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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-

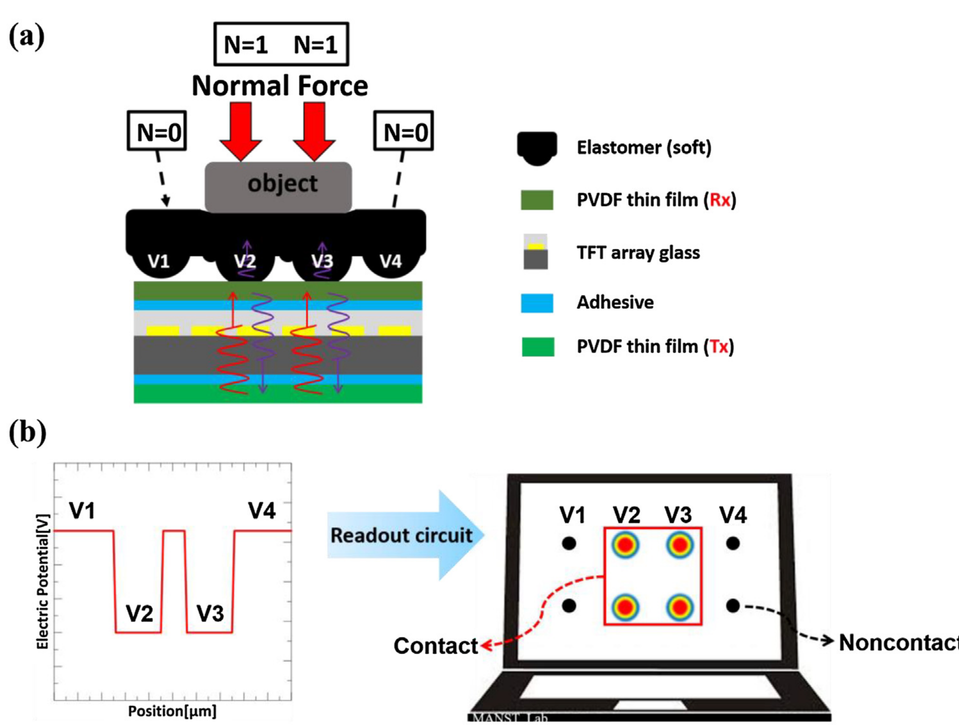

Fig. 1. (a) Schematic of the operation mechanism of tactile sensor, which is based on ultrasonic pulse-echo ranging. (b) The localized piezoelectric voltage output is detected by the TFT array and can be used to generate a 2D ultrasonic greyscale image of contact area. The image can also be analyzed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

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