Towards Development of a Signal-Dense Multimodal Tactile Finger

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I. Introduction

The human "sense of touch" synergizes information about pressure, vibration, texture, curvature, and temperature, all of which are integral to our interactions. Combining these capabilities into a signal-dense robotic tactile finger that can cover the multicurved surfaces of a hand remains an open problem. Almost all state of the art robotic tactile sensors are unimodal, using just one sensing method (e.g., camera, capacitance, resistance, etc).

In this work, we present a prototype of a multimodal tactile sensor that combines capacitive force, vibration, temperature, and proximity sensors into one composite sensor. We have intentionally chosen sensors that detect both static stimuli, like sustained pressure, and dynamic stimuli, like touch onset and vibration due to slip. We hypothesize that exploiting both redundant and complementary sensing capabilities will allow us to achieve high tactile resolution.

II. Sensor Structure

Our prototype (Fig. 1) contains 1-2 instances of each modality and serves as a testbed before integrating more sensor instances together. It features a printed circuit board (PCB) containing the sensors and other electronic hardware, a Teensy 3.6 microcontroller, and a Cypress PSoC 4000 microcontroller. The Teensy communicates over serial with a PC using micro-ROS.

The PCB sits within a 3D printed, acrylonitrile butadiene styrene (ABS) mold. The board's power and microcontroller components are separated from its sensorized section with a gasket and divider. An approximately 7mm thick layer of polydimethylsiloxane (PDMS) is cast onto the sensorized portion of the PCB. The PDMS provides a compliant, deformation prone, uniform sensing surface with tunable durometer and thickness that distributes applied strain across the sensing surface, much like PDMS and similar silicone elastomers do in other tactile sensors [1]–[6].

III. Modalities

1) Projected Mutual Capacitance: We implemented proximity sensing using projected mutual capacitance. Project mutual capacitance relies on the fact that the capacitance formed between two terminals depends upon the dielectric constant of the medium between them. When near an object of higher dielectric constant than air, the field lines between the terminals are disturbed and the measured capacitance increases, therefore enabling proximity measurements. We use the Cypress PSoC 4000 microcontroller for these measurements. In this test prototype, we take capacitance measurements between exposed pads on the PCB; however, we will use a grid of exposed terminals near the surface of the sensor in future work.

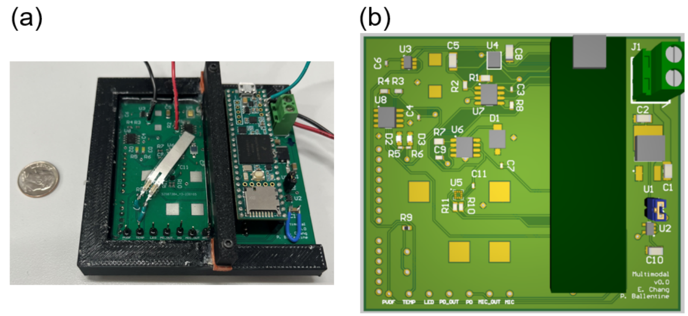

Fig. 1. Our prototype ((a)) and CAD model ((b)) of a multimodal sensor with 1-2 instances of each modality (with a US dime for size reference), in which the sensorized left section has been cast under a PDMS gel. We used this prototype to test and validate the signal from each modality. The right section contains the Teensy and power components. The entire sensor can sit as a shield on top of a Cypress PSoC 4000 microcontroller (not shown). The Singletact is not shown but was tested in a similar prototype.

2) Capacitive Force Sensing: For our capacitive force modality, we are using Singletact (singletact.com): a single axis, capacitive force sensor (tested in a different prototype, not shown in Fig. 1). When multiple instances are distributed across a sensor, they can be used for force and localization feedback. In general, capacitive sensing has the advantage of strong signal to noise ratio and high sensitivity at low forces, which is the justification for our decision to use capacitive sensing over piezoresistive or other force sensing methods.

3) Temperature: We want to measure the rate of heat transfer to other objects using onboard temperature sensors. Measuring rate of heat transfer can give us information about object material properties. For this, we are using temperature to frequency sensors (MAX6577ZUT+T), which produce a square wave with a frequency proportional to the measured temperature. We ultimately plan to incorporate a heater (i.e., a resistor) onboard the sensor to induce more heat transfer between the sensor and the object, as done in other work [7].

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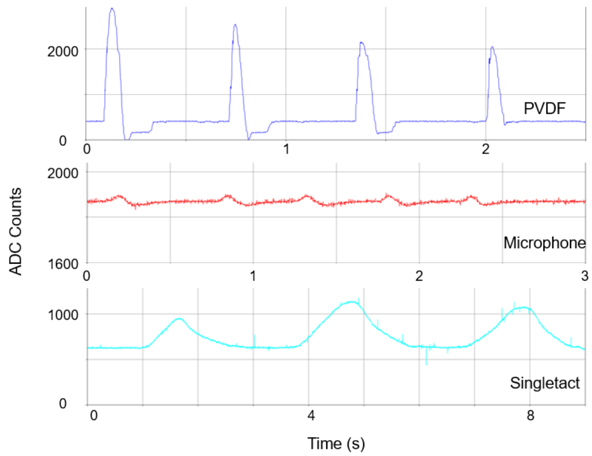

Fig. 2. Sample sensor signals from a PVDF, microphone, and Singletact sensor in response to light touches (PVDF, microphone) or gradual, approximately 3N touches (Singletact) with an indenter. All signals are sampled at 1000 Hz with 12-bit resolution using the Teensy's analog-to-digital converter (ADC). The ADC readings can range from 0 counts (0.0 V) to 4096 counts (3.3 V). Note that the time axes are not shared between the three plots.

4) Piezoelectrics: As one of our vibration sensors, we are using polyvinylidene fluoride (PVDF), a common piezoelectric thermoplastic [8]. Piezoelectrics are materials that produce energy in response to mechanical stress. Importantly, PVDF responds to *changes* in stress (i.e., dynamic stimuli), not constant pressures (i.e., static stimuli). We primarily want to use PVDF to detect vibrations and localization. This modality will be useful for tasks like slip detection, texture detection (via rubbing), and material classification. In this prototype, we use off-the-shelf PVDF sensors from PolyK (https://piezopvdf.com/polyk/), however we plan to fabricate custom PVDF sensors in the future.

5) Microphones and Accelerometers: As additional vibration sensors, microphones and accelerometers were also placed on the PCB under the PDMS. We selected the Knowles SPU0410HR5H-PB analog MEMS microphone due to its top port and small package. We selected the Memsic MC3479 accelerometer due to its small package and ease of use. We communicate with the accelerometer over I2C.

IV. Signal Samples

From tests of our initial prototype, we are encouraged by the signals we observe (Fig. 2). The PVDF and microphones are extremely sensitive to light touches, and these signals propagate well laterally (i.e., the sensor reacts to a contact event at a point a distance away from the sensor), improving the amount to which we obtain overlapping signals from one contact event. Of course, the degree to which this occurs can be tuned with the PDMS thickness and hardness. As expected, the PVDF also becomes more stable under the gel, as compared to in air where disturbances from pyroelectric effects and ambient noise are apparent. The Singletact also has an impressive signal to noise ratio, and we are eager to use this in combination with the vibration sensors.

V. Future Work

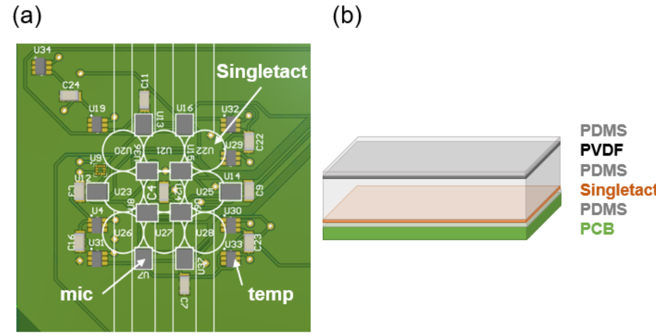

Fig. 3. The PCB CAD model ((a)) and architecture ((b)) of the next iteration of our sensor, containing 10 microphones and 8 temperature sensors on the PCB, 9 Singletacts at an intermediate gel layer (projections shown in (a)), and a PVDF layer with 9 aluminum electrodes, which also act as the proximity sensor terminals, just beneath the surface to maximize vibration detection and proximity sensing (not shown).

We are also working on a second iteration of this sensor, which combines these modalities into a dense, distributed formation (Fig. 3). Our second prototype iteration contains a PCB with ten microphones and eight temperature sensors distributed across it. Nine Singletacts are placed in intermediate layers of the PDMS. Finally, we place nine PVDF sensors just beneath the surface of the gel to maximize vibration and proximity detection. As is done in previous work [9], we will use the PVDF electrodes as the projected capacitance terminals.

Although our first sensor uses off-the-shelf PVDF sensors, our second iteration incorporates custom PVDF sensors with aluminum electrodes deposited in a grid, increasing signal density and customizability and decreasing iteration time. PVDF can be modeled as a current source in parallel with a capacitor, and we take a current measurement of the PVDF signal using a transimpedance amplifier. To handle a high signal count, we multiplex the PVDF signals before reading them with the microcontroller. The PVDF array is wired to a heat seal connector which is connected to the non-sensorized area of the PCB (not shown in Fig. 3).

In addition to combining multiple modalities in hardware, we also aim to exploit this sensor's multimodal nature by using machine learning on top of the overlapping sensor signals. We are particularly excited about using learning on top of piezoelectric and microphone signals. With our planar, signal-dense second prototype, we plan to conduct dropout studies with various permutations of sensors to determine how we can best exploit complementary sensors for different tasks, such as force regression, localization, texture classification, and radius of curvature detection.

Lastly, with none of these sensors necessitating flat surfaces or bulky hardware, we ultimately plan to use what we learn from these prototypes to select a subset of these sensors to incorporate into a robotic finger. We envision leveraging this robotic finger's multimodality to better enable dexterous manipulation.

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