Abstract

We present a multifunctional and stretchable capacitive sensor capable of accurately detecting large strains, pressure and human touch. The device is prepared as a plate capacitor with stretchable thin gold film electrodes. Using conventional patterning techniques, a 3x3 array of stretchable sensors is prepared and implemented as a large-area 9-node touch pad. The array can operate when worn around the wrist or subjected to large deformations (>10% strain), measure pressure (up to 160kPa) and register touch applied with a finger, a metallic or plastic stylus.

Keywords: capacitive sensor; touch; stretchable; metallic conductors; silicone

1. Introduction

Touch sensitive user interfaces based on capacitive sensing are commonly used in a wide range of applications including ATM machines, handheld devices, X-Ray machines, and blood glucose monitors. Touch sensitive keypads work by detecting local changes in electric field fringes when a human finger is brought into close proximity of the emitter and receiver electrodes [1]. An XxY matrix of emitters and receivers can be used to provide information on finger or object localization. Adding mechanical flexibility or even stretchability to those touch interfaces will widen further their field of applications. Touch sensitive keypads may then shape accurately the dashboard of a car or they may be worn “unnoticed” on the user body. Handling, durability and user comfort will be significantly improved.

The mechanical requirements on the stretchable interface are demanding: device materials must withstand large and repeated mechanical strains without mechanical failure, and the sensory devices must reliably operate when bent, twisted or stretched.

We have designed and fabricated a stretchable touch-sensitive sensor array using elastomers and elastic metallic electrodes [3,4]. The matrix can fit a spherical ending of a robotic arm or the wrist of a user and can accompany its repeated twisting and flexing. The matrix has 3x3 elements, can detect and localize touch, but also can record applied pressure and strain. Furthermore the multisensory array functions reliably when held stretched by 20% strain, and subsequently relaxed.

Each node of the matrix is prepared as a multifunctional capacitive sensor using silicone rubber and stretchable metallization. The stretchable PDMS membrane is sandwiched by chromium/gold thin-film electrodes to form the capacitive sensors. The evaporated metallic films are patterned directly onto the PDMS through a shadow mask to form an XxY grid of conductors. The latter can withstand mechanical cycling of tens of percent strain up to a quarter of a million cycles [4] and stretch in 2D by 14% radial strain without electrical failure.
In this paper, we first report on the design and fabrication of the stretchable touch sensitive keypad. Then we detail how the sensor matrix is characterized electrically and electro-mechanically. Finally experimental results are shown to demonstrate that the touch sensor matrix reliably operates in relaxed and stretched configurations.

2. Sensor design

Fig. 1 shows a schematic cross section of a stretchable capacitive sensor along with a top view of the 3x3 matrix. The sensors are fabricated from 50nm thick gold films evaporated onto opposing sides of a 0.5mm thick PDMS dielectric substrate. The electrodes of the plate capacitors have a 2x2mm² surface area, and are interconnected with 1mm wide gold conductors. The sensor substrate is then encapsulated between two 0.5mm thick PDMS membranes. Each PDMS membrane is preliminary treated with a short oxygen plasma to ensure irreversible seal [5]. The touch sensitive keypad is 65mm x 65mm.

The capacitance is monitored for each sensor. Strain and pressure are measured through the change in dimensions of the overlapping electrodes. When mechanical deformation is applied to the sensor, either by stretching in the x/y direction(s) or by compression in the z direction (due to applied pressure), the plate capacitance increases as the electrode surface area increases (stretching) and the dielectric thickness decreases (applied pressure).

The change in capacitance of the device due to strain and pressure are mechanically interlinked, and can be modeled from equation 1.

\[
C = \varepsilon_{PDMS} \varepsilon_0 W(1 - \nu e_L) L(1 + e_L) \left[ T(1 - \sigma / E)(1 - e_L) \right]
\]

Where:  
- \( C \) = Overlapping plate capacitance (F).  
- \( \varepsilon_{PDMS} \) = Permittivity of PDMS \( \approx 2.7 \).  
- \( \varepsilon_0 \) = Permittivity of free space = \( 8.85 \times 10^{-12} \) F/m.  
- \( W \) = Overlapping plate capacitors initial width (m).  
- \( L \) = Overlapping plate capacitors initial length (m).  
- \( T \) = Distance between overlapping electrodes (m).  
- \( e_L \) = Strain applied across the length of the capacitor.  
- \( \nu \) = Possion’s ratio (for PDMS \( \approx 0.5 \)).  
- \( E \) = Young’s Modulus of PDMS \( \approx 1 \) MPa.  
- \( \sigma \) = Pressure applied across the overlapping plates (Pa).

The touch sensitivity is provided by altering the electric field fringing capacitance between the interconnects and the overlapping electrodes, which added to the plate capacitance make up the total capacitance of the sensor. In our configuration each sensor node consists of an emitter electrode and a receiver electrode. A reference capacitor is mounted in parallel to our sensor C, and an oscillating voltage is applied to the common emitter electrode. The capacitance of the sensor is then determined by integrating and comparing the charge induced on the common receiver electrodes of sensor and reference capacitor. When a finger is placed in the electric field fringes of the sensor, the body acts as a charge reservoir and the charge induced on the receiver is reduced. This means that the effective sensor capacitance is also reduced. Conversely if an ungrounded metallic object is placed in the electric field fringe more charges are induced on the receiver electrode, effectively increasing the sensor capacitance.
3. Sensor characterization

First, a single sensor node was characterised to determine its sensitivity to strain, pressure (touch) and proximity. Each stimulus is first applied separately. Then combined stimuli such as strain and pressure or touch and strain, are applied to the sensor. The effect of the material “touching” the sensor surface was assessed by applying the lightest touch to the surface of the sensor node with four different interfaces: a Teflon® post, a Teflon® post with a grounded and an ungrounded metallic plate adhered to its surface, and the user finger. The sensor was strained in 5% strain increments in a bespoke uni-axial stretcher up to 20% strain. Pressure was applied normal to the node using either a 6.3mm dia. Teflon post or the user finger. The pressure was increased by applying weights on top of the post in increments of 100g up to 500g. Applying a weight of 700g at 20% strain resulted in device failure.

Then tests on two sensor nodes of the 3 x 3 array were carried out using the same electronic interface to demonstrate the ability to localize the user finger position on the soft keypad. The matrix response was also evaluated when it was held flat and wrapped around the user’s wrist. The capacitance of the sensor node was measured with an Analog Devices (EVAL-AD7152) evaluation board in differential mode to remove the capacitance of the measuring wires and compensate for the interconnect resistance. The recording electronics has a resolution of 0.25fF, with an excitation voltage of ±1.65 V at a frequency of 32kHz.

4. Results

Figure 2 illustrates the response of an individual node to touch. The initial sensor capacitance $C_0$ (when the sensor is not touched) is about 400fF. When touched, the resulting sensor capacitance depends on the permittivity and electrical bias of the object in contact with the sensor surface. Typically, touching the sensor with a grounded conducting medium drops the capacitance by tens of fF. An insulating object barely changes the sensor capacitance; a metallic but floating object increases the capacitance by 100fF. This response is characteristic of electric field fringe capacitances between the sensor electrode and the body close to it [2]. Our sensor acts as a proximity detector, and can be used to identify the contacting material. Thus the sensor can differentiate and function with multiple input objects such as a metallic or plastic stylus, or a finger. This added function is indicative of this type of sensor [2].

![Sensor response to uni-axial stretch cycle. The sample is not touched (top curves) and touched with a simulated "finger" (bottom curves).](image1.png)

![Sensor response to uni-axial stretch cycle. The sample is not touched (top curves) and touched with a simulated "finger" (bottom curves).](image2.png)

![Sensor response to pressure and uni-axial stretch (strain $\varepsilon$ is increased in 5% steps). The pressure is applied to the sensor surface with a Teflon post with an ungrounded metallic plate.](image3.png)

Figure 3 illustrates the sensor’s responses to stretch and to combined touch and strain. The sensor’s capacitance increases and decreases linearly and reversibly during the strain cycle as the surface area of the plate electrodes are stretched and compressed. The sensor response to strain was fully reproducible during 10 stretch cycles. Touching the sensor surface with a finger reduces its initial capacitance by 100fF. We found that touching the sensor does not affect its response to stretch: its strain sensitivity remains at approximately 3fF/%, and the device has a gauge factor of 0.75. Because the drop in capacitance due to finger touch is larger ($\Delta C_{\text{touch}} \approx 100$fF) than the capacitance increase with strain ($\Delta C_{\text{strain-20%}} \approx +60$fF, both modes can be clearly distinguished. The sensor’s response to applied pressure, and combined pressure and strain is shown figure 4. The sensor capacitance increases with the applied pressure as the thickness of the plate capacitance decreases. The pressure sensitivity of the sensor slightly increases from 14fF/100kPa to 17fF/100kPa at 0% and 20% strain respectively when the sensor is held
stretched and pressed at the same time. This is in agreement with our model from eqn. 1 which predicts sensitivities of 14fF/100kPa and 16fF/100kPa at 0% and 20% strain respectively, over a pressure range of 0 – 160kPa. These results demonstrate that the sensor can reliably operate in all three combined modes.

Figure 5 shows a picture of the 3x3 touch sensitive keypad worn around the user's wrist. Each sensor node has an initial capacitance of approximately 490fF. The plot on the right illustrates the touch pad response, when the user first touches node 3,0, then slides his finger across the pad to reach node 0,0. The corresponding node capacitance decreases (touched) and increases (untouched). Cross-talk between the two nodes allows monitoring of the finger location on the keypad.

These initial data suggest that capacitive sensing combined with stretchable metallization is a promising route to skin-like sensory surfaces.

Fig. 5: (left) Picture of a 3x3 touch sensitive matrix mounted on the wrist. (right) Output from two touch sensitive nodes, where node 0,3 is initially touched with a finger followed by the finger being slid across to node 0,0 (each 100 data points corresponds to approximately 3s).

5. Conclusions and future work

We have demonstrated that stretchable multifunctional capacitive sensors can be fabricated from gold thin films evaporated onto silicone rubber. The sensors can also be used in conjunction with commercial transducer electronics to produce sensory e-skins that can be bent or stretched around complex shapes and maintain their functionality.

Future work will concentrate on optimizing and fully characterizing the sensor array. In particular we will evaluate the effect of sensor node geometry and density on the matrix response to all three detection modes, and analyze the dynamic response of the touch sensor array when it is worn by a user moving his wrist and hand. To achieve this, commercially available electronics with the ability to scan all 9 nodes (such as the Analogue Devices AD7147, which has 13 capacitive sensor inputs and fF resolution) will be implemented. The proximity sensitivity of the nodes will be refined to reduce the cross sensitivity of electric field fringes by reducing the interconnect widths.

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