport's posture analysis, agriculture fruit picking, and consumer products that have potential use of tactile sensing technology. The applications of tactile sensing systems will be rapidly increasing in the future.

Acknowledgment

The authors thank many students and collaborators who worked on this project over the years; Vira Oleksyuk, Sung Choi, Jesse Goldstein, Amrita Sahu, Zicong Wang, Bill Moser, Steve Lash, Suzy Pascarella, and Dina Caroline.

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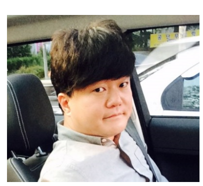

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