Mutual capacitance of liquid conductors in deformable tactile sensing arrays

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Advances in highly deformable electronics are needed in order to enable emerging categories of soft computing devices ranging from wearable electronics, to medical devices, and soft robotic components. The combination of highly elastic substrates with intrinsically stretchable conductors holds the promise of enabling electronic sensors that can conform to curved objects, reconfigurable displays, or soft biological tissues, including the skin. Here, we contribute sensing principles for tactile (mechanical image) sensors based on very low modulus polymer substrates with embedded liquid metal microfluidic arrays. The sensors are fabricated using a single-step casting method that utilizes fine nylon filaments to produce arrays of cylindrical channels on two layers. The liquid metal (gallium indium alloy) conductors that fill these channels readily adopt the shape of the embedding membrane, yielding levels of deformability greater than 400%, due to the use of soft polymer substrates. We modeled the sensor performance using electrostatic theory and continuum mechanics, yielding excellent agreement with experiments. Using a matrix-addressed capacitance measurement technique, we are able to resolve strain distributions with millimeter resolution over areas of several square centimeters.
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The development of stretchable, skin-like tactile sensors has been a longstanding goal of engineering, motivated, in part, by the remarkable functional characteristics of biological skin. While advances in the area of soft electronics have produced a number of interesting sensing devices based on resistive[1–5] and capacitive principles,[6–14] none of those described in the literature is able to perform tactile array sensing over a distributed area via a device that is as soft and conformable as we describe here.

Advances in material and fabrication technologies have yielded flexible sensors with low bending stiffness, but frequently low stretchability, due to the high elastic modulus of the substrate or conductive elements, preventing them from stretching to conform to arbitrary curved or deformable surfaces (for example, to human skin). Stretchable mechanical sensors have been previously developed based on piezoresistive composites, resistive elastomer strain gauges, and liquid metal conductors embedded in elastic polydimethylsiloxane (PDMS) membranes, among other approaches.[9,10] However, the substrates employed have limited the level of stretchability that can be achieved in tactile sensors, resulting in devices that are far stiffer than human skin. Extrinsic stretchability has also been achieved via the geometric patterning of metal film or filament,[11–14] but the maximum strain that can be accommodated in such devices is limited by geometric factors.

Here, we present sensing principles for highly stretchable capacitive tactile sensing arrays (Fig. 1) integrated into thin, compliant polymer membranes. An alternative technique that has been described in prior literature involves resistive sensing arrays in parallel microchannels.[1,2] These devices function well as force sensors, but, due to limitations of the resistive sensing method that is used, they cannot accurately and uniquely capture surface strain, since grossly different strain patterns can elicit identical measurements. This limits them to reconstructing the integrated strain across their entire surface and prevents them from acting as tactile sensing arrays.

The approach we present, based on electronic sensing in a capacitive matrix, avoids this shortcoming, enabling our devices to resolve strain or pressure distributions with high spatial resolution (as low as 1 mm in our prototypes, see Figure 3). The thin profile and high stretchability exceed what is achieved in previous devices, including those based on PDMS substrates. This work is intended to enable wearable tactile sensors that can electronically capture what a physician feels when palpating tissue, and that can be worn unobtrusively, like a medical glove, without impairing their wearer's sense of touch.

Our devices consist of thin, stretchable capacitive tactile image sensors (Fig. 1) that utilize liquid metal electrodes embedded in a low modulus polymer membrane. They are fabricated using a soft lithography method that utilizes a custom

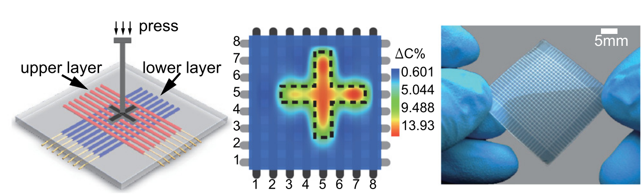

FIG. 1. We present sensing principles for soft tactile sensors for capturing spatially distributed pressure distributions.

mold integrating two arrays of fine nylon filaments to cast low modulus platinum-catalyzed silicone polymer (EcoFlex 00-30, Smooth-On, Inc). After casting and curing, this yields a soft membrane with two groups of microchannels embedded in orthogonal orientation on two separate planes (Figure 2). To functionalize the device, the channels are pinch clamped near the edge (distance: 2 mm) and sealed via injection of liquid silicone polymer at each end. The channels are filled with liquid metal alloy, eutectic gallium indium[15,16] (EGaIn, 75% Ga, 25% In by mass, melting point 15.7 °C) via a syringe pump. Fine wires are inserted into the channels, and the entry points are sealed using silicone adhesive (Sil-Poxy, Smooth-On, Inc). This yields arrays of orthogonally arranged conductive electrodes embedded in two distinct layers within the thin membrane. The metal remains liquid at room temperature, yielding a structure with high stretchability (over 460%, see below). The change in electrical capacitance between every horizontal and vertical channel pair reflects the local strain in region of intersection of the two channels. Once the devices are calibrated, this makes it possible to reconstruct the local strain distribution in the array.

We have fabricated prototypes with channel diameters from 200 to 300 μm and channel spacing as low as 200 μm, yielding spatial resolution of 1 mm^{-1} or higher in arrays of up to 23×23 channels (Figure 3). The two microchannel planes divide the device into three layers (Figure 2(b)). After the microchannel array is filled with eGaIn and sealed, it retains a high degree of stretchability, gently conforming to a human finger or a solid sphere with a diameter of 1 cm (Figs. 2(e)–2(f)). We conducted failure tests by stretching the sample as it was clamped along opposing edges. The device could be reversibly stretched up to a maximum of 460%, with bulk fracture occurring at a force of 13.8 N (cross-sectional stress: 0.57 MPa). Under normal indentation, the device operates normally up to 1 MPa and, beyond this level, continues to recoverably and reversibly compress up to pressures beyond our measurement limits (>10 MPa).

We modeled the coupled electronic and mechanical behavior of the sensor and validated both via indentation testing (Figure 4). The measurements demonstrate excellent agreement with a model based on electrostatic theory and continuum mechanics. As noted, each eGaIn-filled microchannel functions as an electrode with cylindrical geometry and pairs together with each orthogonal microchannel in the opposing layer to form a capacitor. The effective capacitance C_{eff} between an electrode pair can be expressed analytically, yielding an expression of the form

$$C_{\mathrm{eff}} = C_v \int_{-L/2}^{L/2} C_m(x)dx, \tag{1}$$

involving the capacitance C_v of the lower channel relative to ground, and the capacitance per unit length $C_m(x)$ of the upper channel. For an orthogonal electrode pair with cylindrical geometry, one obtains

$$C_{\mathrm{eff}} = \frac{2\pi\varepsilon}{\log\left[h_2/r + \sqrt{(h_2/r)^2 - 1}\right]} \times \int_0^{L/2} dx \frac{\log\left[\frac{x^2 + (h_2+h_1)^2}{x^2 + (h_2-h_1)^2}\right]}{\log\left[\frac{4h_1^2}{r^2}\right] - \log\left[\frac{x^2 + (h_2+h_1)^2}{x^2 + (h_2-h_1)^2}\right]}, \tag{2}$$

where L is the length of the conductive channel, h_1 and h_2 are the respective distances between the channels and the ground surface, r is the channel radius, and ε is the material permittivity. Under axial (normal) loading, the strain-induced change in capacitance of channel pairs is dominated by the reduction in inter-channel distance. If ϵ is the engineering strain in the vertical direction, the height values h undergo a compression given by $h_i' = h_i(1-\epsilon)$. Via numerical integration, Equation (2) yields a predictive model for the change in C_{eff} with strain ϵ. In the large strain limit, the integral expression yields a simpler quadratic dependence of capacitance with strain, $C_{\mathrm{eff}} = C_0 + \alpha\epsilon^2$, where α is a geometry-dependent constant.

In order to experimentally characterize the sensor performance, we subjected the devices to vertical indentation testing using a high resolution force test stand (ES-20 and

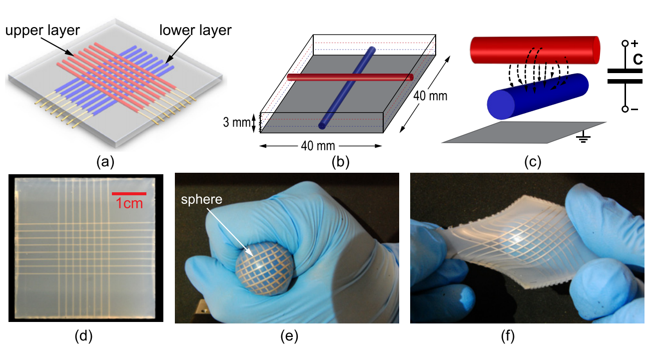

FIG. 2. A sample of the soft, stretchable tactile sensing array, as fabricated via the direct filament casting. (a) and (b) Illustration of the sensing array. (c) Single capacitive element of the sensing array. (d) An 8×8 microchannel array embedded in a silicone rubber membrane with dimensions 4 cm $\times$ 4 cm $\times$ 3 mm. Channels have circular cross section with diameter 300 μm. (e) and (f) The same sensing array conforming, respectively, to a sphere of 1 cm diameter and to a human finger.

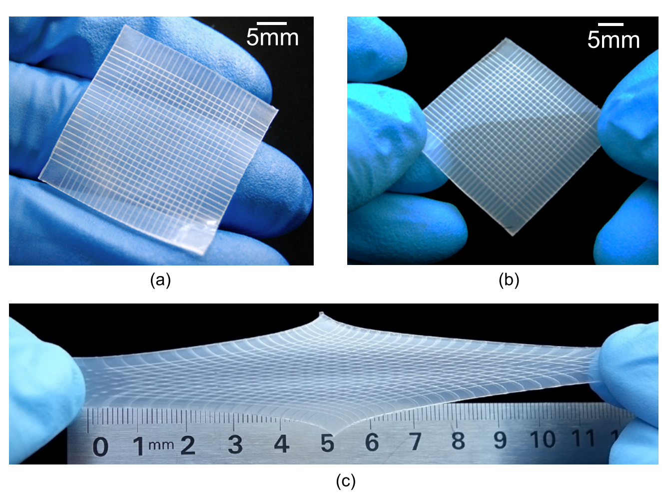

FIG. 3. Prototype sensors using the principles described here. (a) and (b) A 23×23 microchannel array with filament diameters of 200 μm, and thickness of 1 mm. (c) The thin sensing array yields high stretchability, well over 400%.

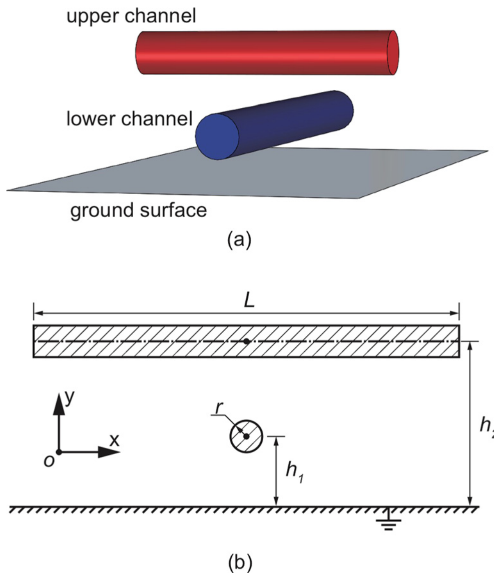

FIG. 4. Modeling the mutual capacitance between two orthogonal conductive channels. (a) Three dimensional view of the channels. (b) Section view, illustrating geometric parameters.

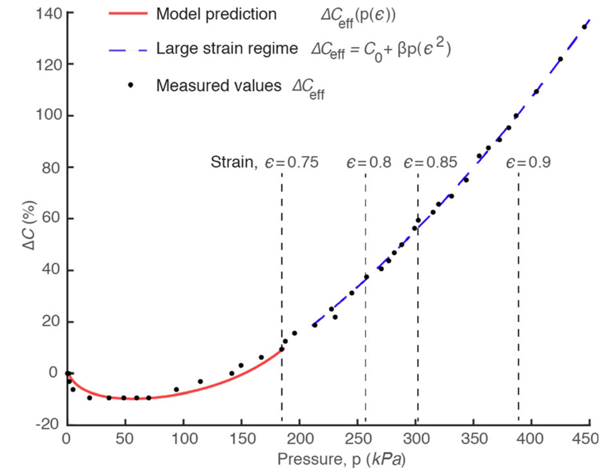

FIG. 5. Comparison of the mutual capacitance between channels and laboratory measurements under force-controlled loading. Capacitance was recorded during indentation testing with a circular contact plate (area: $12\,\mathrm{mm}^2$). The experimental data exhibit excellent qualitative and quantitative agreement with theoretical predictions of the analytical expression (2) up to values of the strain $\epsilon \approx 0.7$ and with the predicted quadratic trend in the large strain limit $\epsilon \to 1$.

M5-20, Mark-10, Inc.) and a circular contact plate (area: $12\,\mathrm{mm}^2$), and concurrently measured capacitance between a single microchannel pair, using an LCR meter, placed in parallel circuit mode, with a probe frequency of 100 kHz. The resulting measurements (Fig. 5) are consistent with model predictions in both small and large strain regimes, including non-monotonic behavior at small strains.

In further experiments, we evaluated the abilities of these devices to capture spatially distributed strain signals that were applied using indentation stamps with different geometries (including a cross profile, shown in Fig. 1), with capacitance recorded under strain-controlled loading. The results demonstrate that the devices are able to transduce spatially varying pressure distributions with resolutions comparable to the spacing between microchannels, which was as low as 1 mm in our samples, and limited only by the resolution of the fixture frame that was used for casting.

In summary, we constructed highly deformable tactile sensors using thin addition-cured polymer membranes with capacitive electrodes formed from multiple layers of microfluidic channel arrays filled with liquid metal alloy. The resulting devices possess high levels of deformability and conformability. Our results demonstrate that the devices are able to perform tactile sensing with high spatial resolution, and that the performance can be predicted from electrostatic theory and continuum mechanics. Compliant tactile sensing devices such as these are relevant for emerging application demands involving wearability and distributed tactile sensing. Further work is needed in order to address the non-monotonic behavior observed at low strains and to adapt the performance of these devices to application specific requirements.

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