Development Towards a PVDF-Based Tactile Finger with Distributed Vibration Sensing

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I. Introduction

In human skin, *dynamic* tactile sensing, or the detection of fast-changing tactile stimuli, plays an important role in detecting the making/breaking of contact, sensing slip, sensing surface texture, and receiving tactile feedback via a held object (e.g., tool use). Transducers of this type have a high frequency response and sensitivity, and often respond only to *changes* in signals, not static forces [1], [2].

In robotics, there are many proven ways to implement dynamic sensing, including accelerometers, microphones, hydrophones, piezoelectrics, and piezoresistors [2]–[7]. Previous work suggests the importance of spatially distributed dynamic sensing across a finger [8]. However, building tactile fingers with distributed vibration sensing across a complex finger-shaped surface remains a challenge.

In this work, we present the preliminary design and fabrication of a tactile finger with distributed vibration sensing using the piezoelectric polyvinylidene fluoride (PVDF). We present two versions of this early-stage prototype: one containing custom-fabricated taxelized PVDF films, and one containing off-the-shelf (OTS) PVDF strips (Fig. 1). The former is an avenue for achieving high-resolution taxelization and compact integration, while the latter is a more accessible solution (i.e., does not require cleanroom fabrication tools). We also discuss our ongoing work towards improving both of these prototypes.

II. Sensor Design

We designed the sensor geometry with robotic tasks in mind. The finger is curved and sensorized everywhere except the back – all areas where contacts are likely. The flat patches on the front encourage stable contacts, and a thinner tip enables picking up small objects off a flat surface with a pinch grasp. The overall size is similar to a human thumb.

The finger contains a rigid, 3D printed resin ”bone,” encased by the elastomer polydimethylsiloxane (PDMS). As with other tactile sensors [7], [9]–[12], the elastomer creates a compliant surface that distributes applied strain. The sensor contains a stiffer outer layer of PDMS to provide a durable coating. The custom version contains 16 taxels distributed across a single film, while the OTS version contains 6 individual strips embedded across the finger surface.

§equal contribution

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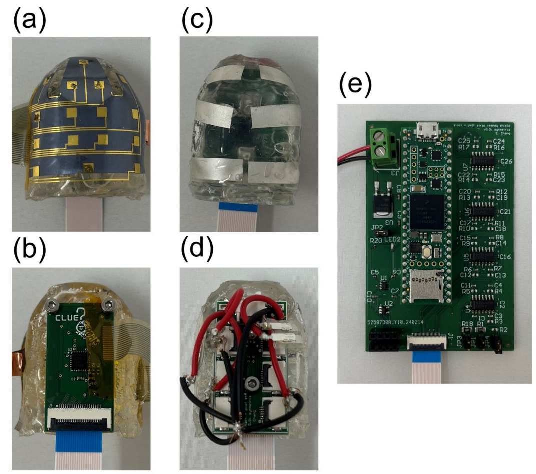

Fig. 1. Two versions of early-stage prototypes of PVDF-based tactile fingers and associated electronics: one with a custom-made, taxelized PVDF film (a, b) and one with off-the-shelf PVDF strips (c, d). A second, off-sensor PCB (e) is shared between the two versions and contains amplifier circuitry and a Teensy 4.1 microcontroller. The fingers measure 29×36×18mm (width×height×depth), approximately the size and shape of a human thumb.

The back of the finger holds a printed circuit board (PCB) which connects to the PVDF via a heat seal connector (custom version) or wires (OTS version). The signals are wired to off-sensor current amplifiers ($R_f = 1\text{M}\Omega$, $C_f = 22\text{pF}$). We use the Teensy 4.1 microcontroller analog to digital converters (ADCs) to sample the signals at 1000 Hz. The Teensy communicates with a PC using micro-ROS [13].

III. Sensor Fabrication

A. Custom PVDF Sample Fabrication (Fig. 2)

Our custom PVDF sensor consists of an array of electrodes with corresponding traces and a back plane to complete each capacitor. The array contains 16 electrodes and traces that run to the edge of the sensor for connection to external electronics. The metal stack on each side is a 20 nm adhesion layer of chrome and 150 nm of gold, which is evaporated via electron beam onto the 4.5cm×4.5cm pieces of 100-micron thick PVDF sourced from PolyK. The array of electrodes and traces are photolithographically patterned using a photomask to pattern photoresist and wet etching to transfer the pattern to the metal stack. The back plane is patterned using shadow mask deposition. Once fully patterned, excess PVDF is cut off with a precision knife to create the final geometry. The sensor is then connected to heat seal connectors via hot bar

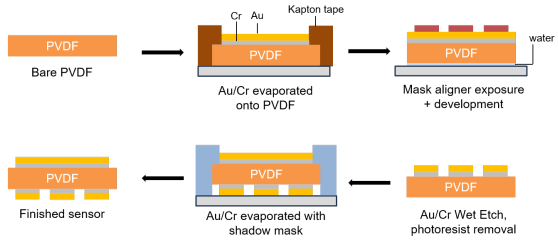

Fig. 2. The process flow for fabrication of custom, taxelized PVDF films.

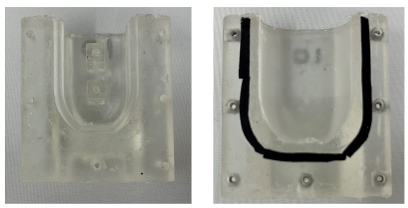

Fig. 3. Back (left) and front (right) resin molds used for finger fabrication. For the off-the-shelf version, we stick the sensors onto the front half of the mold prior to pouring the PDMS.

bonding to the sensor traces for future connection to off-sensor PCBs.

B. *Tactile Finger Fabrication*

Our finger fabrication process involves first casting a layer of PDMS onto a rigid skeleton using molds, followed by applying a stiffer outer layer of PDMS using a dipping process. This two-step process allows us to embed a PVDF sensor between the two layers.

We 3D print a negative mold and inner skeleton using Formlabs photopolymer resin (Fig. 3) and cure the parts under UV light at 60°C for 1 hour. We do an additional heat treatment of the molds at 120°C for 2 hours to prevent leftover photo-initiators in the resin from reacting with PDMS curing agent [14]. We spray the molds with a release agent (Mann Ease Release 200) to reduce adhesion.

To apply the OTS PVDF (sourced from PolyK), we apply a thin layer of PDMS to the mold and partially cure it with a heatgun until it is tacky. Then, we stick the strips to the mold in the desired configuration. We pour mixed and degassed PDMS (30:1 base to curing agent weight ratio) into the prepared mold and cure in the oven at 75°C for 8 hours. After demolding, we remove excess PDMS from the back of the finger with a precision knife. When using custom PVDF, we adhere the sensor to the finger with cyanoacrylate after casting the finger.

Finally, we dip the finger in stiffer PDMS (10:1 ratio) to apply a thin outer coating on top of the sensor, and cure at 75°C for 1 hour. We complete this procedure 3 times to form a ∼1mm coating.

IV. Ongoing Work

In the current prototypes, the working transducers are sensitive to light touches (Fig. 4). However, just 10 of 16 taxels (custom version) and 5 of 6 strips (OTS version) are

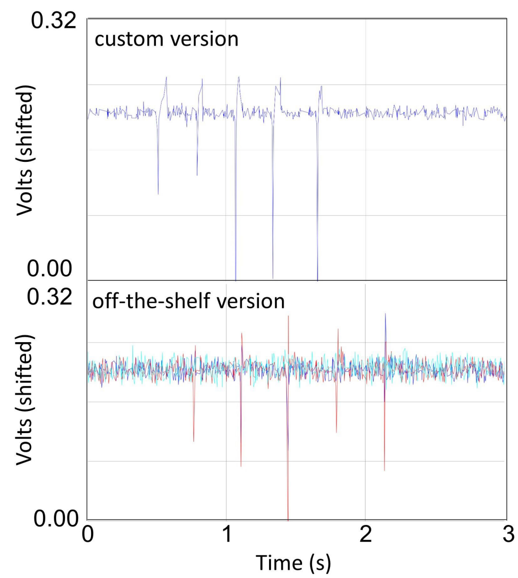

Fig. 4. Signal samples from the custom (top) and off-the-shelf (bottom) versions of the sensor in response to light taps, visualized at 200Hz. The OTS plot shows multiple transducers being stimulated from a single tap. Although the current prototypes are sensitive to light taps, we are working to further improve the sensitivity.

functional. This is due to brittle traces on the metallized film and one of the strips breaking during the demolding process. We are actively working to improve these and other issues.

Fabrication process. In the custom samples, we're investigating using titanium in the adhesion layer to improve trace ductility and robustness. We also plan to develop a housing around the electronics which will allow us to establish strong, testable connections prior to casting and will protect these connections during the fabrication process. In the current molding process, placing the OTS strips in controlled locations is a challenge, as the strips tend to move when assembling the mold. We are investigating using a spray-on adhesive to adhere the sensors to the mold, as well as an assistive "stencil" to aid in placing the sensors in precise, repeatable locations.

Signal quality. We are also working to improve the sensitivity and signal to noise ratio of the sensor. One possible step in this direction is to amplify and/or digitize the signals on the sensor PCB to avoid routing unamplified, analog signals over long cables. However, there is a tradeoff between sensor size and the ability to include electronics on-sensor, and we would ultimately like to further miniaturize the sensor.

Multimodality. We ultimately plan to incorporate force sensing into this finger. We are currently working to integrate capacitive sensors beneath the PVDF array. We aim for such a finger to act as a platform to study multimodal tactile sensing. We want to investigate how combining distributed vibration sensing with force sensing can aid manipulation capabilities. We also want to study learning multimodal tactile representations that combine vibration and force sensing, in addition to other modalities.

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