PrintSense: A Versatile Sensing Technique to Support Multimodal Flexible Surface Interaction

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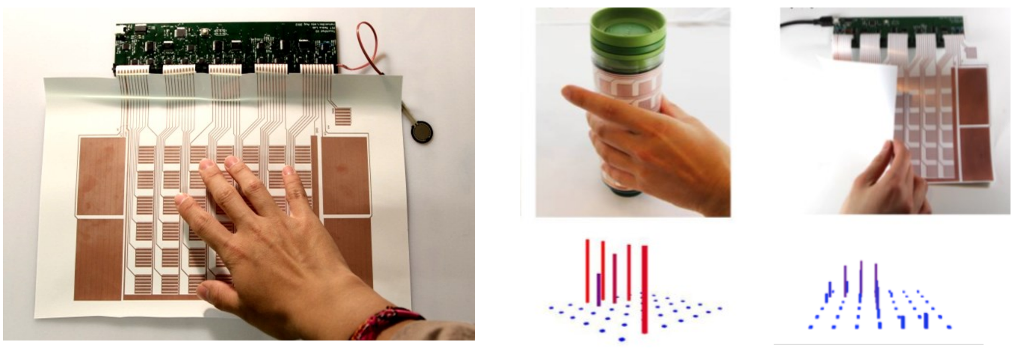

Figure 1. The PrintSense technique supports the development of multi-modal sensing arrays, printed as a single layer onto a flexible substrate and connected to a custom hardware module (left). It supports capacitive touch and proximity sensing along with resistive pressure sensing (centre) & bend sensing of the substrate (right).

ABSTRACT

We present a multimodal on-surface and near-surface sensing technique for planar, curved and flexible surfaces. Our technique leverages temporal multiplexing of signals coming from a universal inter-digitated electrode design, which is printed as a single conductive layer on a flexible substrate. It supports sensing of touch and proximity input, and moreover is capable of capturing several levels of pressure and flexing. We leverage recent developments in conductive inkjet printing as a way to prototype electrode patterns, and combine this with a new hardware module for supporting the full range of sensing methods. As the technique is low-cost and easy to implement, it is particularly well-suited for prototyping touch- and hover-based user interfaces, including curved and deformable ones.

Author Keywords

Interactive surface, touch input, multimodal input, flexible sensor, conductive inkjet, printed electronics.

ACM Classification Keywords

H.5.2 Information interfaces and presentation: User Interfaces- Input devices and strategies.

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INTRODUCTION AND RELATED WORK

While standard multi-touch sensors are now well established in a variety of HCI applications [1], flexible sensors are attracting increasing interest. For instance, prior work has contributed sensors for pressure input [7] and for deformation sensing [2]. However, these sensors are often complex to work with and modify, requiring special materials and components. Moreover, each sensor captures only limited and pre-defined modalities. Recent advances in conductive inkjet printing [3] provide an easier way to produce sensor electrodes [7] and allows an end-user to create their own electrodes with consumer grade hardware [5]. This can be highly beneficial for prototyping user interfaces [6, 8]. However, printing a single layer of passive conductive traces has to-date restricted use to basic touch sensing [6, 8].

We present PrintSense, a technique for multimodal sensing on planar, curved or flexible surfaces. In contrast to previous work, we show how a single-layer sensing electrode design may be used in conjunction with a variety of signal generation and processing techniques. This diversity supports a greater range of sensing than conventional printed touch and multi-touch sensors, including pressure, folding and proximity detection. PrintSense consists of an array of electrodes printed on a flexible substrate, and a custom-made electronic circuit that processes electrode signals. We present both components. By pairing the electronic circuit with a suitable sensor electrode design and configuring how it generates and processes sensor signals, we show that it is possible to extend sensing capabilities beyond touch input for several interactive scenarios. These scenarios include grasp detection on curved objects as well as detecting pressure and folding on flexible sheets.

Our overall aim is to highlight a spectrum of sensing techniques for flexible conductive surfaces, to illustrate usage scenarios and new opportunities for this low-cost, flexible surface interaction, and to enable other practitioners to replicate and extend our work.

PRINTSENSE DESIGN AND IMPLEMENTATION

The primary sensing modality supported by PrintSense is capacitive. However, unlike many previous capacitive sensing systems, we support several different sensing modalities which extend basic touch interaction to include proximity and folding. Moreover, we add resistive sensing – capable of capturing different levels of contact pressure – to the same electrode design.

Capacitive Touch Sensing

The basic operating principle of the majority of simple, single-layer electrode capacitive touch systems is to repeatedly charge up an electrode and then time how long it takes to discharge. When a finger, hand or other body-part is close to the electrode, its rate of discharge will change; this can be detected and inferred as touch [10]. PrintSense supports this mode of touch sensing which we refer to as *load sensing*. We use two interleaved sets of conductive 'inter-digitated' (IDT) fingers for each electrode, as shown on the left of Figure 2. Unfortunately, the detection range of basic capacitive sensing is limited; therefore, we include two more sensing modes for proximity sensing.

Capacitive Proximity Sensing

Using the same sensing electrode design and layout, PrintSense also supports a completely passive capacitive sensing mode, which we call *AC hum detection*. In this condition, each electrode is connected to an analog sensing circuit, which detects any mains electricity noise coupled into it [10]. Just as touching an audio cable that is attached to an amplifier causes noise to be picked up, so proximity to a sensing electrode can be detected. More specifically, we implement a band pass filter centered at a frequency of 50 to 60 Hz to match the power line alternating current (AC). After the band pass filter, a peak detector holds the AC signal amplitude, outputting a DC voltage equal to the peak value of the AC signal. This mode provides hover detection with a ~10 cm range (Figure 2).

An alternative approach to proximity detection is an active *transmit-and-receive* scheme [10]. This active sensing approach offers a way to reference the distance (or even angle) between two electrodes, which can be not achieved with passive capacitive detection.

In this mode of operation, electrode fingers are either used to transmit or receive an electric field. When one set of electrode fingers (the 'transmitter') is stimulated with an AC signal, a second set (the 'receiver') will pick up the same signal. If part of a user's hand is in contact with the transmitting electrode, it will act as an extension to the transmitting electrode and increase the signal transfer to the receiving electrode. Conversely, when a hand is in-between the electrode pair, it tends to block the electric field, and creates a signal drop. These effects are used for proximity detection.

Detecting Folding

In addition to capacitive proximity sensing, the active transmit-and-receive capacitive technique may be used in a slightly different way to detect folding of the array of electrodes by estimating the distance between specific pairs of electrodes. In this case one electrode acts as a transmitter and is detected by others across the sensing substrate (see Figure 6).

Resistive (GSR) Pressure Sensing

The final sensing modality we support is resistive pressure sensing. This exploits the fact that when a fingertip comes in contact with a bare IDT electrode it will allow current to pass between the two electrode fingers. Although there is a considerable variation in baseline skin resistance between users due to a number of factors, in our experience applying an increasing pressure always decreases resistance. The advantage of resistive sensing compared with capacitive sensing is this analog force detection couple with an immunity to environmental RF noise. Note that measuring skin resistance is inherently akin to measuring conductance, i.e. galvanic skin response (GSR).

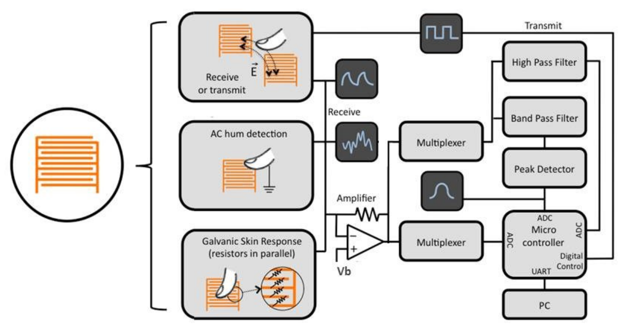

Figure 2. Three different signal detection schemes supported by PrintSense's inter-digitated electrodes. From top to bottom: active transmit-and-receive capacitive sensing for proximity and folding detection, AC hum detection for touch and proximity detection, and resistive pressure sensing.

Electrode Substrate

To test and evaluate the techniques described in this paper, we designed a single pattern of conductive electrodes as shown in Figure 1, and manufactured it using Conductive Inkjet Technology [3]. As it is single-layered it is easy and inexpensive to print, even by non-experts with off-the-shelf hardware [6]. The central area contains a grid of 42 IDT electrodes. Each is around 1.5 cm^2 with a roughly 0.5 cm separation between adjacent electrodes designed for detecting finger presses. The size of the electrode can be easily customized depending on the application. Two larger 3 x 6 cm electrodes were included for greater transmission range in proximity detection mode.

Hardware Implementation

The PrintSense controller is based on a 16 MHz ATmega 328 microprocessor, which can support 46 inter-digitated electrodes. The microcontroller controls a pair of three 16:1 multiplexers (MUXes, CD74HC4067) in order to switch each input between sensing modes. Each input electrode is first fed into an amplification stage for current-to-voltage conversion before the analog MUX scans through and transmits the voltage levels to a 10-bit analog-to-digital converter (ADC). A second MUX is connected to the same amplifier outputs, but feeds an analog active filter circuit with extra gain.

The geometry of the controller and the associated sensing substrate was chosen to support full-hand interactions. The connection between the flexible substrate and the controller board was made with flex circuit connectors (JST-10FDZ). For the AC hum detection, we designed a band-pass filter, 50-160 Hz with gain of 100. For the receiving electrode of each transmit-receive pair, the high pass filter has a cut-off frequency around 1.6 kHz. The ADC sampling rate of our microprocessor is approximately 10 kHz. The whole system samples 46 channels with both modalities at 84 Hz. The raw hum-detection data is envelope-detected in the hardware before being sent to the computer. The sensor board is USB powered, and a FTDI USB serial chip is used for the serial communication between the microcontroller and a PC.

CHARACTERISATION OF OPERATION

Resistive Sensing

Across all the sensing modalities supported by PrintSense, we were most interested to evaluate its suitability as a resistive force sensor which can distinguish more than simple touch/no-touch states because to our knowledge this has not been explored previously. Therefore our evaluation aims to distinguish between three different levels of pressure across users. We conducted a user study with 5 users in which we compared the average response and stability of two sensors: a standard force sensitive resistor (FSR, #402) and one of our IDT electrodes for GSR measurement which was glued underneath the FSR. Each unit has line width of 10 mm and spacing between lines of 0.5 mm, and roughly represents the physical footprint of a single finger. FSRs are well established for measuring pressure in interactive applications. Typically, the part-to-part repeatability tolerance is ± 15-25% of an established nominal resistance [4]. We used a voltage divider with a unity gain follower and a 10 kΩ measuring resistor [4] to determine pressure; this circuit configuration was used for GSR measurement as well, but with a 2 MΩ resistor.

Figure 3 shows the raw data output when a user was asked to tap, press gently, and press hard on the electrode. We calibrated the force with FSR resistance readings and kept samples within three force ranges: 0-200 g, 300-600 g and 700-1000 g. The user was asked to perform each gesture five times, and we took 100 samples in each gesture. Although there may be some error due to differential non-linearity, this relative pressure is effectively calibrated by the FSR measurement. The GSR measurement has less dynamic range detection, as seen in the plot. To better understand the performance of GSR over time across users, five users were recruited and asked to touch the GSR/FSR input stack 10 times for 5 seconds, each with an interval of 5 seconds between touches. To get the most stable measurement, we only used the first second of data (1000 samples) of each touch, windowed to remove the applied pressure transient. Figure 3 shows the relative pressure ratio (GSR/FSR) across users and at different times of day. The error could be improved with smaller electrode design to ensure the finger covers the same area during every touch. The GSR measurement varies between users, touches, and on different occasions, attesting to its utility mainly as a relative parameter. Long-lived implementations will need to deal with tarnishing as well; this however is less problematic in prototyping, where the ability to iterate designs rapidly is more important.

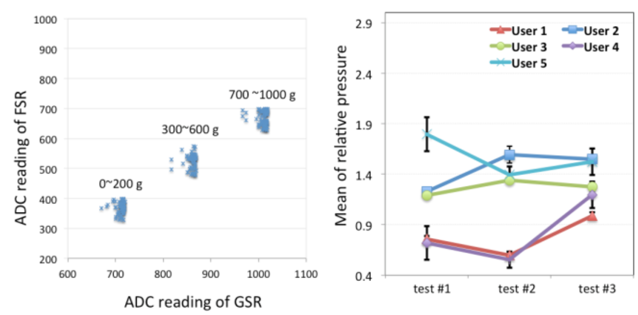

Figure 3. Left: Raw GSR and FSR ADC data from "tapping" (0~200 g), "pressing gently" (300~600 g) and "pressing hard" (700~1000 g). Right: Mean values of the GSR/FSR ratio for each user across time.

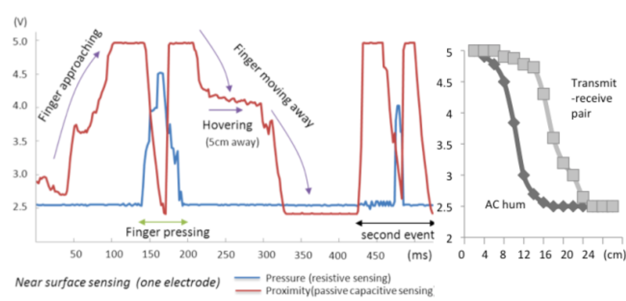

Figure 4. Left: Near surface sensing signal responses. Right: Proximity range comparison between AC hum detection and transmit-receive pair in our design.

Capacitive Proximity Sensing

Figure 4 demonstrates the raw signal responses of one electrode using AC hum passive capacitive detection and also using resistive pressure sensing. The X-axis is time and Y-axis signal amplitude. The user pointed one finger at a single electrode, approached it, touched it and pressed into the electrode before slowly moving away. The blue line indicates pressure level from the resistive sensing signal; as the user presses the electrode, the signal becomes stronger.

With AC hum detection we are able to detect hands around 10 cm above the surface. The red line shows how this signal increases as the finger approaches, until the finger touches the IDT electrode and shunts the capacitive signal to ground, whereupon the signal immediately drops to the 2.5V bias voltage. We also achieved a greater dynamic range of up to 20 cm with active capacitive sensing (transmit-receive pair) as seen in Figure 4.

EXAMPLE USE CASES

In order to demonstrate application scenarios for PrintSense, we selected two examples requiring different sensor configurations. User interaction and machine learning based gesture detection for these scenarios are demonstrated in the video that accompanies this paper.

Grasp Detection for Curved Objects

The first use case is grasp detection for curved objects, in which the main sensing method is resistive sensing. Our test object is an insulated coffee beaker wrapped with a substrate of printed electrodes. Figure 6 shows the capture of different levels of pressure and hovering. This enables a more detailed capture of grasps than previous work, which was restricted to touch contact sensing [9].

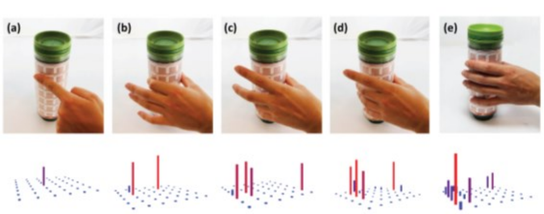

Figure 5. Grasp detection and raw data on curved objects. (a) One finger touch. (b) Pinch – two fingers input. (c) Three fingers touch. (d) Four fingers touch. (e) Whole hand grasp. Data visualization below each image is from resistive sensing.

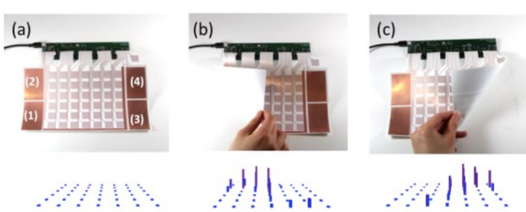

Figure 6. Using PrintSense to detect folding. The raw data image in the bottom row shows the bigger electrodes actively transmitting signals, and signal received by the remaining IDT electrodes.

Manipulation of Flexible Surfaces

In our second use case (Figure 6), we demonstrate detection of the manipulation of a flexible surface, and more specifically bending and folding the corners of this surface. An example application is navigation with a flexible e-book reader. Note that two of the corner electrodes (1) and (3) are transmitting a signal in alternation, and this is picked up by nearby electrodes.

DISCUSSION AND CONCLUSION

In this paper we presented PrintSense, a multiplexing architecture which uses flexible printed conductive electrode arrays to support a range of sensing modalities. It supports interactions such as touch, proximity, pressure and folding. The advantage of our approach over other surface sensing platforms is the multi-modal sensing using a single layer printed conductor. The size of the electrode was selected for basic finger pressing detection, and can be modified easily for different applications. The trade-off is between detection range and resolution. We characterized GSR sensing as a method for inferred force detection and tested across users and time. Although the variance among users is higher than other sensing methods, the simplicity of this method may make it a good alternative for rapid prototyping in conjunction with capacitive proximity and touch sensing. Finally, we provided two proof-of-concept examples that illustrate some of the scenarios that PrintSense can support. We hope that our work will be useful to others who need to iterate touch- and proximity-based interactive prototypes and will in turn inspire new interactive possibilities.

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