Review of Transduction Techniques for Tactile Sensors and a Comparative Analysis of Commercial Sensors

Aasheesh Tandon[1], Paxaj Shukla[2], and Himanshu K Patel[3]

[1,2] Instrumentation & Control, Nirma University, Ahmedabad, India,
[3]Associate Professor, Instrumentation & Control, Nirma University, Ahmedabad, India

***Abstract-* Tactile sensing is acquiring information via physical contact. Various parameters like pressure, position, temperature, shape, etc. can be measured by this. Despite being one of the most crucial senses by which a being perceives its environment, little research has been done in the field with the scope of application in industries. This paper aims at briefly discussing the various techniques used for tactile sensing followed by their comparison. Next, different commercial tactile sensors along with appropriate performance criteria are discussed and compared. Finally, currently existing commercial sensors are talked about in detail, including their leading manufacturers, products, and description.**

***Keywords* - Artificial skin, Commercial, Data Acquisition Devices, Physical Contact, Sensors, Tactile Sensor, Transducer.**

I. INTRODUCTION

The word Tactile means – 'perceptible by touch'. So sensors that acquire information related to tactility, through physical touch are known as tactile sensors. Tactile sensing relates to the measurement of quantities such as pressure distribution, moisture, shape, slippage, texture, temperature, thermal conductivity and vibrations by a direct contact between the 'object' and the 'subject'. Concisely, tactile sensing can be defined as continuous variable sensing of a quantity by individual sensing elements in an array, see fig. 1[1]. Pressure and torque are important properties for tactile sensing and hence they can be considered useful to get tactile information. However, they aren't formally used to define tactility.

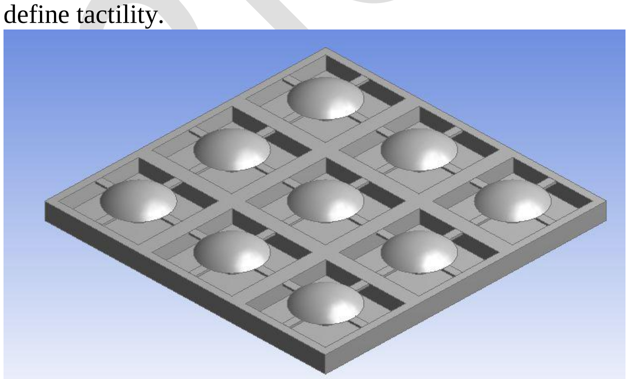

Fig 1. A sensor array

II. PERFORMANCE CRITERIA

Selecting the right transduction technique for a tactile sensing application can be intimidating. There are a variety of models available, and from a number of vendors. Hence, the approach should be to narrow down the list by comparing them on some common grounds. Here, we mention some important criteria for tactile sensors, of which some were initially discussed by [2]. However, it should be noticed that some of these criteria may be interdependent and related. So at times, some adjustments have to be made, for balancing other criterions as well.

Table I. Performance Criteria

Sensitivity	Response time/ Recovery time	Overall Size and Weight
Dynamic Range	Spatial resolution and size	Pre-processing capability
Linearity/ Non-linearity	Measurement speed	Elastic properties, hysteresis, etc.
Drift	Defect tolerance	Communication capability
Signal to noise ratio	Reliability	Integration and fabrication
Susceptibility to external inference	Robustness	Force Direction

III. TACTILE TRANSDUCTION TECHNIQUES

A few popular tactile transduction techniques are resistive, capacitive, inductive, piezoresistive, piezoelectric, magnetic, optoelectric, ultrasonic and tunnel effect methods. In this section, we give a brief review of these methods and their relative advantages and disadvantages. These are also summarized in Table II.

A. Resistive Tactile Sensors

This sensor typically consists of two conductive sheets separated by some insulation. A voltage gradient is produced on one of the sheets, by applying a reference voltage on one of its two opposite ends [3]. When the second sheet is brought in contact with the first one by the applied force, it acts analogous to a slider in a potentiometer, i.e., a voltage divider is made at the contact point [3]. This is used for locating the point of contact. These sensors are generally sensitive and inexpensive in terms of investment, however, they consume a lot of power. An improved design of tactile sensor using resistive sensing technology was reported in (Zhang & So 2002) [3]. The design involves arranging the sensors in an array and hence enables the measurement of many contact points. However, a critical problem which still remains is the lack of contact force measurement.

B. Capacitive Tactile Sensors

In this technique, the area between the plates of the capacitor is varied or the space between them is altered by application of force. Typically it consists of two conductive plates separated by a dielectric material. For parallel plate capacitors, the capacitance can be expressed as, $C = [(A\varepsilon_o\varepsilon_r)/d]$. Where C is the capacitance, A is the area of the two plates, ε_o is the permittivity of free space, ε_r is the relative permittivity of the dielectric material and d is the distance between the plates [14]. Capacitive sensors can be made very small, which allows the construction of dense sensor arrays. In general, capacitive tactile sensors exhibit a good frequency response, good sensitivity, high spatial resolution, and have a large dynamic range [3]. Major drawbacks for this mode of transduction are stray capacitance, severe hysteresis, and susceptibility to noise, especially in mesh configurations because of crosstalk noise, field interactions, and fringing capacitance. Relatively complex electronics are required to filter out this noise.

C. Inductive Tactile Sensors

Based on the principle of EMI, they work similar to an LVDT (Linear Variable Differential Transformer) in the sense that the magnetic core is the mobile part. Modulation of phase and amplitude of the induced voltage occurs, when a touch is sensed, which displaces the movable core, thereby causing flux linkage from the primary coil to the secondary. The advantages include a high dynamic range and a rugged construction, but the spatial resolution is limited by the large size of individual taxels. The use of mechanical parts causes low repeatability and the prerequisite of AC for functioning requires a more complex circuitry than that of resistive or capacitive transducers.

D. Piezoresistive Tactile Sensors

Central to this type of sensor is a piezoresistive crystal, which, on the action of force, changes its resistance and thus changes the magnitude of charge on it. A change in resistance is observed by changing the current (or voltage), keeping the voltage (or current) constant. Each taxel contains a pressure sensitive crystal in the form of conductive rubber, elastomer or conductive ink. Measuring change in resistance requires a simple circuitry and hence, these are simpler to manufacture. Applied for touch sensing in anthropomorphic hands (Weiss & Worn 2004), piezoresistive tactile sensing, has become popular among the MEMS and silicon type tactile sensors (Woffenbuttel & Regtien 1991; Beebe, Hsieh et al. 1995).

E. Piezoelectric Tactile Sensors

These sensors work on the principle that a voltage is generated when a material, such as certain crystals and ceramics, is distorted. The generated voltage, V, is directly related to the applied force, pressure or strain. The structure of the crystal decides its sensitivity to transverse, shear or longitudinal forces. These sensors exhibit a very good high-frequency response, which makes them an ideal choice for measuring vibrations; however, this very same reason prevents them from measuring static forces as effectively. The charge developed decays with a time constant which is determined by the internal impedance and dielectric constant of the piezoelectric film [3]. The input impedance of the interface electronics must be considered, during sensor design, as it significantly affects the response of the device. Piezoelectric materials are temperature sensitive and this becomes a concern in their application.

F. Magnetic Tactile Sensors

These sensors work by detecting changes in magnetic flux, due to the application of force on a small magnet. The measurement of this flux can be done using Hall Effect, magneto-resistive or magneto-elastic sensors. Tactile sensors based on this method of transduction have advantages such as high sensitivity, wide dynamic range, very low hysteresis, linear response and general robustness. However, they are susceptible to magnetic interference and noise. Hence, these sensors cannot be used in magnetic environments. Moreover, the physical size of the sensing device limits the application to areas where size is not under consideration.

G. Optoelectric Tactile Sensors

Sensors with optical mode of transduction employ a light source, a transduction medium, and a photodetector. It comprises a clear plate, a light source, and a compliant membrane stretched above it but not in 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 total internal reflection occurs when there is no force applied. If there is an applied force, then reflection is diffused. A CMOS camera is used to record the diffused reflection in the imaging area. Hence, the light intensity (bright or dark patches on image) obtained can indicate how close the object is to the surface. These sensors are immune to electromagnetic interference, have high spatial resolution, and are flexible, sensitive and fast. Their size and rigidness are major disadvantages.

Another problem is the loss of light, which causes distortion in the signal. This technique gives a high-frequency response but also consumes a lot of power.

H. Ultrasonic Tactile Sensors

Another technology that has been used for the development of tactile sensors is acoustic ultrasonic sensing. Microphones are known to be useful for detecting surface noise that occurs at the onset of motion and during slip. A Polyvinylidene Fluoride (PVDF) polymer rubber uses receiver arrays to pinpoint the contact location. This technique enables slip and roughness detection, even during motion and quite adeptly at that. 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 softness of objects. They exhibit fast dynamic response and good force resolution. However, controlling PZT in miniaturized circuits can be tough.

I. Tunnel effect Tactile Sensors[1][3]

Quantum Tunneling Composite (QTC) is a composite with an elastomeric polymer binder with metal particles. It exhibits a quick reduction in resistance when it is distorted. Under no pressure condition, the polymer behaves as an insulator and when subjected to suitable pressure, it allows electrons to leap from irregularities in some particles to irregularities in others. This transfer, which happens without any contact between the particles, identified as the 'quantum tunneling' effect, allows for rapid drop in electrical resistance in QTC under pressure. The resistance drop is exponential and the changeover from insulator region to the conductor region follows a smooth and repeatable curve. These QTCs were used in NASA's Robonaut in 2012, which was able to survive and successfully complete its objective in space (See Fig. 2).

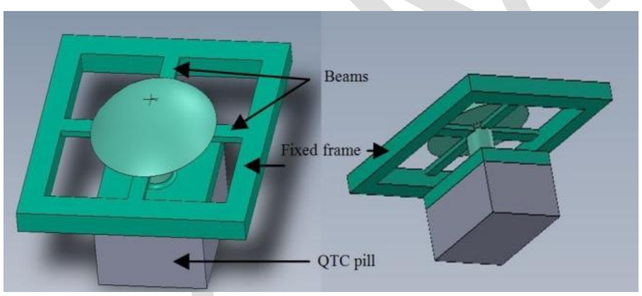

Fig. 2 Proposed sensing mechanism for a force sensor using QTC

IV. COMMERCIAL TACTILE SENSORS IN MARKET

A. Capacitor Based Tactile Sensor[4]

Leading Manufacturer: *Pressure Profile Systems, Inc*.
Product Name: *DigiTacts System*

Patented by PPS(Pressure Profile System), the DigiTacts System employs pads with a number of sensitive capacitive sensors, embedded with digital output, to enable tactile sensing in applications as varied as medical (prosthetics), Robotics (Barrethand and many grippers), Automotive (pressure mapping), sports (foot pressure mapping, knee joint pressure mapping).

It consists of intelligent sensors equipped with microcontrollers and is easy to install (communication to a computer via USB or Bluetooth), thus making it ideal for designers and engineers. Easily scalable, either higher resolution can be achieved or a larger area of sensing can be achieved or both.

The user interface is provided by PPS's "Chameleon Tactile Visualization and Acquisition", providing common and often used features like exporting, saving, processing data, see Fig.2.

1) Sensor Characteristics and Performance

Pressure Range: *5, 20 or 40*
Pressure Sensitivity: *0.2%*
Signal to Noise Ratio (SNR):*700:1*
Repeatability Error: *0.5%*
Linearity: *99.7%*
Accuracy Error: *<=2%*
Contact Surface Material: *Cloth & Polyimide*
Sensor Thickness: *0.02 in (0.5 mm)*
Cable Length: *59 in (1.5m)*
Operating Temperature:*-20°C to 100°C*

2) ELECTRONICS SPECIFICATIONS

Sample Rate: *30-100Hz*
Computer Interface: *Bluetooth*
ADC Resolution: *16 bit*
Input Voltage: *5V*
Input Power: *2.5W*
Enclosure Size: *3×1.5×0.5 in. (75×40×12.8 cm)*
Weight: *0.12 lbs. (55 g)*

B. Conductive Rubber Type Tactile Sensor [5]

Leading Manufacturer: *Weiss Robotics*
Product Name: i*) DSA 9330/5: Highly Miniaturized Tactile Transducers for Handling Tasks*
ii) DSA 9205: Tactile Transducer for Handling Tasks

1) DSA 9330/5[6]: Well suited to handling tasks like gripping, these miniaturized sensors are robust with high noise immunity. Suitable for both planar and curved surfaces, these can be connected/disconnected using an electrical connector at their ends, making them versatile and easy to use transducers. Scalability isn't an issue as a larger sensing area can be achieved by combining multiple transducers, see Fig. 3

TABLE II. Transduction techniques and their relative merits and demerits

Sr. No.	Type	Classification	Merits	Demerits
1	Resistive	Normal pressure	Good Sensitivity Low Cost	High Power Consumption Generally detects single contact point Lack of contact forces measurement
2	Capacitive	Normal pressure	Excellent sensitivity Good spatial resolution Large dynamic range	Crosstalk Stray capacitance Noise susceptible Complexity of measurement electronics Hysteresis
3	Inductive LVDT	Skin deformation	Linear output Unidirectional measurement High dynamic range	Moving parts Low spatial resolution Bulky Poor reliability
4	Piezoresistive	Skin deformation	High spatial resolution High scanning rate in mesh Structured sensors	Lower repeatability Hysteresis High power consumption Temperature sensitive
5	Piezoelectric	Dynamic tactile sensing	High-frequency response High sensitivity High dynamic range	Poor spatial resolution Dynamic sensing only Temperature sensitive
6	Magnetic	Skin deformation	High sensitivity Good dynamic range No mechanical hysteresis Physical robustness	Suffer from magnetic interference Complex computations Somewhat bulky High power consumption
7	Optoelectric	Normal pressure Skin deformation	Good sensing range Good reliability High repeatability High spatial resolution Immunity from EMI	Bulky in size Non-conformable
8	Ultrasonic	Skin deformation	Fast dynamic response Good force resolution	Limited utility at low frequency Complex electronics Temperature sensitive
9	Tunnel effect	Skin deformation	Good Sensitivity Physically flexible	Non-linear response

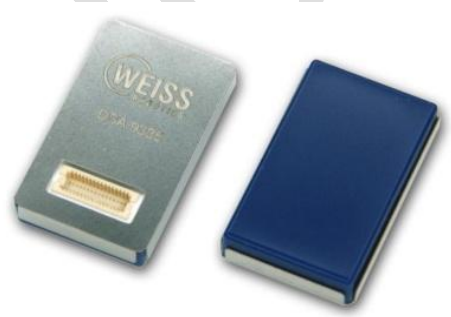

Fig. 3 DSA 9330/5

2) DSA 9205[7]: Designed with a special emphasis on gripping applications, it consists of a 6 x 14 point pressure sensitive matrix with as impressive a spatial resolution. Not compromising on the robustness and the signal transmission quality, as much attention to detail has gone into designing the DSA 9205 as on DSA 9330/5. A stand-out point is a design to allow easy cleaning of the transducers, crucial to pharmaceutical and food processing industries; see *fig. 4*.

3) SPECIFICATIONS

Table III. The DSA series 9330/5 Common Specifications

Power Supply	5V ± 10 %, 10mA
Spatial Resolution	3.8 mm
Operational Temperature Range	0- 40° C
Media Connected Parts	Stainless Steel, Silicone Rubber

Table IV. Differing Specifications

	DSA 9330	DSA 9335
Sensing Points	4x6	4x7
Sampling Rate	800 fps	700 fps
Dimensions (L x W x H)	18 x 25.6 x 5 mm	18 x 29.6 x 5 mm

Table V. DSA 9205 Specifications

Power Supply	5V ± 10 %, 10mA
Spatial Resolution	3.4 mm
Operational Temperature Range	0-40°C
Measurement Range	250 kPa
Media Connected Parts	Stainless Steel, Silicone Rubber
Sampling Rate	230 fps
Dimensions	24.4 * 51.4 * 5.4 mm

Fig. 4. DSA 9205

C. *Variable Resistance Type Tactile Sensors*

Leading Manufacturer: *Spectra Symbol*
Product(s) Name:

1) *SoftPot Membrane Potentiometer [8]:* Suitable for actuators and hand-held medical devices, Spectra Symbol, a trusted name, has designed this tactile sensor using the principle of potentiometers, i.e., variable resistance. It prides itself in being the thinnest linear sensor available today. Using it only requires mounting it on the desired surface. Having a wide working range temperature, being economical and easy to use, it has become quite popular in varied applications. It can give the desired linear output regardless of the shape of the surface on which it's mounted.

2) *HotPot Membrane Potentiometer [9]:* Perfect for usage in volatile and hot environments, it is as much a reliable sensor as any. In tune with the other products by Spectra Symbol, a low form factor ensures a thin transducer and is still very much economical. Ideal for highly precise position sensing applications such as those found in the military, it's truly robust (dust and water proof) and with a long functional life. It's highly resistant to temperature fluctuations and yet easy to install.

3) *ThinPot Membrane Potentiometer [10]:* Made from the polyester substrate, its features are similar to that of SoftPot, the only difference being the thickness. ThinPot is narrower than SoftPot.

Table VI. Specifications

Electrical Specifications	SoftPot	ShieldedPot	HotPot
Resistance	1k – 100k ± 20%	1k – 100k ±2 0%	5k – 100k ±2 0%
Effective Electrical Travel	8 – 2400 mm	10 – 1200 mm	10 – 1200 mm
Power Rating	1 W max @ 25° C	1 W max @ 25° C	1 W max @ 25° C
Mechanical specifications			
Live Cycle	> 1 Million	> 5 million	> 10 million
Length	≤ 0.51 mm	≤ 0.70 mm	≤ 0.51 mm
Actuation force			
-40 ° C	0.8 – 1.8 N	2 – 4N	3 – 5N
-25 ° C	0.8 – 1.8 N	2 – 4N	2 – 5N
+23 ° C	0.6 – 1.5 N	0.8 – 2N	0.8 – 2N
+75° C	0.5 – 1.4 N	0.7 – 1.8N	0.7 – 1.8N
Operating Temperature	-40V to +50° C	-40°C to +75° C	-40°C to 125° C

D. *Quantum Tunneling Composite Type Tactile Sensor[11][12]*

Leading manufacturer: Peratech Holdco Ltd.
Product Name: QTC Touch Processing Unit
Developed and patented by Peratech Holdco Ltd., the central part of the QTC Touch Processing unit is the QTC (Quantum Tunneling Composite) – a new electrically conductive material with improved sensitivity, perfect for making touch-sensing skins. It uses piezoresistive composite materials based on the Quantum Tunneling effect. However, the only drawback is low repeatability.
As stated on the company catalog, "QTC Touch Processing Unit is an ARM-based resistive multi-touch system with pressure scanning and interpolation of the acquired data".

Table VII. Comparison between Conventional Carbon Composites and QTC

Regular carbon composites	QTC
Even in unstressed state, shows some conduction	Acts as an insulator in unstressed state and as a conductor in a stressed state. Thus, it can be used as a solid-state switch – "off" in unstressed, "on" in stressed conditions.
In stressed condition, resistance decreases to only a few hundred ohms. Hence, it can't be used to measure small changes.	In stressed condition, resistance decreases to less than 1 ohm and hence can be used to detect very small changes.
Control overload is difficult.	Allows significant current to flow through it and hence control over the load.

Table VIII. Comparison of different composite Tactile Sensors [13]

Parameters	Piezoresistors	Strain Gauges	QTC
Sensitivity	High	High	High
Repeatability	High	High	Hysteresis Problem
Spatial Resolution	High	Quite High	Low
Working Area	Small (fingertip)	Small (fingertip)	Small + Large area
Working Range	Low	Medium	Very High
Fabrication	Costly	Costly	Simple
Electronic Integration	Easy	Easy	Complex

V. CONCLUSIONS

Different tactile transduction techniques were discussed in brief and the actual commercial sensors available in the industry were quoted, discussed, and compared based on the mentioned techniques. Most popular techniques are resistive and capacitive, owing to the ease of measurement and easy integration into the electrical circuitry, and consequently, communication with the microcontroller. They provide good resolution and sensitivity. Newer technologies such as QTC are extremely efficient in measuring even the lightest of tactile signals as well as those with a high magnitude. However, a shortcoming of all of the mentioned technologies is their inherent disability to differentiate between shear stress and normal stress.

REFERENCES

[1] YWR Amarasinghe, AL Kulasekera, and TGP. Priyadarshana. "Quantum Tunneling Composite (QTC) Based Tactile Sensor Array For Dynamic Pressure Distribution Measurement", 2013 Seventh International Conference on Sensing Technology, IEEE.

[2] Rajeev Agrawal and Ramesh Jain (1986). Overview of tactile sensing, Centre For Research On Integrated Manufacturing, The University of Michigan, Ann arbor.

[3] Ravinder S. Dahiya and Maurizio Valle (2008). Tactile Sensing for Robotic Applications, Sensors: Focus on Tactile Force and Stress Sensors, Jose Gerardo Rocha and SenentxuLanceros-Mendez (Ed.), ISBN: 978-953-7619-31-2, InTech.

[4] Pressure Profile Systems Inc., [Online]. Available: http://www.pressureprofile.com/digitacts-sensors

[5] Peratech Ltd., [Online]. Available: http://www.peratech.com/qtc-science.html

[6] Weiss Robotics, [Online]. Available: http://www.weiss-robotics.de/en/tactile-sensing/tactile-sensors/tactile-sensor-dsa9330-35.html

[7] Weiss Robotics, [Online]. Available:http://www.weiss-robotics.de/en/taktile-sensorik/taktile-sensoren/tactile-sensor-dsa-9205.html

[8] Spectra Symbol, [Online]. Available: http://www.spectrasymbol.com/potentiometer/softpot

[9] Spectra Symbol, [Online]. Available: http://www.spectrasymbol.com/potentiometer/hotpot

[10] Spectra Symbol, [Online]. Available: http://www.spectrasymbol.com/potentiometer/thinpot

[11] National Center for Biotechnology Information, [Online]. Available: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC4003994/table/t2-sensors-14-05296/

[12] Peratech Ltd., [Online]. Available: http://www.peratech.com/qtc-technology.html

[13] National Center for Biotechnology Information, [Online]. Available: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC4003994/

[14] Mohsin I. Tiwana, Stephen J. Redmond, Nigel H. Lovell (2012). A review of tactile sensing technologies with applications in biomedical engineering, Elsevier B.V., (17-20).

[15] L. Harmon, Automated tactile sensing, The International Journal of Robotics Research 1 (2) (1982) 3–32.

[16] L. Harmon, Touch-sensing technology – a review, Society of Manufacturing Engineers (1980) 58

[17] G. Murali Krishna and K. Rajanna. Tactile Sensor Based on Piezoelectric Resonance, IEEE sensors journal, vol. 4, no. 5, October 2004

[18] M. H. Lee and H. R. Nicholls, "Review Article Tactile sensing for mechatronics—a state of the art survey," Mechatronics, vol. 9, no. 1, pp. 1–31, 1999.

[19] Dexmart, http://www.dexmart.eu/fileadmin/dexmart/public_website/downloads/presentations/USAAR-Workshop-B2.pdf

[20] Sensors (Basel). 2014 Mar; 14(3): 5296–5332

[21] Weiss, K., Worn, Heinz(2005), The working principle of resistive tactile sensor cells, Mechatronics and Automation, 2005 IEEE International Conference, ISBN: 0-7803-9044-X

[22] Beebe, D. J., Hsieh, A. S., Denton, D. D., and Radwin, R. G. (1995). "A silicon force sensor for robotics and medicine". Sensors and Actuators A: Physical, 50(1):55–65.