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Tactile Sensing for Robotic Applications

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1. Introduction

Robotic devices – limited to the structured environment of manufacturing plants until few years ago – are slowly making way into human life, which has led to the emergence of interaction and learning issues in robots. Such issues are important for future robot to be able to learn autonomously and to interact safely with the environment i.e. without causing any harm to it or to the objects with which it is interacting. In this context, it becomes important to study the ways and means of robot's interaction with the environment. Humans interact and explore the environment through five main sense modalities viz. touch, vision, hearing, olfaction and taste. Loss of any of these modalities will result in the incomplete information about the environment. Irrespective of their importance with respect to each other, the study of their individual contribution in collecting information from environment is important for improving the sensing capabilities of any future robotic system.

This chapter provides an overview of tactile sensing in robotics. This chapter is an attempt to answer three basic questions:

- What is meant by Tactile Sensing?
- Why Tactile Sensing is important?
- How Tactile Sensing is achieved?

The chapter is organized to sequentially provide the answers to above basic questions. Tactile sensing has often been considered as force sensing, which is not wholly true. In order to clarify such misconceptions about tactile sensing, it is defined in section 2. Why tactile section is important for robotics and what parameters are needed to be measured by tactile sensors to successfully perform various tasks, are discussed in section 3. An overview of `How tactile sensing has been achieved' is given in section 4, where a number of technologies and transduction methods, that have been used to improve the tactile sensing capability of robotic devices, are discussed. Lack of any tactile analog to Complementary Metal Oxide Semiconductor (CMOS) or Charge Coupled Devices (CCD) optical arrays has often been cited as one of the reasons for the slow development of tactile sensing vis-à-vis other sense modalities like vision sensing. Our own contribution – development of tactile sensing arrays using piezoelectric polymers and involving silicon micromachining - is an attempt in the direction of achieving tactile analog of CMOS optical arrays. The first phase implementation of these tactile sensing arrays is discussed in section 5. Section 6 concludes the chapter with a brief discussion on the present status of tactile sensing and the challenges that remain to be solved.

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2. Tactile sensing: definition

The 'sense of touch' in humans comprises of two main submodalities – cutaneous and kinesthetic - characterized on the basis of their neural inputs. *Cutaneous sense* receives sensory inputs from the receptors embedded in the skin and *kinesthetic sense* receives sensory inputs from the receptors located within muscles, tendons and joints. In context with these submodalities, most researchers have distinguished among three sensory systems – cutaneous, kinesthestic and haptic. In the terminology of Loomis and Lederman (Loomis & Lederman 1986), *cutaneous system* involves physical contact with the stimuli and provides the awareness of the stimulation of the outer surface of body by means of receptors in the skin and associated somatosensory area of central nervous system (CNS). The *kinesthetic system* provides humans the information about the static and dynamic body posture (relative positioning of the head, torso, limbs and end effectors) on the basis of afferent information originating from the muscles, joints and skin, and the efference copy. The *haptic system* uses significant information about distal objects and events both from cutaneous and kinesthetic systems (Loomis & Lederman 1986; Klatzky & Lederman 2003). It should be noted that the sensory inputs are not only mechanical stimulation but also include heat, cooling and various stimuli that produce pain.

Human tactile sensing has generally served as a reference point for tactile sensing in robotics. A number of design parameters – discussed later - for robotic tactile sensors are derived from human sense of touch. Even though human tactile sensing has been a reference point for robotic tactile sensing, the way tactile sensing is defined in robotics falls short of what it means in humans. Most of the times, the robotic tactile sensing has been associated with detection and measurement of forces in a predetermined area only. The tactile or cutaneous sensing is associated with the detection and measurement of contact parameters which can be mechanical stimulation (force, stress, roughness etc.), temperature, moistness etc. In this context, definition of a tactile sensor by Lee et al. (Lee & Nicholls 1999) is more complete as the tactile sensor is defined as a device or system that can measure a given property of an object through contact in the world. Various studies on cutaneous sensing in humans show that some coding or pre-processing of the stimulus information takes place at the receptor or sensor level (Johannson & Birznieks 2008).

Going by these observations we define tactile sensing as the process of detecting and measuring a given property of a contact event in a predetermined area and subsequent pre-processing of the signals at the sensor level itself – before sending them to higher levels for perceptual interpretation (Dahiya, Metta et al. 2008) Similarly, the touch sensing can be termed as tactile sensing at single contact point. This distinction between touch and tactile sensing is followed throughout this chapter.

For the cutaneous and kinesthetic sensing in humans, the analogous terms in robotics are extrinsic/external and intrinsic/internal touch sensing respectively. In robotic applications, extrinsic touch sensing is achieved through tactile sensing arrays or a coordinated group of touch sensors. The extrinsic touch sensors or sensing arrays are mounted at or near the contact interface and deal with the data from localized regions. Intrinsic sensors are placed within the mechanical structure of the system and derive the contact data like magnitude of force using force sensors. Hereafter, unless otherwise stated, the term 'tactile sensing' is used for 'extrinsic touch sensing' in robotic applications.

3. Tactile sensing: why?

What happens if the humans have all sense modalities other than the sense of touch? The importance of touch/tactile sensing is implicit in this question which can be answered by performing a simple experiment of exploring the objects after putting hands on an ice block for a while or by making the hand numb through local anesthesia. In one such experiment, presented in (Westling & Johannson 1984), the skin on volunteers' hand was anesthetized so that mechanoreceptors – specialized nerve endings that respond to mechanical stimulation (force) - activity was no longer available to the brain. It was observed that even though volunteers' could see what they were doing, they could no longer maintain a stable grasp of objects. The movements become inaccurate and unstable when 'sense of touch' is lost. Real-world objects exhibit rich physical interaction behaviors on touch. These behaviors depend on how heavy and hard the object is when hold, how its surface feels when touched, how it deforms on contact and how it moves when pushed etc. 'Sense of touch' allow us not only to assess the size, shape, and the texture of objects, but, also helps in developing awareness of the body. It is also a powerful conduit for emotional connectedness. The ability to discriminate among surface textures, stiffness, and temperature, to sense incipient slip, and roll an object between fingers without dropping it are some of the reasons why touch/tactile sensing is needed.

In robotics, the touch information is useful is a number of ways. In manipulative tasks, touch information is used as a control parameter (Berger & Khosla 1991; Howe & Cutkosky 1990; Li, Hsu et al. 1989) and the required information typically includes contact point estimation, surface normal and curvature measurement and slip detection (Fearing 1990) through measurement of normal static forces. A measure of the contact forces allows the grasp force control, which is essential for maintaining stable grasps (Bicchi, Salisbury et al. May, 1990). The Grasp force along with manipulator displacement is also helpful in compliant manipulators (Cutkosky & Kao April 1989). In addition to magnitude, the direction of force is also critical in dexterous manipulation to regulate the balance between normal and tangential forces to ensure grasp stability - the so-called friction cone (Murray, Li et al. 1994). For full grasp force and torque determination, shear information is also required (Domenici, Rossi et al. 1989; Rossi, Canepa et al. 1993). The need for shear stress information is also supported by finite element analysis (FEA) (Ricker & Ellis May 1993; Ellis & Qin May 1994). Shear information is useful in determining coefficient of friction and a unique surface stress profile when the sensor is covered with elastomeric layer (Novak May 1989).

During interaction with the environment a significant portion of the information about contact objects e.g. shape (Charlebois, Gupta et al. 2000; Fearing & Binford Dec, 1991; Russell & Parkinson May 1993), surface texture (Maheshwari & Saraf 2006), slip (Howe & Cutkosky May 1989; Tremblay & Cutkosky May 1993), etc. comes through the detection of normal and shear forces. A real world contact parameters measurement also involves material properties such as hardness (Shikida, Shimizu et al. 2003), temperature (Yuji & Sonoda 2006) etc.

A range of sensors – based on various types discussed in the following section - that can detect object shape, size, presence, position, forces and temperature have been reported in (Dario & de Rossi 1985; Howe 1994; Lee & Nicholls 1999). Few examples of sensors that could detect surface texture (Maheshwari & Saraf 2006), hardness or consistency (Shikida, Shimizu et al. 2003; Omata, Murayama et al. 2004) are also reported. Very few examples of

sensors that can detect force as well its direction have also been reported (Chu, Sarro et al. 1996; Torres-Jara, Vasilescu et al. 2006). Recently, the importance of dynamic events has been recognized and sensors are being developed for detecting stress changes (Howe & Cutkosky 1993; Schmidt, Mael et al. 2006), slip and other temporal contact events.

It should be noted that some of the above mentioned tasks involve both intrinsic and extrinsic touch sensing. As an example, pouring of water in a bottle requires intrinsic touch sensors for grasping the bottle and extrinsic tactile sensors to detect any slippage. Whereas, detection of parameters like smoothness may require signal from extrinsic tactile sensors only. As a matter of fact, all daily works that we perform with hands involve both extrinsic and intrinsic tactile sensors.

4. Tactile sensing: how?

The development of robots capable of operating in unstructured environments or intended to substitute for man in hazardous or inaccessible environments, demands the implementation of sophisticated sensory capabilities, far beyond those available today. Cues from the human tactile sensing system can be helpful in bringing the level of tactile sensitivity and acuity that humans possess, to the manipulators and to other human/machine interfaces. A general purpose robotic tactile system, in addition to being cost effective, should possess the following characteristics (Dario & de Rossi 1985; Howe 1994; Dahiya, Metta et al. 2008; Dahiya, Valle et al. July, 2007):

- A large number of taxels; typical estimated range should be between 25- 256 elements.
- Human like spatial sensitivity viz. 1mm.
- Sensitivity to forces spanning from 1gmf (0.01N) to 1000gmf (10N) with incremental force resolution of 1 g.
- Discrete taxel response bandwidth of 1000 Hz.

Besides these, a reasonable response linearity, negligible hysteresis and capability to measure contact parameters like hardness, temperature etc. are also desired. These design parameters are obtained with considering human sense of touch as reference. A large number of tactile sensors and sensing arrays have been reported in literature exploring nearly all possible methods of transduction - with or without above mentioned design parameters. The main transduction methods that have been reported are: Resistive/Piezoresistive, based on Tunnel Effect, Capacitive, Optical, Ultrasonic, Magnetic, and Piezoelectric. Relative merits and demerits of these methods are given in Table 1. Selected examples of robotic tactile sensors reported in the literature based on thsese transduction methods are discussed below.

4.1 Resistive sensors

Resistive sensors typically involve two conductive sheets separated by air, microspheres, insulating fabric, etc. One of the sheets carries a voltage gradient generated by applying a reference voltage and ground on its two opposite ends. The second sheet when brought in contact with the first by the applied force, serves like the slider in a linear potentiometer. A voltage divider is made at the contact point and the voltage of the sheet, which is acting as slider, can be used to find location of the contact point. Such an approach is limited to measurement of only one contact location. Touch sensors based on resistive principle are generally sensitive and inexpensive in terms of investment, but, they are expensive in terms of power consumption. An improved design of tactile sensor using resistive sensing

technology is reported in (Zhang & So 2002). The design involves arranging the sensors in an array and hence enables the measurement of many contact points. But, the lack of contact force measurement still remains a critical problem.

4.2 Piezoresistive sensors

Piezoresistive touch sensors are made of materials whose resistance changes with force/pressure. Touch sensing system using this mode of transduction have been reported for use in anthropomorphic hands (Weiss & Worn 2004). Piezoresistive tactile sensing is particularly popular among the MEMS based and silicon based tactile sensors (Woffenbuttel & Regtien 1991; Beebe, Hsieh et al. 1995). FSRs (Force Sensing Resistors) based on piezoresistive sensing technology are widely used in pointing and position sensing devices such as joysticks and are commercially manufactured by Interlink (Interlink Electronics Inc. 2008). The FSR sensors have a large appeal, because of low cost, good sensitivity, low noise and simple electronics and are found in many experimental tactile systems. One of their drawbacks is the relatively stiff backing. Although examples of advanced robotic hands equipped with FSRs exist (Diftler, Platt Jr et al. 2003), these sensors generally require serial or manual assembly, provide highly non-linear response and suffer from hysteresis.

4.3 Tunnel effect tactile sensors

Tactile sensors based on Quantum Tunnel Composites (QTC) have come up recently and are commercially available from Peratech (Peratech-Ltd). QTC's have the unique capability of transformation from a virtually perfect insulator to a metal like conductor when deformed by compressing, twisting or stretching of the material. The transition from insulator to conductor follows a smooth and repeatable curve, with the resistance dropping exponentially. In QTCs the metal particles never come into contact. Rather they get so close that quantum tunneling (of electrons) takes place between the metal particles. Robot hands with QTC based tactile sensors have also been reported in literature (Walker July 2004). A sensor based on electron tunneling principle is reported in (Maheshwari & Saraf 2006). The device directly converts stress into electroluminescent light and modulation in local current density, both of which are linearly proportional to local stress. With thin film used with metal and semiconducting nanoparticles the spatial resolution better than that of the human fingertip (~40μm) is reported.

4.4 Capacitive sensor

Capacitive sensors consist of a plate capacitor, in which, the distance between plates or the effective area is changed by the applied force by shifting their relative position. Capacitive sensors can be made very small, which allows the construction of dense sensor arrays, and also allow dynamic measurements. Few examples of capacitive touch sensors are reported in (Schmidt, Mael et al. 2006). There are also commercially available capacitive-based touch sensors such as RoboTouch and DigiTacts from Pressure Profile Systems (Pressure Profile Systems 2007) and commercial products like 'iPodtouch' (Apple Inc. 2008) also use capacitive touch sensing. Touch sensors based on this mode of transduction are very sensitive but stray capacity and severe hysteresis is major drawback. An 8x8 capacitive tactile sensing array with 1 mm^2 area and spatial resolution at least 10 times better than the human limit of 1 mm is reported in (Gray & Fearing 1996). Capacitive sensing technology is also popular among the tactile sensors based on MEMS and silicon micromachining (Gray and Fearing 1996; Schmidt, Mael et al. 2006).

4.5 Optical sensors

Tactile sensors with optical mode of transduction use the properties of optical reflection between media of different refractive index. The transducer structure is composed of a clear plate, a light source and a compliant membrane stretched above, but not in close contact with, the plate. The lower surface of the plate acts as the imaging area. Light is directed along an edge of the plate and it goes through total internal reflection (when no force is applied) or diffuse reflection (when force is applied). The light coming out of plate due to diffuse reflection can be recorded by CCD or CMOS cameras placed in the imaging area. The intensity of the light (bright or dark patches on image) is proportional to the magnitude of the pressure between object and plate. Optical fiber based tactile sensors capable of measuring normal forces are reported in (Heo, Chung et al. 2006). The sensor can measure forces as low as 0.001N with the spatial resolution of 5 mm. An optical three axial tactile sensor capable of measuring normal and shear forces is reported in (Ohka, Kobayashi et al. 2006). Some cases of large area skin based on LEDs (light-emitting diodes) has also been reported (Cheung & Lumelsky 1992; Ohmura, Kuniyoshi et al. 2006). Optical based tactile sensors are immune to electromagnetic interference, are flexible, sensitive and fast, but at times they are bulky. Other problems associated with optical sensors are: the loss of light by micro bending and chirping, which causes distortion in the signal.

4.6 Ultrasonic sensors

Acoustic ultrasonic sensing is yet another technology that has been used for the development of tactile sensors. Microphones are known to be useful for detecting surface noise that occurs at the onset of motion and during slip. A device that senses contact events from their ultrasonic emission at the contact point is described in (Milighetti, Emter et al. 2006). A Polyvinylidene Fluoride (PVDF) polymer is used in a 2 x 2 array of receivers to localize the contact point on a silicone rubber sensing dome. The sensor is reported to be very effective in detecting slip and surface roughness during movement. The change in resonance frequency of PZT (Lead Zirconate Titanate), in accordance with object's acoustic impedance has been reported (Omata, Murayama et al. 2004) for detecting hardness and/or softness of objects. Tactile sensors based on ultrasonic approach have fast dynamic response and good force resolution, but materials like PZT are difficult to handle in miniaturized circuits.

4.7 Magnetism based sensors

Tactile sensors based on magnetic transduction measure the change in flux density caused by applied force on a small magnet. The flux measurement can be made by either a Hall Effect (Jamone, Metta et al. 2006) or a magneto resistive device. A few tactile sensors that use the magnetic mode of transduction have been reported in literature (Nowlin 1991). The tactile sensors based on magnetic principle have a number of advantages that include high sensitivity and dynamic range, no measurable mechanical hysteresis, a linear response, and physical robustness. Major drawback of magnetic based tactile sensor is that they cannot be used in magnetic medium and involve complex computations.

4.8 Piezoelectric sensors

The piezoelectric materials have the property of generating charge/voltage proportional to the applied force/pressure. Alternatively, they are capable of generating force due to

electrical input. Thus, they can be used both as sensors and actuators and due to this property they fall under the category of 'Smart Materials'. Piezoelectric materials are suitable for use as tactile sensors. While quartz and some ceramics (PZT) have good piezoelectric properties, the polymers such as PVDF normally have been used in touch sensors because of some excellent features, such as, flexibility, workability and chemical stability (Flanagan & Wing 1993). The use of PVDF for tactile sensing was reported for first time in (Dario & de Rossi 1985) and thereafter a number of works based on PVDF or its copolymers have been reported in literature (Kolesar, Reston et al. 1992; Dargahi, Parameswaran et al. 2000; Yuji & Sonoda 2006). Temperature sensitivity of piezoelectric materials is a major cause of concern in their use as tactile sensors.

4.9 Sensors based on different physical/mechanical nature – recent trends

In the past, most devices have relied on fairly rigid, solid materials for their construction. Following studies of human tactile performance and the physical nature of the tissues and skin, it now seems that softer materials may have much to offer. Elastic overlays and compliant contact surfaces are often advocated for their frictional and other properties, although their low pass filtering behavior can be a disadvantage. But now even softer materials, such as rubber, fluids and powders, are being examined. Already, there are some commercially available touch sensors such as those from Tekscan (Pressure Sensitive Ink 2008) that use pressure sensitive ink or rubber. A number of touch sensors using conductive rubber as transducer have also been reported (Someya, Sekitani et al. 2004). They take advantage of change in impedance due to the applied force/pressure. Presence of hysteresis and non linearity are some of their drawbacks. Conductive gels having remarkable softness show a 20% change in impedance for pressure 0-400 kgf/cm^2 (Kageyama, Kagami et al. 1999). A range of materials with different consistencies have been examined in (Shimoga & Goldenberg 1992) for impact and strain energy dissipation conformability to surfaces and hysteresis effects. It is found that soft surfaces have more desirable characteristics for contact surfaces than hard materials. Among soft materials, gels are better than plastic, rubber, sponge, or paste, with powders being the second best.

5. Piezoelectric polymer – microelectrode arrays (MEA) based tactile sensing arrays

Robot's guidance and force based control has typically depended on the tri-axial or 6D force sensors placed on the robot's wrist or in other words, it has depended on the intrinsic touch sensing. However, intrinsic touch sensing method is sensitive to the accuracy of force/torque sensor calibration and can provide erroneous information as it is difficult to model dynamic forces. Further, inertia and compliance of manipulator can also generate some errors due to which intrinsic touch sensing is insufficient for the tasks that require precise manipulation. Such errors can be reduced by bringing the sensors closer to the contact points or in other words by using distributed touch sensors or tactile sensing arrays on the fingertips. As in humans, the combined signals from intrinsic and extrinsic tactile sensors can be used for various tasks. In addition to the tasks performed with hands, various safety and interaction issues call for tactile sensors distributed all over the body of robot. A number of tactile sensing arrays and artificial skin prototypes – using transduction methods, discussed earlier - have also been reported in literature. With large number of tactile sensors the number of interconnects needed to read and transfer the signals also

Type	Merits	Demerits
Resistive	• Sensitive • Low Cost	• High Power Consumption • Generally detect single contact point • Lack of Contact force measurement
Piezoresistive	• Low cost • Good sensitivity • Low noise • Simple electronics	• Stiff and frail • Non linear response • Hysteresis • Temperature sensitive • Signal drift
Tunnel Effect	• Sensitive • Physically flexibile	• Non Linear response
Capacitive	• Sensitive • Low cost • Availabilityof commercial A/D chips.	• Cross-talk • Hysteresis • Complex Electronics
Optical	• Immunity to electromagnetic Interference • Physically flexible • Sensitive • Fast • No interconnections.	• Bulky • Loss of light by micro bending • Chirping • Power Consumption • Complex computations.
Ultrasonic	• Fast dynamic response • Good force resolution	• Limited utility at low frequency • Complex electronics • Temperature Sensitive
Magnetic	• High sensitivity • good dynamic range, • no mechanical hysteresis • physical robustness	• Suffer from magnetic interference • Complex computations • Somewhat bulky • Power Consumption
Piezoelectric	• Dynamic Response • High Bandwidth	• Temperature Sensitive • Not so robust electrical connection.
Conductive Rubber	• Physically flexible	• Mechanical hysteresis • Non linear response

Table 1. Relative merits and demerits of various tactile sensor types.

increase – which is a big hurdle in the usage of distributed touch sensing or tactile sensing arrays. As for human tactile sensing, it is desirable to have tactile arrays with density and spatial distribution of taxels (tactile elements) according to the location where the sensors are installed. In this sense, the sensors can be divided in two classes: tactile sensing for body locations like fingertips and for body locations like belly, palm etc. The work presented here, focuses on the development of tactile sensing arrays for fingertips.

Considering the limited available space on the robot finger (~1 cm x 1 cm), miniaturization of sensing devices is a possible solution to accommodate large number of sensors in a small space. Miniaturization of tactile sensors has been achieved by two main approaches: MEMS based approach (Kane, Cutkosky et al. 2000) and polymer based sensors realised on organic substrate (Someya, Sekitani et al. 2004). With the MEMS based approach, it is possible to get higher spatial resolution, but, MEMS based tactile sensing devices cannot withstand large forces/pressure due to their inherent fragile nature. Also, it is difficult to realize physically flexible tactile sensing arrays by the MEMS approach. The tactile sensors realized on organic substrates have limited real time capability as they suffer from the slow time response.
As an alternative to these approaches, we proposed a novel approach for the development of tactile sensing chips for the fingertips, as shown in Fig. 1 (Dahiya, Valle et al. 2008). With this `sense and process at same place' approach, the tactile sensing arrays are developed for fingertips of robotic hand by directly coupling the "smart materials" like piezoelectric polymers with the Integrated Circuits (ICs). The working principle of the tactile sensors developed with this approach, is described in the following paragraph.

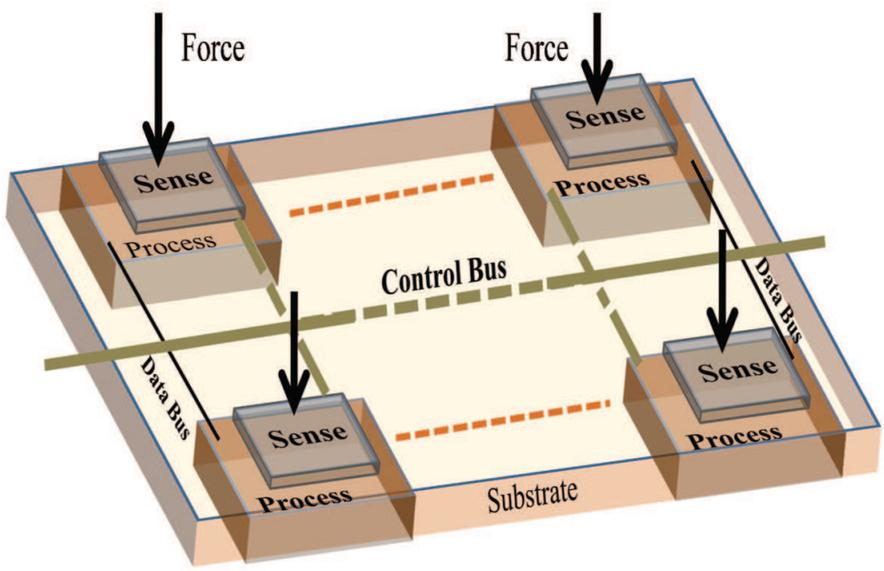

Fig. 1. 'Sense and Process at same place' approach for development of tactile sensign arrays (Dahiya, Valle et al. 2008).

A piezoelectric film working in the generating mode, produce a charge/voltage which is proportional to the applied stress. Hence by replacing the polysilicon gate of a MOSFET device with a piezoelectric polymer film, the charge in the induced channel of MOSFET can be controlled by the charge generated on the piezoelectric polymer film due to the applied stress. In other words, the charge in the channel is modulated by the applied mechanical stress. The signal is amplified by the MOSFET and is then further processed by electronic circuitry. While the piezoelectric polymer film as a sensing element would improve the speed of response; the marriage of sensing material (PVDF-TrFE) and electronics using MOS technology will improve force resolution, spatial resolution, signal to noise ratio and may help in reducing the wiring complexity – a key robotic problem. As earlier said, the lack of any tactile analog to Complementary Metal Oxide Semiconductor (CMOS) or Charge Coupled Devices (CCD) optical arrays has often been cited as one of the reasons for the slow

development of tactile sensing vis-à-vis other sense modalities like vision sensing. With the proposed approach, a tactile analog of CMOS optical arrays can be obtained and hence the approach will advance the research in tactile sensing. The only disadvantage of using IC technology is lack of physical flexibility of tactile sensing chips. A possible trade off is to cover the chip with a thick and protective layer of silicone. Due to low thermal conductivity, such a layer would be helpful in reducing the effect of ambient temperature variations also – which otherwise introduces noise in the output during measurement of forces. However, a careful study is needed as such materials suffer from creep, hysteresis and in practice work as low pass filters (Shimojo 1997). Nonetheless, the advantages offered by proposed approach far outweigh the disadvantages.

As a first step towards realization of tactile sensing arrays based on the above said approach, arrays of tactile sensors were developed by directly coupling thin piezoelectric polymers films to 32 taxel MEAs realized on silicon die, as shown in Fig 2. The MEAs in this case act as the extended gates of FETs devices, which are external to the chip. Somewhat similar approach is used by Swartz et al. (Swartz and Plummer 1979) and Fiorillo et al (Fiorillo, Spiegel et al. 1990) to develop ultrasonic sensors and by Kolasar et. al. (Kolesar, Reston et al. 1992) to develop tactile sensors. While the former used the epoxy-adhered PVDF film, later one used a thin film of PVDF-TrFE directly deposited from solution on to the extended gates.

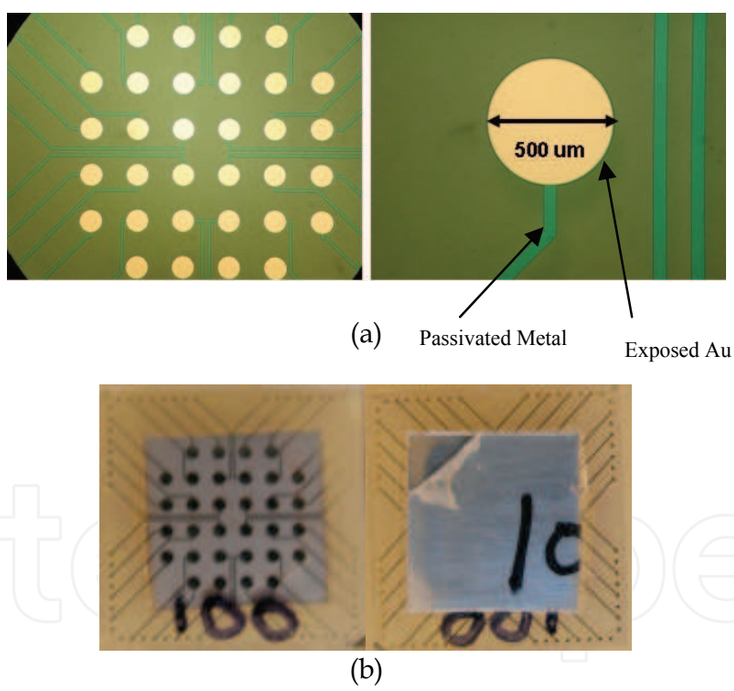

Fig 2. a) MEA for the extended gate-FET approach. Chip dimension is 1cm x 1cm. and diameter of the taxels is 500µm (b) Back and front sides of MEA with 100 µm polymer covering all the electrodes. A general purpose protecting tape can also be seen. (Dahiya, Valle et al. July, 2007)

One of the test structures devoted to characterize the polymeric material and to perform the electrical/mechanical tests to refine the read out electronics is shown in Fig. 2(a). To study the electrical response of different taxels PVDF-TrFE polymer with 25, 50 and 100 µm have been deposited. The fabrication steps for these test structures are given in Table 2. The front

and backside of the MEA after depositing polymer is shown in Fig. 2(b). The fabrication of MEA is implemented on a fuse silica quartz substrate a Al:Si 1% /Ti/TiN, respectively of 410/30/140 nm thick, low resistance multilayer for both microelectrodes and electrical connections. The TiN top-layer has been introduced to guarantee a low contact resistance to the final Au/Cr (5/150 nm) seed-layer. The metal wires passivation has been guaranteed by a SiO_2/Si_3N_4 (20/210 nm) layer deposited by PECVD. These thicknesses have been chosen to keep the substrate capacitance low and hence to get the maximum of the voltage produced by polymer at the gate terminal. Fig. 3 shows the average response of three touch sensing elements - to forces up to 0.4 Kgf, when a sinusoidal force was applied at 15 Hz. The response is linear over a large range of forces. It can be noticed that unlike MEMS based sensors, the range of detectable force is higher in this case. Similarly the sensors based on silicon micromachining are known to have a mobility of three orders of magnitude higher that of organic based devices and hence they have faster response time. A further characterization is required to study the behaviour of sensing array over broad range of frequency.

Fabrication Process	
a.	Substrate: 500 µm thick quartz wafer.
b.	A Ti/TiN/Al/TiN multilayer is deposited by sputtering.
c.	This multilayer is patterned by photolithography and plasma dry etching to form the electrodes, lines and the contact pin zone.
d.	A layer of Si_3N_4 (200 nm) is then deposited by PECVD, in order to insulate the metal lines.
e.	Contacts are opened through the Si_3N_4 layer by plasma dry etching
f.	Evaporation of Cr and Au is carried out (5 nm and 150nm, respectively)
g.	The Chromium and Gold layers are patterned by wet etching.
h.	Deposition of piezoelectric polymer. The film was deposited using epoxy adhesive on the MEA, covering all 32 taxels. The film was covered with glass slide and the arrangement was again kept under vacuum to remove air between polymer and MEA and to ensure uniform thickness of the adhesive. For better adhesion the arrangement was kept at 65 degrees for thirty minutes.

Table 2. Fabrication steps of piezoelectric polymer-MEA based tactile sensing arrays.

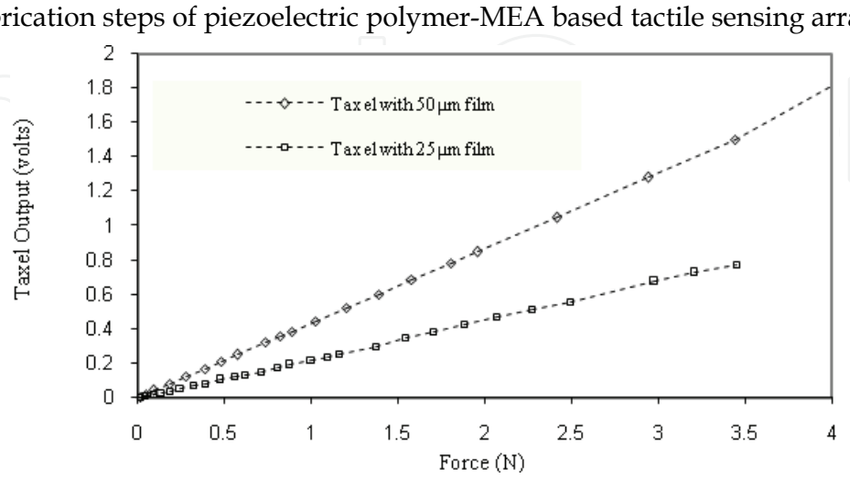

Fig. 3 Average taxels response when variable dynamic force is applied at 15 Hz (Dahiya, Valle et al. 2008).

6. Conclusion and future development

Despite an important role and being a component of robotics roughly as long as vision, the use of touch sensing in robots is lesser than other sensory modalities e.g. vision and auditory sensing, thereby restricting the cognitive capabilities of the robots and strongly limiting their real world interaction capabilities. The lesser usage of touch sensing could partly be attributed to the complex and distributed nature of tactile sensing and partly also to the non availability of satisfactory tactile sensors. The physical problems like placement, robustness of sensors, wiring complexity etc. also pose a hurdle in effective utilization of tactile sensors. The interaction of robots with environment through tactile sensing has largely been limited to the measurement of static interaction forces whereas real world interaction involves both static and dynamic forces. Similarly, most of the sensors are designed to measure static pressure or forces from which it is difficult to obtain information like friction, stickiness, texture, hardness and elasticity. In real world, one needs to measure all these contact parameters which may require use of more than one transduction method simultaneously. As an example measurement of stress and stress rate can be done by having capacitive and piezoelectric transducers. Thus, more and more multifunctional tactile sensors – very few of which have been reported (Engel, Chen et al. 2005) - are required for real world interaction.

The pursuit of tactile sensing for robotic applications, in the last two decades, has resulted in the development of many touch sensors - exploring nearly all modes of transduction -but; none could produce a tactile analog of CMOS optical arrays. Clearly, the emphasis, `only' on the sensor development has resulted in a large number of 'bench top' sensors – suitable in a laboratory environment, and having limited practical usage in the robotic systems. This is surprising, considering the long history of gripper design for manipulative tasks. It is believed that the lack of the system approach has rendered many of them unusable, despite having a good design and performance (Dahiya, Valle et al. March, 2008). It is evident from the fact that very few works on tactile sensing have taken into account system constraints, like those posed by other sensors or by the robot controller, processing power etc. As an example, large numbers of tactile sensors put a pressure on the computing power required to process large number of data, whereas same can be solved (or at least reduced) by having distributed computing starting right from the transducer level (Dahiya, Valle et al. March, 2008). A system approach for the tactile sensing can be helpful in filling the gaps between tactile sensing and other sense modalities.

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Sensors: Focus on Tactile Force and Stress Sensors

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This book describes some devices that are commonly identified as tactile or force sensors. This is achieved with different degrees of detail, in a unique and actual resource, through the description of different approaches to this type of sensors. Understanding the design and the working principles of the sensors described here requires a multidisciplinary background of electrical engineering, mechanical engineering, physics, biology, etc. An attempt has been made to place side by side the most pertinent information in order to reach a more productive reading not only for professionals dedicated to the design of tactile sensors, but also for all other sensor users, as for example, in the field of robotics. The latest technologies presented in this book are more focused on information readout and processing: as new materials, micro and sub-micro sensors are available, wireless transmission and processing of the sensorial information, as well as some innovative methodologies for obtaining and interpreting tactile information are also strongly evolving.

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