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Ultrasonic tactile sensor integrated with TFT array for force feedback and shape recognition

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ABSTRACT

In this study, we propose an ultrasonic tactile sensor for real time contact force measurements and high-resolution shape recognition to enable safe and reliable robotic grasping of objects that may vary in compliance or texture. The sensing mechanism utilizes piezoelectric transduction where pulsed alternating voltage signals are applied to a polyvinylidene fluoride (PVDF) thin film, which generates pulses of ultrasound waves that travel upwards through the sensor components to the object contact interface. These waves are reflected back onto a receiver PVDF thin film that produces a localized voltage output, which is detected by the TFT (Thin-Film Transistor) array layer and converted into a two-dimensional grayscale image after signal processing. The ability of the tactile sensor to detect contact forces can be attributed to the sensor surface having a thin compliant polymer layer with a microstructure array. When the sensor contacts objects, the microstructures act as force concentrators, resulting in the localized deformation of the polymer layer that can be observed by the proposed ultrasonic imaging technique with an observed linear response to normal static forces in the range of 1–6 N. Furthermore, the shape sensing resolution and force detection range of the tactile sensor can be tuned by varying the number of microstructures in the array and the utilization of polymers with varying hardness, respectively.

1. Introduction

While robots have been widely employed in industry for automated manufacturing, their applications are beginning to diversify for e.g. the development of humanoid robots to assist humans in everyday activities and work cooperatively to perform tasks like exchanging objects. Smart robots that can safely work in unstructured everyday environments will require detailed object information from different sensing sources like vision and touch. While visual feedback has been widely utilized for positioning and shape recognition, there is also a need for tactile or coordinated touch sensing to enable better handing of objects. Visual feedback has limitations for robotic grasping applications as it may suffer from occlusions and incorrect calibrations and is not suitable to work in the dark. Furthermore, vision does not provide crucial information about object properties like deformability and texture. Mechanical compliance, for instance, is key to efficiently deal with fragile objects without causing damage. Tactile sensing in robotics aims to meet two haptic requirements, which include object identification (determination of shape, textural features and compliance) and object manipulation (closed loop control over grip force). Most unstructured applications generally require a combination of the two where exploratory movements can gain information about the object through touch followed by implementation of intelligent strategies to enable effective handing. Consequently, several tactile sensor designs have been proposed to improve object grasping and manipulation by measuring and analysis of spatial distribution of forces [1,2]. Furthermore, the detection of normal and shear forces have been used to gain additional information like contact shape, surface texture and roughness and slippage detection [3–8].

One of the main limitations of tactile sensing in robotics has been the absence of sensitive yet robust sensors that can be easily incorporated into anthropomorphic mechatronic fingers for use in everyday environments, similar to those in which human hands function. Wide varieties of tactile sensing technologies have been attempted which include optical [9], resistive [10], capacitive [11], piezoelectric [12], magnetic [13] and surface acoustic waves [14] among others. However, while significant progress has been made in robotic tactile sensing for contact point estimation, surface normal and curvature measurement and slip detection, there are still improvements that need to be made to take them from structured laboratory environments to practical usage in real world robotic applications [15]. For example, while large numbers of tactile sensors put pressure on the computing power needed to process

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the data, this can be solved or at least reduced by having distributed computing starting right from the transducer level [16]. To achieve tactile sensing comparable to humans, it is desirable for robots to have a dense and spatial distribution of taxels or tactile elements. The need to fit a large number of tactile sensors in a small space increases the number of interconnects that is needed to read and transfer signals. While MEMS technology has gone a long way in achieving miniaturization, these devices are generally unable to detect large forces due to their fragile nature. An interesting approach to solve this problem is to directly couple smart materials like piezoelectric polymers with integrated circuits. An example of this approach is to replace the polysilicon gate of a metal-oxide semiconductor field-effect transistor (MOSFET) device with a piezoelectric film [17]. The electrical output of this film in response to a mechanical stress can directly modulate the charge in the induced channel of the MOSFET. These piezoelectric sensing materials can act as extended gates of field effect transistor (FET) devices. This integration of the sensing element with IC technology can improve spatial force resolution, signal to noise ratio and reduce wiring complexity that is a major issue in robotic tactile sensing.

While tactile approaches based on resistance, capacitance and direct piezoelectric conversion of mechanical stress into electrical signals are simple for signal acquisition, they do have certain drawbacks relating to lack of sensitivity and repeatability, mainly due to hysteresis phenomena or cross-talk between the sensor elements and thus their implementation could be limited in some high-precision applications [18]. The main problem in these direct mechanical-electrical coupling systems is that it is highly improbable to optimize one form of transduction without compromising the other. While several researchers have utilized piezoelectric transducers for tactile sensing, they have only measured the charge output in response to a mechanical stress when contacted by the object [19]. Due to the transitory nature of this signal, the sensor is incapable of measuring static contact forces due to rapid charge dissipation. Furthermore, distributed sensing elements embedded in elastomers often leads to reduction in spatial resolution by increasing cross talk effect in neighboring sensing sites [20]. These issues could be solved by using piezoelectric transducers for ultrasonic tactile sensing which can effectively uncouple mechanical transduction from electrical transduction through the use of ultrasonic pulse-echo ranging, so that both the mechanical and electrical transduction are optimized [21]. Shinoda et al. developed a tactile sensing device consisting of a flexible fingertip with a quadruple sound sensing piezoelectric matrix to detect localization of acoustic emissions during touch or contact movement [22]. Piezoelectric transducers are of great importance as measurement tools for a wide range of pulse-echo based ultrasonic applications in areas like medical diagnostics, robotics and proximity detection [23,24]. Multilayer transducers produced from piezoelectric polymers like PVDF have been used to increase overall transducer efficiency on both the transmitter and receiver side [25]. PVDF is a well-known piezoelectric polymer that can generate flexural ultrasonic waves because of its flexibility and shows suitability for tactile sensing due to advantages like high piezoelectric voltage sensitivity, workability, responsiveness over a wide frequency range and inertness to chemical agents [26].

In this study, we propose an ultrasonic tactile sensor integrated with a TFT array for real time contact force measurements and high-resolution identification of object shape. The tactile sensor can effectively identify static normal forces due to the presence of a top polymer layer with a microstructure array. When a normal force is applied between the object and the sensor, it results in the deformation of the polymer microstructures that act as force concentrators. The ultrasonic pulses generated by a transmitter PVDF film propagate through the polymer layer and are reflected by the target object and collected by a receiver PVDF film. By measuring the transit time or time of flight of the ultrasound pulses, it is possible to measure the change in contact area of the microstructures under compression, which can be related to the stress-strain characteris-

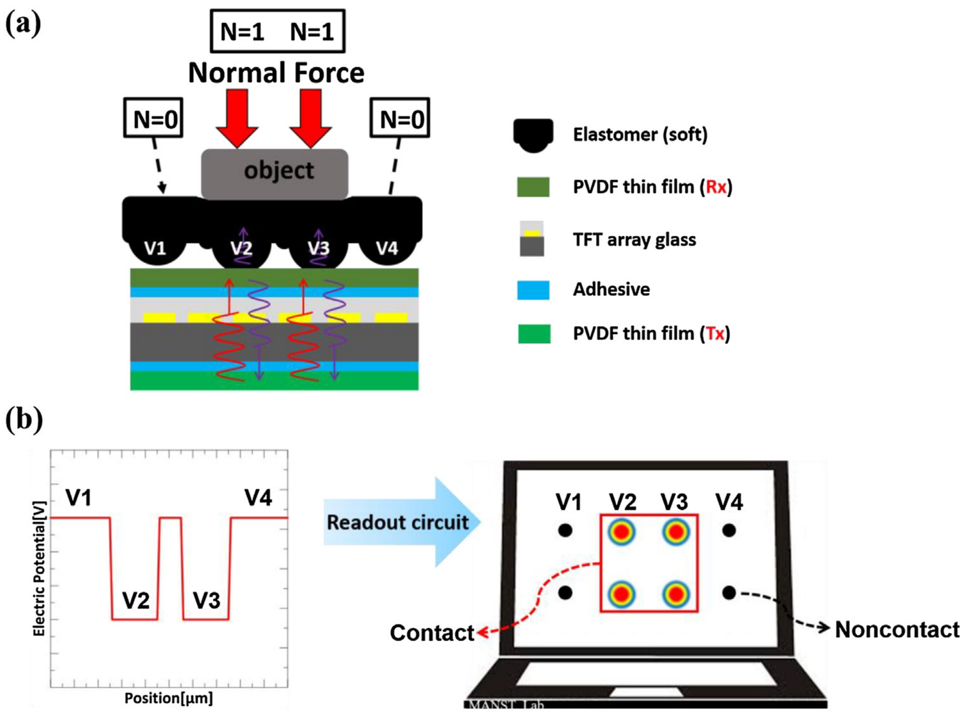

Fig. 1. (a) Schematic of the operation mechanism of tactile sensor, which is based on ultrasonic pulse-echo ranging. (b) The localized piezoelectric voltage output is detected by the TFT array and can be used to generate a 2D ultrasonic greyscale image of contact area. The image can also be analyzed to give contact force information based on the deformation of the PDMS microstructure array.

tics and hence provides a measure of the applied contact force. In other words, increasing the applied normal force increases deformation of the microstructures and results in a larger contact area and this can be observed by ultrasonic imaging. The comparative analysis of the contact area pixels to the total image pixels enables identification of contact force. Based on the 2D greyscale image of polymer microstructure deformation, we have successfully measured applied normal forces in the range of 1–6 N. Furthermore, the tactile sensor can also differentiate between object contact shapes while the resolution of shape recognition can be enhanced by increasing the density of the microstructure array. The proposed dual-purpose tactile sensor has good practical applicability for effective robotic manipulation in unstructured environments.

2. Sensor design

2.1. Sensing mechanism

The sensing mechanism utilized in this tactile sensor is analogous to ultrasonic pulse-echo ranging used in medical imaging or sound navigation and ranging (SONAR). The sensor consists of a TFT layer sandwiched between a piezoelectric PVDF transmitter and receiver layer as shown in Fig. 1a. The top of the sensor consists of a thin compliant layer made of a soft polymer like PDMS (Polydimethylsiloxane) with an array of semi-circular bump like microstructures. Typically, a pulsed AC signal is applied to the transmitter layer that generates an ultrasonic pulses of a few megahertz that propagate through the device until they are reflected from the exposed surface of the polymer layer. The transit time and amplitude of these reflected pulses depends on the thickness of the PDMS layer, which changes when deformed on contact with an object under a normal force. The reflected ultrasonic waves received by the PVDF receiver layer results in a voltage generation, which is detected by the TFT array. A readout module analyzes the output of the TFT array and a computer software produces a two dimensional grayscale image of the contact area. When no object is in contact with the PDMS layer, 100% of the acoustic energy is reflected from the PDMS/air interface, which results in increased output of the PVDF receiver layer (V1 and V4) as shown in Fig. 1b. However, in the case when an object contacts the sensor surface, only part of the acoustic energy is reflected and this results in a relatively lower voltage output (V2 and V3). Although an ultrasonic sensor can provide a high-resolution image due to the TFT array, the obtained 2D image can only reveal the contact area without force information. In this study, we tried to utilize the advantage of ultrasonic imaging to measure the contact force as well as contact area by adding the microstructure array to the PDMS layer. As the object applies a compressive force, it results in deformation of the PDMS microstructures and an increase in the contact area, which can be observed in the obtained 2-D ultrasonic image, thus enabling real time force detection. A brief theoretical explanation of the stress-strain relationship is provided when polymers are deformed. In general, the high elasticity of polymers can be related to their molecular structure. Under Brownian thermal motion, polymer molecules are long and coiled up in random configuration. When a force is applied, they are straightened out under deformation and then recoil back as soon as the force is released. Elastic materials can be described in terms of their bulk modulus which is a measure of the resistance to compression. The bulk modulus, K, can be mathematically expressed as the relationship between the applied pressure, P, and the consequent shrinkage (ΔV) of the original volume, V, as shown below:

$$P = K\left(\frac{\Delta V}{V}\right) \qquad (1)$$

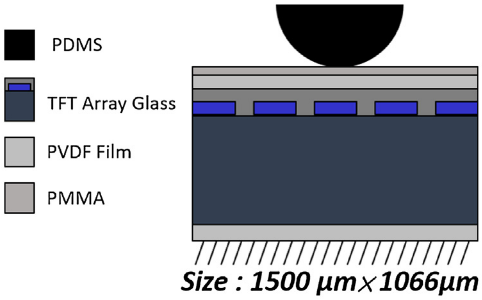

Fig. 2. The 2D model of the ultrasonic tactile sensor for numerical simulations.

Table 1
The physical specifications of tactile sensor.

Materials	Diameter (μm)	Thickness (μm)
PMMA	1500	10
PDMS	1000	500
TFT Array Glass	1500	500
PVDF Film	1500	28

Table 2
Properties of materials present in tactile sensor.

Property	Units	PVDF	Glass	PDMS	PMMA
Density	kg/m^3	1780	2203	970	1190
Young' s modulus	Pa	–	73.1e9	75e4	3e9
Poisson's ratio	–	0.35	0.17	0.50	0.40
Relative dielectric constant	–	11	2.09	2.75	3
Speed of sound	m/s	1500	3962	1485	2000

This relationship explains the linear behavior observed between an applied normal force and the subsequent deformation of elastic materials. Furthermore, the Young's modulus, E, which is a measure of the stiffness of a linear elastic solids, is the ratio of the tensile stress (σ) to the corresponding tensile strain (ε). The Poisson's ratio can be defined as the ratio of the transverse contraction strain normal to the applied force to the longitudinal extension strain in the direction of the applied force. The Young's modulus (E), Shear modulus (G) and the Poisson's ratio (γ) for linear elastic materials are related as shown below:

$$G = \frac{E}{2(1+\gamma)} \qquad (2)$$

While it is difficult to measure the Poisson's ratio of elastomers accurately, they generally have a value of about 0.3 to 0.5.

2.2. 2-D numerical simulations

A 2D model of the ultrasonic tactile sensor was established as shown in Fig. 2 and analyzed using commercial finite element software, COMSOL. Table 1 indicates that all dimensions are the same with the finished sensor, while Table 2 lists the material properties of each part. A hemispherical PDMS structure is contacted to the sensor surface under different normal static forces that correspond to contact areas of 200 μm and 900 μm while the bottom surface was set as a fixed-end boundary condition as shown in Fig. 3a. The maximum element size used is 25 μm and the total number of elements used is about 31,700. The PVDF transmitter film is excited by the application of an AC signal with a frequency of 10 MHz to produce the ultrasonic waves. The reflected ultrasonic waves after interaction with the PDMS structure excite the receiver PVDF film that produces a voltage output. It can be seen from the simulation results that the observed electric potential is higher at the sensor/air interface while it drops in the region where the ultrasound

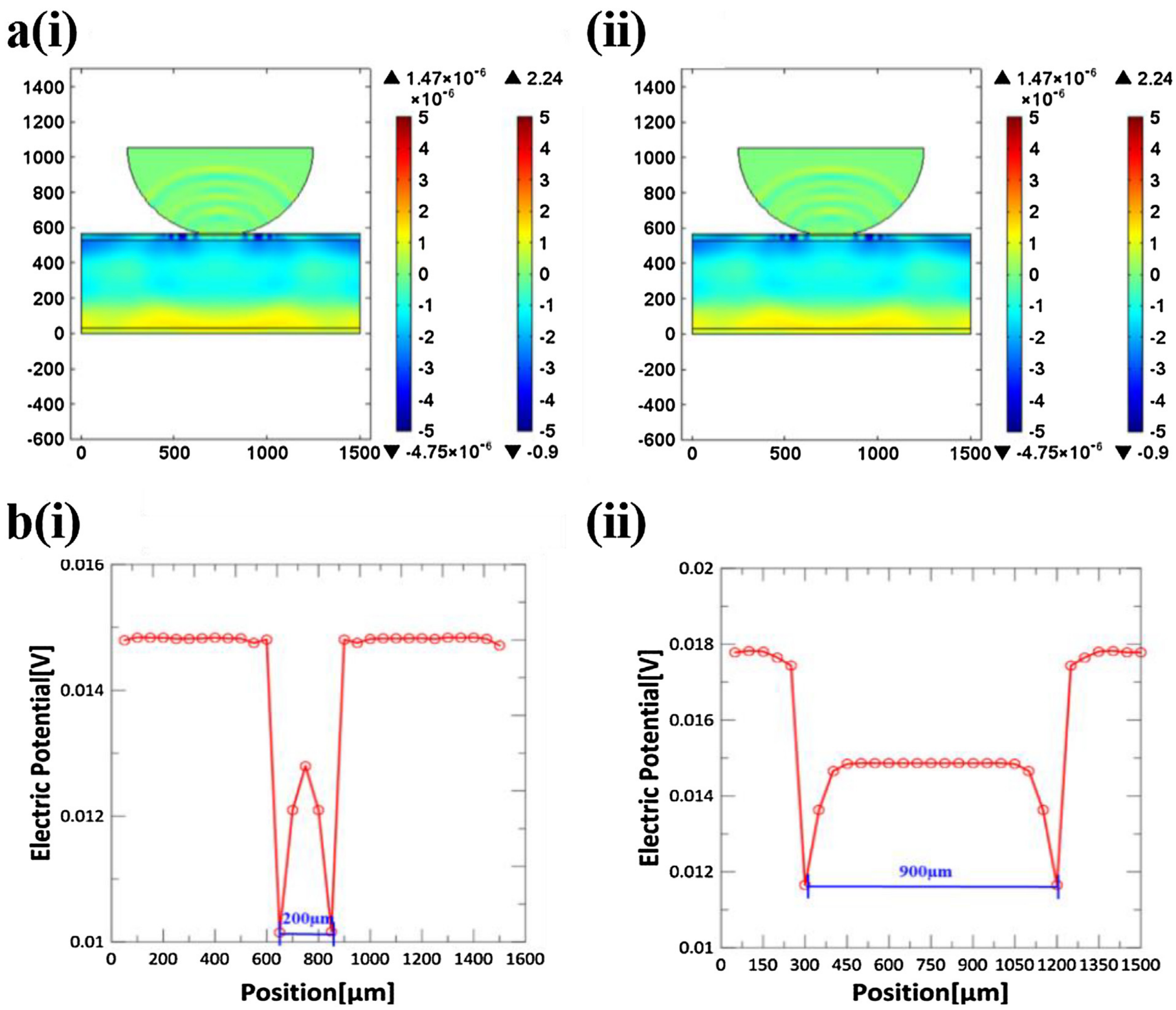

Fig. 3. (a) 2D numerical simulation results of reflected ultrasonic waves and (b) electrical potential values when the sensor is in contact with a hemispherical PDMS structure with (i) Cross sectional contact length of 200 μm and (ii) Cross sectional contact length of 900 μm.

waves contact the PDMS structure. This is because the strength of the reflected wave depends on the acoustic properties of the material in contact with the sensor surface. At the sensor/air interface, 100% of the acoustic energy is reflected back which results in a higher voltage output by the PVDF film. In general, for either no object contact or the presence of a metallic object, large echo signal are produced which are significantly higher than when contacting polymer materials whose characteristic acoustic impedance

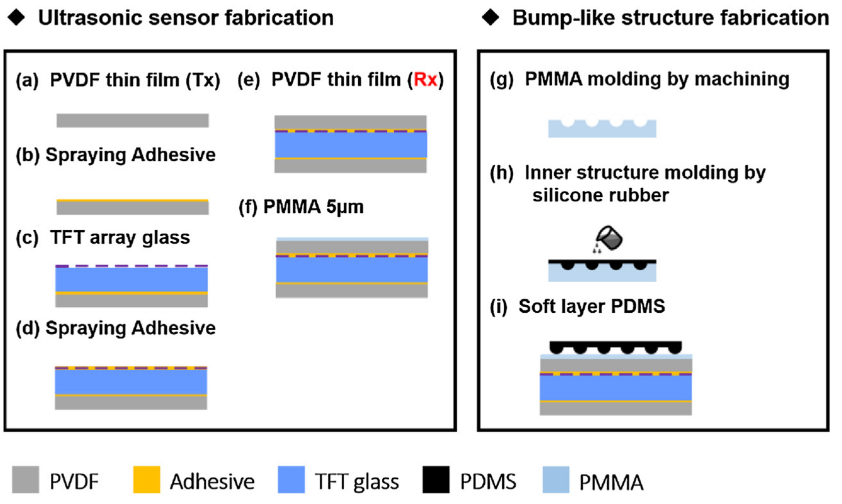

Fig. 4. Schematic of systematic fabrication protocol of ultrasonic tactile sensor.

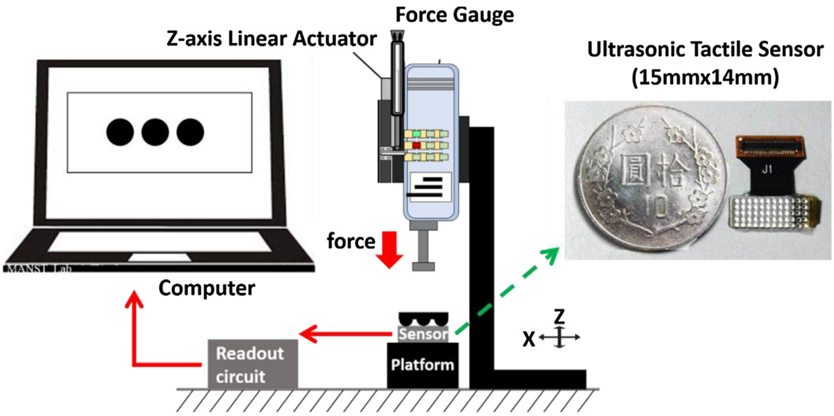

Fig. 5. The experimental setup for contact area and force measurements.

is closer to the PMMA top layer. The hemispherical PDMS contact areas of 200 μm and 900 μm can be confirmed by the observed electrical potential values with respect to position as shown in Fig. 3b. Consequently, the simulation results show the feasibility of this ultrasonic tactile sensor design for detecting the contact area of the PDMS microstructures that varies based on the applied normal force.

2.3. Sensor fabrication

The fabrication protocol of the ultrasonic tactile sensor, which consists of five layers, is schematically illustrated in Fig. 4. A commercial 28 μm-thick PVDF film (Measurement Specialties Inc., USA) is used as the ultrasonic transmitter and receiver layer. A 500 μm TFT glass layer is sandwiched between the bottom (ultrasonic transmitter) and top (ultrasonic receiver) PVDF films using a spray adhesive which is key to minimizing acoustic energy losses. The fourth layer provides encapsulation of the ultrasonic tactile sensor and is made of 5 μm thick Poly (methyl methacrylate) (PMMA). The fifth and uppermost layer is made of PDMS (Sylgard 184 Silicone Elastomer, Dow Corning Co., USA) with bump-like microstructure array and is the layer that contacts with the object. These microstructures are fabricated using an acrylic mold process with controlled structural dimensions. The obtained PMMA mold is then sprayed with a releasing agent in order to facilitate the demolding process. Next, the PDMS is poured into the mold and cured in a vacuum oven at 90 °C for one hour. The microstructures are fabricated in three arrangements consisting of 3 × 6, 4 × 9 and 6 × 15 arrays with individual semicircular spheres having a diameter of 1.2 mm, 1 mm and 0.4 mm, respectively. We have tested three different polymeric materials for fabricating the top soft layer, which include PDMS (Sylgard 160 Silicone Elastomer and Sylgard 184 Silicone Elastomer) and UV-curable polymer resin. The top layer is just placed on the sensor and not attached using an adhesive, primarily because we can test multiple polymeric layers (with different compliance and microstructure densities) on the same sensor while also achieving satisfactory results. However, for practical robotic grasping, it would be necessary to first identify which polymeric layer

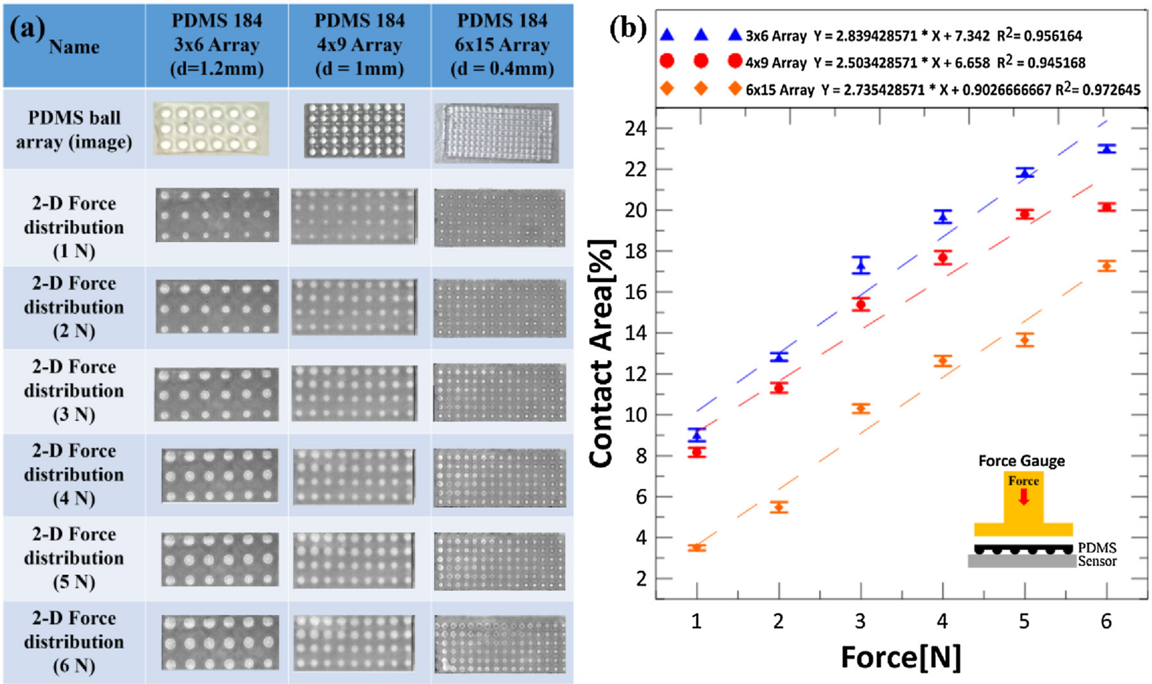

Fig. 6. (a) 2-D greyscale image observed when tactile sensor with different microstructure array arrangements is contacted under a normal static force ranging from 1 N to 6 N. (b) The linear relationship between the normal static force and observed contact area.

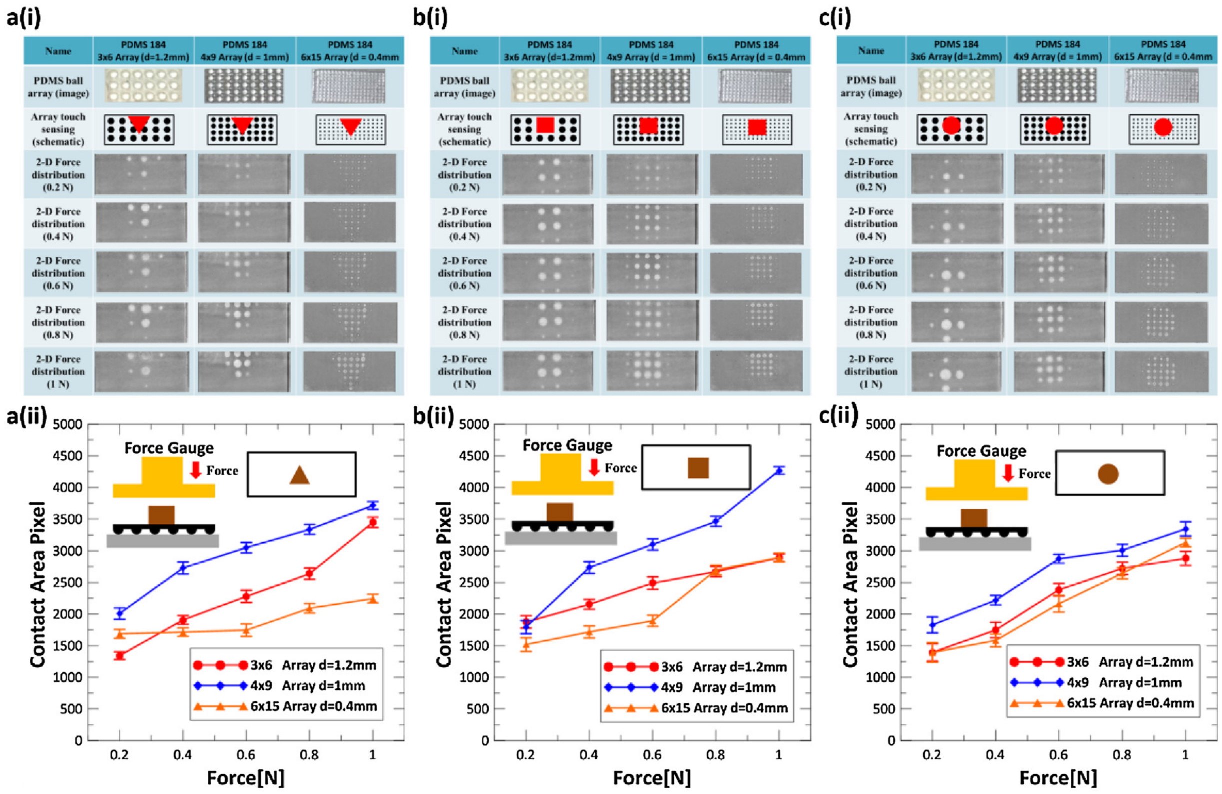

Fig. 7. (i) 2-D greyscale image and (ii) contact area observed when tactile sensor with different microstructure array arrangements is contacted under normal static force ranging from 0.2 N to 1 N with (a) Triangular shaped PMMA, (b) Square shaped PMMA and (c) Circular shaped PMMA.

would be most suitable based on the requirement and then this layer can then be attached to the sensor.

2.4. Experimental setup

The experimental setup for contact shape recognition and force distribution is shown in Fig. 5. A force gauge (Algol HF-10, Japan Instrumentation System Co., Japan) is mounted on a Z-axis linear actuator to accurately move it to contact the upper polymeric layer of the tactile sensor and apply a normal static force in the range of 1–6 N. As the sensor is in contact with the force gauge, the signal output of the TFT array passes through the readout circuit where it undergoes filtering and rectification before the data is transferred to a computer. An inbuilt software analyzes the data and converts it into a 2-dimensional greyscale image displaying the contacted area. Furthermore, to simulate object shape recognition, we have used a 1.2 mm thick PMMA sheet cut into three different shapes (circle with a diameter of 3 mm and square and triangle with side dimensions of 3 mm each). The shaped PMMA is placed in the center of the sensor surface before being contacted by the force gauge under normal applied forces ranging from 0.2 N to 1 N. Both the contact area and force distribution measurements were performed for all three microstructural arrangements (3 × 6, 4 × 9, and 6 × 15 arrays) and materials used. Based on the normal force applied and the corresponding area, the lowest recognizable stress corresponding to a force of 0.2 N is 0.002 MPa. In addition, the normal stress detection range that we have tested is 0.002 Mpa–0.25 MPa.

3. Results and discussion

3.1. Normal static force detection

The 2D greyscale image obtained when the force gauge is contacted with the tactile sensor (top layer made of PDMS 184 with different microstructural array arrangements) under an applied static force of 1–6 N is shown in Fig. 6a. As the applied force increases from 1 to 6 N, the contact area of the microstructures also increases due to larger deformation. The total contact area is calculated as a percentage of the image pixels corresponding to the microstructures as a function of the total image pixels. As expected, the percentage of contact area increases almost linearly as the contact force increases for all microstructural array arrangements as shown in Fig. 6b. While a similar trend is observed for all arrangements, the sensitivity for contact force measurement decreases in the case of high microstructural density (6 × 15 array) and this effect is more pronounced at large contact forces. This is because the larger the contact force, greater is the deformation of the microstructures, and consequently an increased cross talk effect is observed when the microstructures are located closer to each other.

3.2. Shape recognition

The 2D greyscale images observed when three different shaped PMMA sheets (triangle, square and circle) are contacted with the tactile sensor (top layer made of PDMS 184 with different microstructural array arrangements) under normal applied forces ranging from 0.2 N to 1 N is shown in Fig. 7. It can be seen that the tactile sensor can successfully identify the contact shape even at a low normal applied force of 0.2 N. This should enable the robotic fingers to map the contact area while grasping the object before a suitable force is applied for effective object manipulation. An increase in the density of the microstructures results in improved spatial resolution for contact area detection. The resolution of shape sensing depends on the diameter of the hemispherical PDMS microstructures present in the top layer. The smallest diameter (0.4 mm) and pitch (0.6 mm) that we have utilized is for the 6 × 15 array, although their size and density can be tuned depending

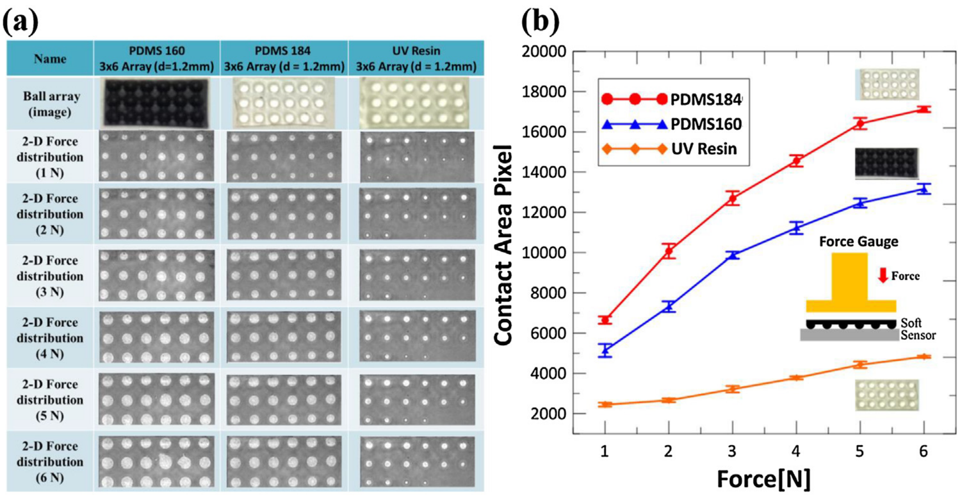

Fig. 8. (a) 2-D greyscale image observed when tactile sensor with top layer made of different polymeric materials of varying hardness is contacted under normal static forces ranging from 1N to 6N. (b) The linear relationship between the normal static force and contact area observed for all three materials.

on the application need and fabrication protocol used to fabricate the microstructures. However, as mentioned in the previous section, high-density microstructures can also result in cross talk effects especially at high applied forces. Therefore, the density of the microstructures can be tuned to suitably match the application need. It is also observed that the contact area of the microstructures in the greyscale image shows a linear dependence on the applied normal force, thus confirming the feasibility of the tactile sensor for both contact shape recognition and force detection.

3.3. *Material selection for top polymeric layer with microstructures*

We have used three different polymeric materials with varying hardness (PDMS - Sylgard 184 Silicone Elastomer, PDMS - Sylgard 160 Silicone Elastomer and UV-curable polymer resin with shore hardness values of 43, 56 and 76, respectively) to fabricate the top layer with embedded microstructures. The 2-D grey scale image obtained using the three polymeric materials with a 3 × 6 microstructure array arrangement in a force range of 1–6 N is shown in Fig. 8a. It can be seen that the contact area for the same applied force is higher for the two PDMS materials as compared to the UV-cured polymer resin. This is because they have relatively smaller shore hardness values as compared to the UV-cured polymer resin, which is significantly harder and deforms less. The non-uniformity of the contact area of different microstructures observed for the UV-cured resin layer could be related to inherent defects introduced during the micromachining process such as demolding issues and will be optimized in future works. Thus, the choice of material used to fabricate the top layer determines the force range that can be sensed. For general-purpose robots, which function in environments similar to humans, soft elastomeric polymers are more suitable as they have similar mechanical properties to human skin. However, harder materials may be more suitable where larger forces need to be sensed as in the case of certain robotic applications in industry. All three materials demonstrate a linear relationship between the applied force and the observed contact area as shown in Fig. 8 b. The sensitivity which can be described as the rate of increase of contact area with respect to applied normal force and is the slope of the curve is highest for PDMS 184. This is due to the fact that PDMS 184 has the lowest shore hardness of the three materials and hence deforms the most under the same applied force, resulting in the largest increase in contact area. The most novel feature of this design is the ability to use the same tactile sensor for a range of applications by simply tuning either the type of polymeric material used to fabricate the top layer that contacts the object or changing the density of microstructures.

4. Conclusions

Despite their importance and presence in robotics for nearly as long as vision, tactile sensors have still not realized their full potential and are used much less as compared to other sensory modalities. Lack of high performance tactile sensing strongly limits their cognitive ability and restricts their real world applicability. Their lower usage can be attributed to challenges that arise due to the complex distributed requirements of tactile sensing. Furthermore, a lack of system approach by researchers like not taking into account the wiring complexity and required processing power has limited their use. The distributed nature of tactile sensor networks often requires high computing power and an interesting approach would be to have distributed computing right from the transduction level. We have used this approach by employing a TFT array for localized signal transduction instead of distributed sensing elements that are often utilized in piezoelectric tactile sensors. The developed ultrasonic tactile sensor can not only detect the contact area with high resolution owing to the TFT array but can also detect contact force due to presence of microstructures. Increased microstructure density and reduced size results in improved resolution of shape recognition. However, this results in reduced sensitivity of contact force measurement, especially when the applied force is large. By identifying the contact area of the object and the reverse thrust force, the tactile sensor can be effectively used for actual robotic applications, both in industry and for human-robot interaction. To further extend usability and make the tactile sensor suitable for flexible applications, future works will include looking into replacing the rigid TFT layer with an organic thin film transistor (OTFT) layer. Besides their excellent flexibility and ease of large area, low cost fabrication, they also possess integrated functionality of signal transduction and amplification [27–29]. An example of similar work is the realization of a tactile sensor by P. Cosseddu et al. where they integrate a piezoelectric polymer with a low voltage OTFT on flexible plastic substrates [30]. In this way, the transducing element is directly connected to the OTFT via an extended gate. Consequently, this makes OTFTs excellent candidates for use in ultrasensitive tactile sensing and integration into electronic skins.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.sna.2018.01.022

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