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Current Trend of Tactile Sensor in Advanced Applications

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Abstract: Tactile sensor is one of the important tactile technologies which discovered in the 1980s. It grows in line with development of robotics and computers. From current development trends, varieties of application areas from tactile sensor have been proposed. In this paper, developments of tactile sensor have been reviewed and the applications from previous five years journals are discussed. The transduction techniques, their relative advantages and disadvantages, latest application area of tactile sensor and contribution are analyzed. *Copyright © 2012 IFSA.*

Keywords: Tactile sensor, Tissue elasticity, Human-interactive robot, Polydimethylsiloxane (PDMS), Capacitive sensor, Ionic polymer metal composite (IPMC), Fabric tactile sensor.

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1. Introduction

Today, we realized that vision, taste, touch, smell and sound sensory receptors are very important. Interaction with environment would make more meaningful in daily life. If one of sense not functions, human will not feel pleasure life such as before. Due to this, tactile sensor is created and develops to overcome and applied in the real life application.

Although tactile sensor was not a main research field compared the other sensor, the use of tactile sensor in products to improve quality of human life especially in the field of biomedical, robotic, and medical [1].

Early researchers, such as Harmon sees robotics fields have a good potential and future application of tactile sensing. Due to technical difficulties and low return investment, Harmon experience tactile sensing is not suitable for medicine and agriculture fields. Furthermore, other researchers such as Whitney and Nevins argued that passive monitoring will eliminate the need of tactile sensing.

Beginning of 21st century, it was predicted that this tactile technology would have the potential to sustain the growth of more intellectual system and product. In directly, it would develop the quality of human life [2]. However, tactile technology unsuccessful to expand and achieved the target market in 1990s. Unawares, tactile technology gradually grow and known time by time with many researcher. Now, it is not only useful in robotics area but it also has been involved in medical and biomedical engineering.

Four papers have been selected from the past five years journals to review their development to the variety of applications in medical field [3], robotics fields [4], image processing fields [5, 6] and biomedical field [7-10]. Details of the discussion will highlighted in part III, IV, and V.

2. Theory

2.1. What is Tactile Sensor

The term of tactile sensor is refers to the transducer that is sensitive to touch, force and pressure [1]. It is devices which receives and give feedback or respond to a signal having to do with force. Furthermore, it is required tactile information through physical touch. The temperature, vibration, softness, texture, shape, composition and shear and normal forces are the properties of measured parameter for tactile sensor. One or more of these properties can be measured by tactile sensor. Even though pressure and torque sensing is often not included in the definition of tactile sensing, pressure and torque are also important properties, typically acquired by physical touch, and can be included as tactile parameters.

2.2. Tactile Transduction Techniques

Normally, tactile transduction techniques are based on capacitive, piezoresistive, piezoelectric, and optoelecric methods. All of these techniques have their own advantages and disadvantages. Usually, capacitive, piezoresistive, piezoelectric, and optoelecric methods give a better performance and effectiveness. It always becomes a best choice to many sensor designers in order to develop the tactile application. In this section, all of these methods and their relative advantages and disadvantages will be discussed. These are also has been summarized in Table I [1].

2.2.1. Capacitive Tactile Sensors

A capacitive sensor contain of two conductive plates with a dielectric material between them [1]. The capacitance can be expressed as, $C = (A\varepsilon_0 r)/d$ for parallel plate capacitors which is C is the capacitance, A is the overlapping area of the two plates, ε_0 is the permittivity of free space, r is the relative permittivity of the dielectric material and d is distance between the plates. Generally, capacitive tactile sensors show a good frequency response, high spatial resolution, and have a large dynamic range. Furthermore, these sensors are more liable to noise, especially in mesh configurations. It is due to crosstalk noise, field connections and fringing capacitance and also requires relatively complex electronics to filter out this noise.

2.2.2. Piezoresistive Tactile Sensors

A pressure sensitive element is included for this sensor. It changes its resistance upon application of force. Simple resistive element can be expressed as, V = IR for the voltage-current characteristic which is V is the voltage, I is the current and R is the resistance of the material. Usually some property of the voltage is fixed. Then change in resistance is observed by a change in the current. This resistive element generally takes the form of a conductive rubber, or conductive ink which is pressure sensitive. They commonly need less electronics only. Change in resistance can easily be quantified and it's easier to manufacture and integrate. They are less disposed to noise and therefore work well in mesh configurations as there is no cross talk or field interaction. The hysteresis will give bad impact to resistive tactile sensors and produce a lower frequency response if compared to capacitive tactile sensors.

2.2.3. Piezoelectric Tactile Sensors

A variety of materials such as certain crystals and some ceramics will generate a voltage potential when the crystal lattice is distorted [11]. Its structure may influence the sensitivity of the crystal and allowing it to distinguish between transverse, longitudinal and shear forces. The voltage, V, generated is directly proportional to the applied force, pressure or strain. These sensors give a very good high-frequency response, which makes them an ideal choice for measuring vibrations. However, due to their large internal resistance, they are limited to measuring dynamic forces and are unable to measure static forces. The charge developed decays with a time constant which is determined by the internal impedance and dielectric constant of the piezoelectric film. While doing sensor design, the things that should be considered are the input impedance of the interface electronics. It is because it significantly will affect the response of the device.

2.2.4. Optoelectric Tactile Sensors

Optoelectric sensors use a light source, transduction medium and a photodetector, the latter often in the form of a camera or a photodiode. Usually transduction occurs when changes in the tactile medium modulate the transmission or reflectance intensity, or the spectrum of the source light, as the applied force varies. The advantages of this sensor are they have high spatial resolution, and are not affecting to common lower frequency electromagnetic interference that generated by electrical systems. However, it still has some disadvantages. The disadvantages for this sensor are due to their size and rigidness (Table 1).

In our review, four papers were chosen as below:

i. Flexible Tactile Sensor for Tissue Elasticity Measurement [3];
ii. Development of Tactile Sensor System of a Human-Interactive Robot "RI-MAN" [4];
iii. Large-size Fabric Tactile Sensor for Detecting Contacted Objects [5];
iv. A Tactile Sensor for Biomedical Application Based on IPMCs [7].

3. Literature Review

For the first paper [3], in the early stages of tactile sensor research, some weaknesses were found due to the material used in construction. For the purpose of measuring the elasticity, some active sensor prototype developed. However because of the active element in the sensor application, several limitations raised. In a study done by Peng Peng et al [3], they come up with new findings in which they suggested the use of passive tactile sensor. It is chosen because of the ability to measure tissue elasticity and detecting contact force as well as the pressure distribution on the surface of the sensor.

Table 1. Techniques and relative advantages and disadvantages.

Technique	Modulated Parameter	Advantages	Disadvantages
Capacitive	Change in capacitance	• Excellent sensitivity • Good spatial resolution • Large dynamic range	• Stray capacitance • Noise susceptible • Complexity of measurement electronics
Piezo-resistive	Changed in resistance	• High spartial resolution • High scanning rate in mesh	• Lower repeatability • Hysterisis • Higher power consumption
Piezo-electric	Strain (stress) polarization	• High frequency response • High sensitivity • High dynamic range	• Poor spatial resolution • Dynamic sensing only
Opto-electric	Light intensity/ spectrum change	• Good sensing range • Good reliability • High repeatability	• Bulky in size • Non-confirmable

Sensor fabrication built on polydimethylsiloxane (PDMS) process because it provides a facility to integrate the sensor to medical instruments. PDMS was chosen because the properties of the advantages such as flexibility, ductility, and bio-compatibility. This sensor consists of two sensing elements with different stiffness values.

The sensing elements can be illustrated like a spring as shown in Fig. 1. The sensor is built with two different spring constant, soft spring (k_s) and hard spring (k_h), where one of spring more elastic than the other. This is because, when a force is applied, it will cause a deflection on the spring and k_s suffer more than k_h. The compatibility condition can be derived as shown in:

$$\partial x_1 = \partial x_2 \rightarrow \frac{F_1(k_h + k_\tau)}{k_h k_\tau} = \frac{F_2(k_s + k_\tau)}{k_s k_\tau} \tag{1}$$

The tissue stiffness can then be calculated from:

$$k_\tau = \frac{k_s - k_h \frac{\partial x_h}{\partial x_s}}{\frac{\partial x_h}{\partial x_s} - 1} \tag{2}$$

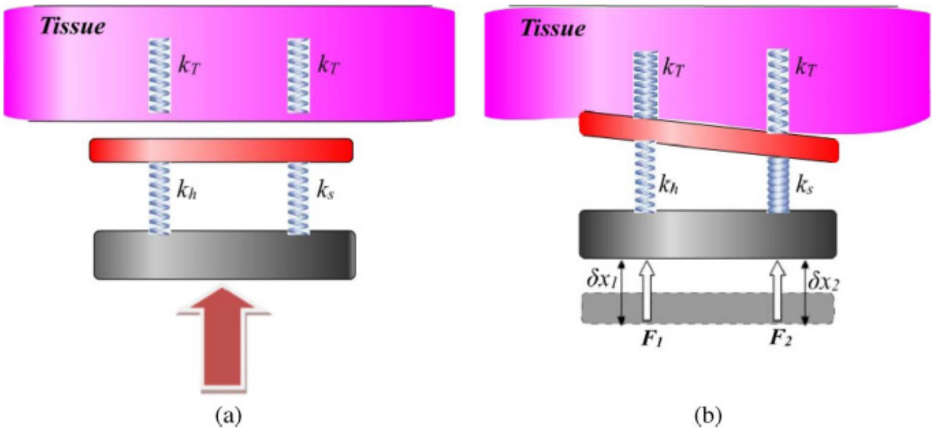


Fig. 1. (a) Schematic diagram of the tactile sensor and the tissue under investigation, (b) Schematic diagram of the contact condition between the tactile sensor and targeted tissue.

From (2), shows the relative deflection of the two sensing elements ($\delta x_h/\delta x_s$) serves as an integral part in calculation tissue stiffness. Capacitive sensing scheme is applied to precisely measure this deflection. To implement the sensing concept, a capacitor pair is designed. Different sizes of sensing membrane are fabricated to vary the stiffness of these diaphragms. The capacitor pair with different sizes is shown in Fig. 2. Each capacitor comprises one top electrode, one bottom electrode, and one single air gap. When the sensor is pushed toward targeted tissue, relative deflection of two sensing membranes can be precisely measured by the capacitive change of each element as shown in Fig. 2(b). This sensor consists of 5 x 5 sensing element and can be attached to any medical instruments built due to thinness of the sensor.

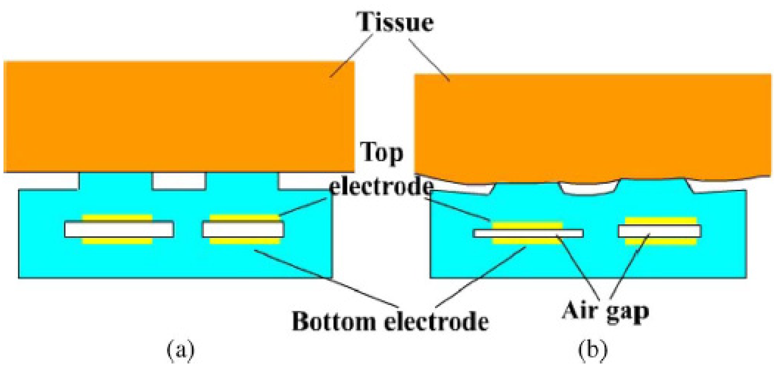


Fig. 2. (a) Conceptual diagram of the proposed flexible tactile sensors under contact with tissue. (b) Different sizes of air gaps of the tactile sensors squeezed by different amounts while pushing toward tissue.

The second paper [4] reflects the usage of tactile sensor for robots. Tactile sensor systems need to be design to implement on the human-interactive robot (RI-MAN). In previous research done by other researcher, sensor developed on the basis of MEMS technologies have high density but narrow covering area. For application of covering large body this will not be suitable. Tactile sensors which have been design for use on robot fingers are mostly able to detect tangential stress and this is good in grasping or force control. Unfortunately, it is suitable only for small area such as finger. The need for tactile sensor for human-interactive robot is need for manipulate objects, interacts and communicate with humans by touch and it should be soft and compatible with curved robot surfaced.

Previously some soft tactile systems for large surface have been developed. It is not suitable, when a physical labor using a tactile sensation is required. Flexible fabric-based tactile sensors using an electrically conductive fabric also propose but since the sensors are binary switches and it is difficult to build. Toshiharu et. al. [4] are currently developing soft areal tactile sensor by embedding semiconductor pressure sensors as pressure sensing elements in an elastic body. This is to provide pressure strength and distribution that can be used to control manipulator.

Few specifications are highlighted for tactile sensor system. First is spatial resolution. This is necessary to realize a resolution similar to that o a human. Second is measurement resolution. This is necessary for the feedback control to be smooth. For tactile sensor controller, some specification also highlighted. First, each controller should located nearby or tactile sensor. This is to reduce cable length, where it will reduce electric noise. Second, controller should form a network. Third, controller should be small. Fourth, the controller should output abstract compressed features. Lastly, the sampling period should be synchronous. Five places tactile sensors are installed such as the chest, the right and the left of the upper arms and forearms as shown in Fig. 3.

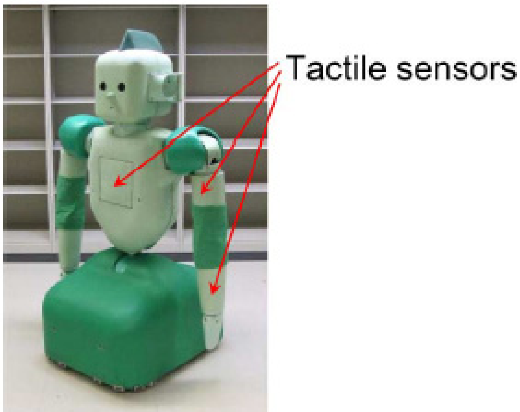


Fig. 3. Tactile sensors in RI-MAN.

In the next paper [5], to detect the hardness of contacted objects, the authors' group proposed to integrate an actuator mechanism onto the tactile sensor. Due to high space and time resolutions, tactile sensors been applied by embedding them into clothes and daily commercial products. Unfortunately it is difficult to be used due to the brittleness of the material. As an alternative, researchers start to use resin materials to fabricate flexible type of sensor structures. A knitted structure was proposed by Konishi et al. and N. Chen et al. [5].

In previous research, the implementation of a tactile sensing function on a fabric structure has been proposed by the Kita et. al. [5] by proposing an artificial hollow fibre as an MEMS material. Through their studies, they investigate the effect on fabric tactile sensor by applying a hand loom, and observe the characteristic of contacted object detection. Fig. 4 shows the schematic view of the fabric tactile sensor. Fig. 4(a) illustrates an artificial hollow fibre. The changes in capacitance between the warp and weft fibres occurred due to load applied at intersection points. It will also cause deformation, as shown in Fig. 4(b).

Lastly [7], in previous proposed devices, some drawback were detected although they able to give a reliable result. Shikida et al. [8], report on an active tactile sensor able to detect both contact force and the hardness of an object. However, precise pneumatic drive and control of a matrix of these sensors could be a formidable task. Helmes et al. [9] and Lindahl et al. [10] used another approach to detect the physical properties, stiffness, and elasticity of tissue, utilizes a piezoelectric sensor oscillated at resonance frequency. The bimorph could be favored in robotic guided applications in conjunction with a force-torque sensor, but it cannot be used by a human neurosurgeon. Therefore, Claudia [7] proposes a prototype of a multifunctional tactile sensor based on ionic polymer metal composites (IPMCs) as an alternative solution. If mechanical deformation occurred, a low voltage will be generated across their thickness and causes the IPMCs bend.

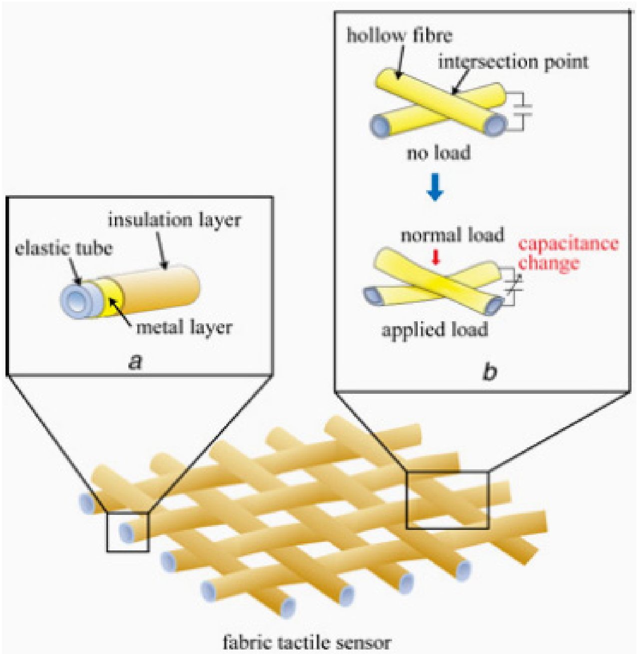


Fig. 4. Schematic view and operation principle of a fabric tactile sensor:
(a) Artificial hollow fibre, (b) Operation principle.

4. Result Outcomes and Contribution

Tactile sensor that has been in fabrication has thickness of about 20 μm. From the tests carried out, for the larger size of the membrane, it shows a large deflection for the same load applied. From these tests, the readings for both capacitive sensing began to saturate with a load greater than 0.06 N due to closure of the air gap. It is advisable for every membrane force more than 0.04 N should not be applied. This is to maintain the linear response between capacitive readout and the applied load.

The responses off the pressure sensing element were measured. It shows that the time response has a smooth sinusoidal shape; also the sensor output is almost linear with the applied force. The frequency response of the sensor also was measured. It shows that the system is ideal to about 100 Hz. In the third experiment, the effectiveness of the proposed structure was evaluated. Three difference conditions were tested. The results show the proposed structure has the highest sensitivity.

Other test was to measure the output when weights 1 – 8 kg with an area of 25 mm × 25 mm were placed on the tactile sensor. Results show the tactile sensor has a satisfactorily measurement resolution. The tactile sensor are placed in five areas, the chest, and the right and left of the upper arm and fore arm. In demonstration on the RI-MAN, a 16 kg dummy human are lift up. In Fig. 5, the realized roll angle and the load detected by the tactile sensors are shown. This shows the tactile sensors succeeded in the detecting changes in the load.

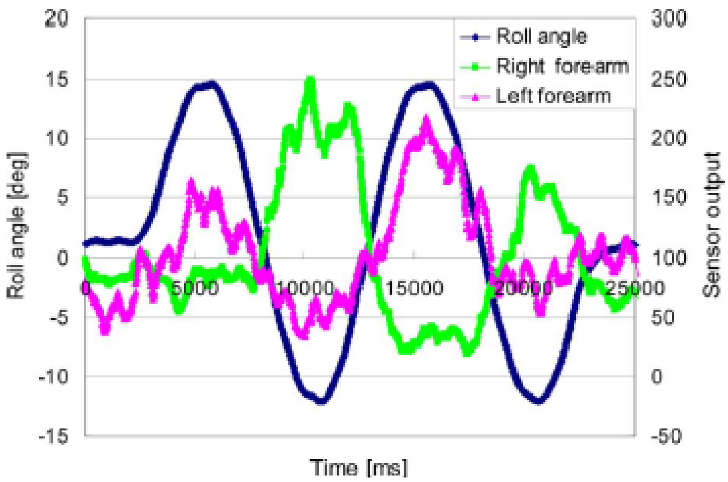


Fig. 5. Cross Roll angle and the load detected by tactile sensors.

Two kinds of fabric tactile sensors having different sizes 87.5 × 52.0 mm and 180.0 × 56.0 mm were produced by applying the handloom. The pitch values of the detection point at the horizontal and vertical directions were 7.0 and 7.0 mm, respectively, in the former sensor, and they were 18.0 and 14.0 mm, in the latter one. The developed fabric sensor successfully detected the 2D shape of the contacted objects. It can be referred in Fig. 6.

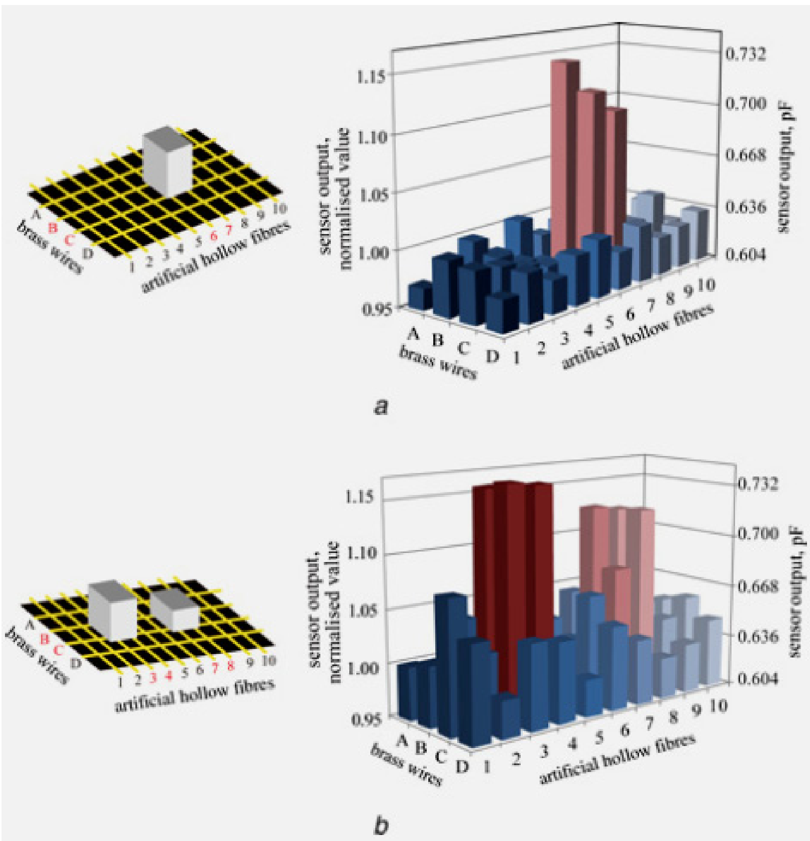


Fig. 6. Detection of the applied distributed force and the object shape:
(a) Square plate (size: 20 × 20 mm, force: 2925 mN), (b) Two different weight of square block (left: 269 g, right: 187 g, size: 24.2 × 24.2 mm).

The variation of the signals among the detecting points was less than 1.5 % when the concentrated force was applied to the each sensing point. The sensor output increased with increasing applied load, and it depended on the size of the contacted area. Refer to Fig. 7. The sensor output was the same when the applied pressure on the fabric was the same, even if the contacted areas were different. Refer to Fig. 8.

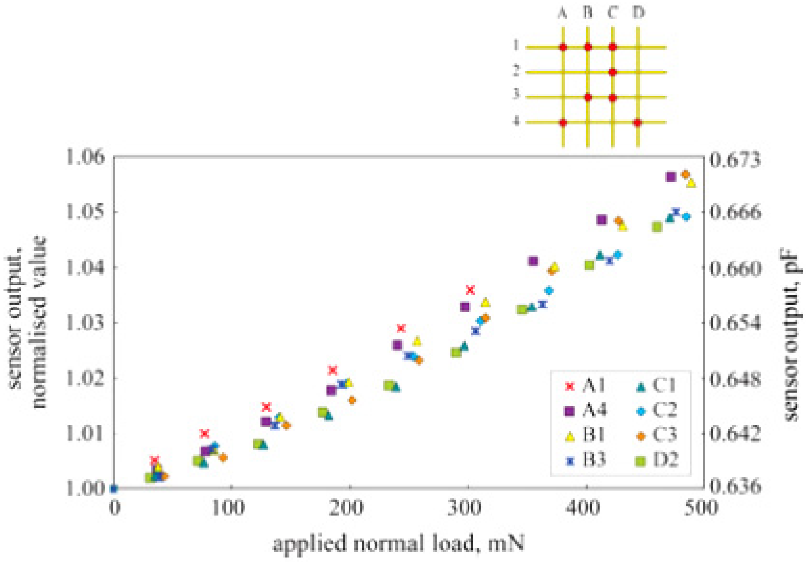
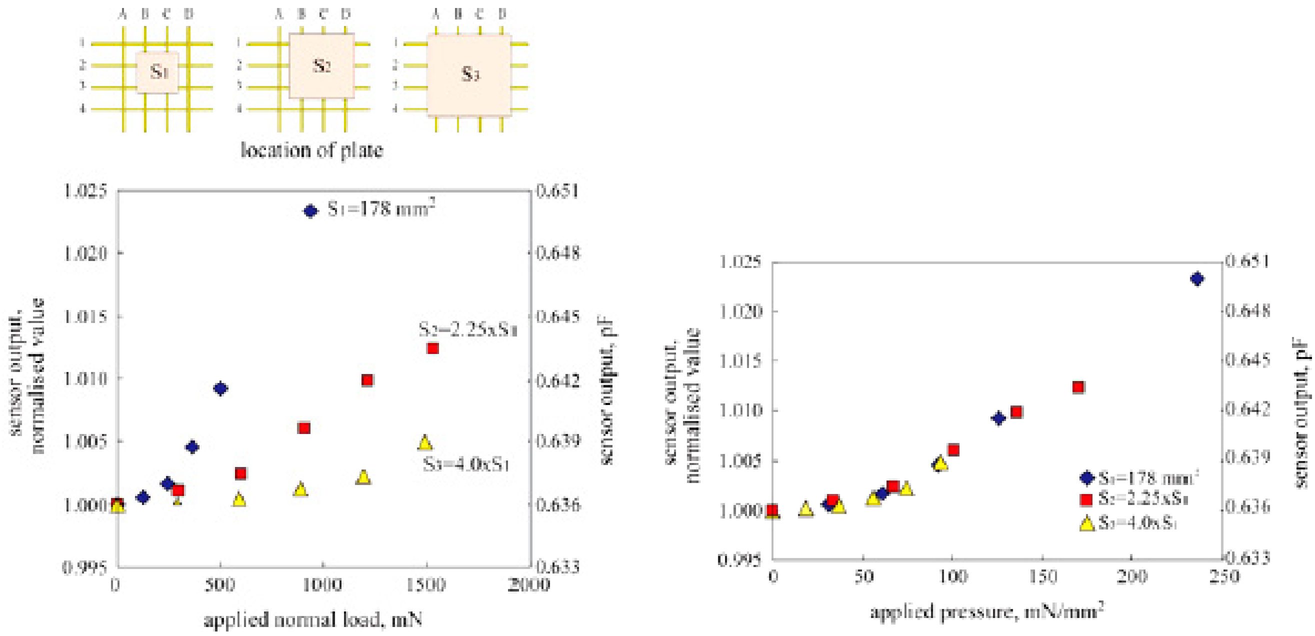


Fig. 7. Relationship between the applied loads and the sensor output at various detecting points (concentrated load was applied to the sensor).



(a) (b)

Fig. 8. Characteristics of the contacted object detections under the condition of three different contacted areas at the sensing point of C2: (a) Relationship between the applied load and the sensor output detected, (b) Relationship between the applied pressure and the sensor output detected.

Fig. 9 shows the results relating to testing the on–off mode, where both the actuator input voltage and the sensor output voltage are plotted while the system is moved inside the tube with the window, using a variable-speed motor drive at a constant speed. From the figure it is possible to recognize two different responses by the sensor that corresponds to passing through the closed tube and the window respectively: an alternate signal is obtained when the sensing element is passing through the window while an almost zero signal refers to the passage inside the tube.

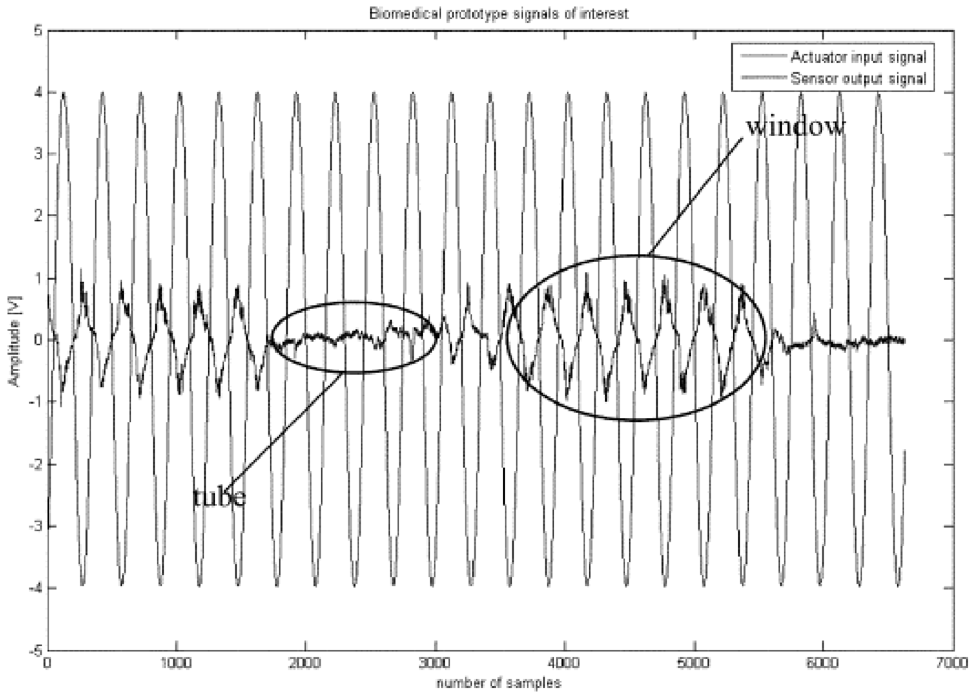


Fig. 9. Actuator input signal and the sensor output signal.

From Figs. 10 and 11, it can be noticed that the sensor output signal is affected by noise. However, the noise does not affect the information required, which is only the amplitude of the sensor output signal.

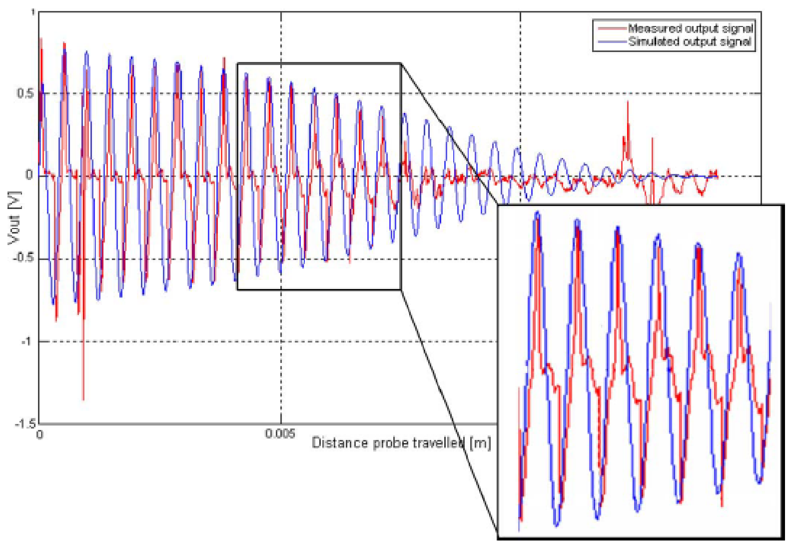


Fig. 10. Sensor output signal while the probe is moved through the window in the tube under the cantilever target.

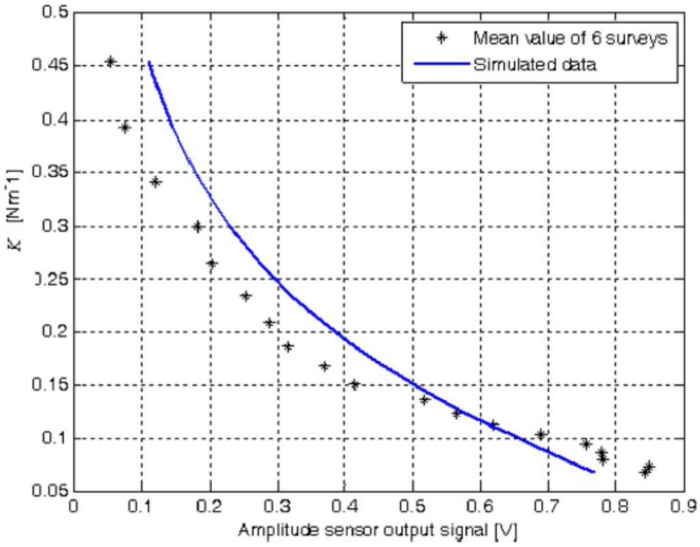


Fig. 11. K versus the maximum amplitude of the sensor output signal at a temperature *t = 25 °C* and humidity *h = 35 %.* The dotted line refers to the mean value of 6 different surveys, while the solid line refers to simulated data.

Fig. 11 shows the characteristic curve of K versus the sensor output signal, where the mean value of six different surveys is plotted. The curve obtained shows that each value of the sensor output corresponds to a different elastic constant value.

5. Discussion

The proposed sensor has been successfully fabricated by utilizing five-layer PDMS structure. Due to its size, the sensor can be mounted on any medical instruments. The tactile sensor can detect changes as small as 0.01 MPa on polymer specimen ranging from 0.1 to 0.5 MPa.

Tactile sensor systems for the RI-MAN successfully build. RI-MAN able to detect the magnitude and position of the load based on the experiment performed. There is still some space for improvement in future research. First are to improve the measurement resolution and noise tolerance. Second, is improved the controller and third is to optimize the tactile sensor features so that it will be able detect human tactile sensation such as stroking and hitting.

Regarding on the experiment that have been done in order to investigate the characteristic of the contacted object detection, the authors enlarged the size of the fabric tactile sensor by applying a handloom. Trough the experiment conducted, the fabric tactile sensor able to detect the load by measuring the capacitance changes. Four advantages can be concluded for the fabric tactile sensor:

1. Tactile sensing on arbitrary surface.
2. Tactile sensing of large surface area.
3. Wearable sensors.
4. Detection of two-dimensional (2D) contact force distribution.

A prototype of biomedical application has been developed which exploit the reversibility of the IPMC conversion property. The advantages of using IPMCs are lightweight, low-power consumption, softness, low-cost, and biocompatibility. By recognizing the tissues coming into contact, the device able to recognize and give information on their stiffness. Besides of its simple structure, the device is easy to be operating.

6. Conclusion

Developments and applications in tactile sensor trends over the last five years have been analyzed. Based on the tactile technology, it's not limit to certain application only but it has been growth with variety of application especially in medical [3, 12-14], robotics [4], object recognition [5, 6] and bio-medical [7-10] fields.

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because of it is a peer reviewed international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per year by International Frequency Sensor Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc. Since 2011 the journal is covered and indexed (including a Scopus, Embase, Engineering Village and Reaxys) in Elsevier products.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
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