# FlexTouch: Extending Interaction Sensing beyond TouchScreens using Flexible and Conductive Materials

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## ABSTRACT
In this paper, we present *FlexTouch*, a technique that enables large-scale interaction sensing beyond the spatial constraints of capacitive touchscreens using a passive low-cost conductive film. This is achieved by fabricating custom 2D circuit-like patterns with an array of conductive strips that can be easily attached to the sensing nodes on the touchscreen's edges. This retrofit requires no other external hardware or internal hardware modification to the device. We show that our technique is compatible with various conductive materials (copper tape, silver ink, ITO frame, and carbon paint), as well as fabrication methods (cutting, coating, and ink-jet printing). *FlexTouch* supports 2D continuous touch interaction and activity detection with a large coverage range (>1 meter) as well as object presence sensing. Finally, we demonstrate the versatility and feasibility of *FlexTouch* through applications in the domain of hand/body posture detection, human/objects' presence sensing as well as enhanced VR/AR interactions.

## ACM Classification Keywords
H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

## Author Keywords
Capacitive sensing; touch interface; fabrication; continuous touch input; posture detection

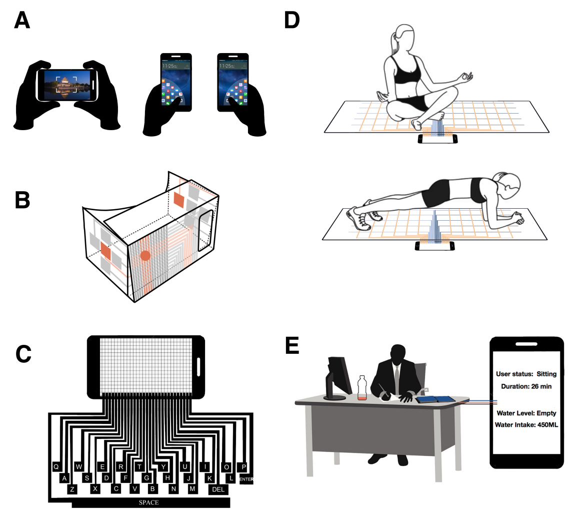


**Figure 1. *FlexTouch* supports various applications with different configurations through extending the capacitive sensing ability of touch screen to surrounding areas. A. hand gesture detection. B. two-dimensional touch panel for phone-based VR interactions. C. full-size extension keyboard. D. body posture detection on the yoga mat with built-in capacitive sensing matrix. E. smart surfaces for object presence and state detection**

## INTRODUCTION
Capacitive touch sensing is a popular interaction modality on smart devices, providing seamless, intuitive interaction between users and digital media. However, the sensing space is limited to the area where touch sensors are embedded, constraining natural user interactions to the surfaces of these smart devices. In this paper, we explore easy fabrication of customizable touch-sensitive interfaces that can be easily attached to the phone to extend touch sensing capabilities into the surrounding physical environments to support interactive applications with everyday objects (Figure 1).



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The advancement of the Internet of Things brought smart devices into our everyday living. Many of these devices such as smartphones and tablets carry capacitive touchscreens. Similar to our work presented in this paper, researchers demonstrated interesting sensing and interaction possibilities by expanding the sensing area of touch screen via attaching conductive materials [Kato and Miyashita 2015a, Kato and Miyashita 2015c, Kato and Miyashita 2016]. Even though these 'Extension Sticker' approaches allows for touch sensing beyond the surface of the touchscreen, it can only support one-dimensional touch widgets such as scroll-up, scroll-down sliders, limiting the design space of interactive applications.

Researchers also explored the possibility of enabling various touch interaction methods on everyday surfaces or objects [Ono et al. 2013, Ono et al. 2014, Sato et al. 2012, Xiao et al. 2013, Zhang et al. 2017]. However, these prior work require dedicated sensing platforms such as the Arduino embedded systems to power these touch interfaces and to enable wireless communication with digital devices. These requirements create barriers for end users to easily fabricate customizable touch interfaces.

In this paper, we present *FlexTouch*, a technique for extending 2D continuous touch beyond the surfaces of capacitive touchscreen leveraging flexible conductive materials such as copper tape, customized Indium Tin Oxide (ITO) film, carbon painting or printable silver ink. We also introduce fabrication techniques such as conductive inkjet printing to create varies 2D patterns of passive conductive patterns that can be easily attached to the edges of capacitive screens.

We built a specialized Android kernel for *FlexTouch* to capture the raw signal from the capacitive touch sensor matrix, and apply signal processing and machine learning to capture the capacitance changes caused by the touch events on the extended surfaces. *FlexTouch* can support a variety of applications including 2D continuous touch interface, hand/body posture sensing, object presence detection, as well as enhancing phone based virtual reality experiences. In general, *FlexTouch* extends the capacitive sensing capability of the touchscreen to everyday objects and ambient environments to support interactive applications. Our contributions in this paper are as follow:

1. We create techniques that leverage a variety of conductive materials and fabrication methods to customize extensions of touchscreens to support continuous 2D touch on everyday objects and ambient surfaces.

2. We apply signal processing and machine learning techniques to support versatile sensing and interactive applications leveraging raw capacitive touch sensor data captured by a specialized Android kernel.

3. We evaluated the limit of our approach including the coverage area. Furthermore, we conducted user studies to benchmark the performances of proposed sensing applications including hand/body posture sensing, object state detection as well as the enhanced virtual reality applications.

## RELATED WORK

We categorized three groups of literature's related to *FlexTouch*. Firstly, we review a broader set of works aiming to enable touch interaction on everyday surfaces and objects. Then we review prior work in the field of capacitive sensing related to our sensing method. And finally we narrowed down to a specialized area of literature focusing on enhancing interaction on surfaces near touch screens of mobile devices which are in close proximity to better position our proposed method.

### Touch Interaction on Everyday Surfaces and Objects

Researchers have explored various methods or techniques to enable interactive interface on everyday surfaces and objects. One popular method to enable touch interaction on everyday surfaces or objects is through projecting the 2D user interfaces using projector which can be combined with computer vision to recognize user interactions. For example in the projects including Everywhere Display Projector [Pinhanez 2001], Light Wedgets [Fails and Jr. 2002], Light Space [Wilson and Benko 2010], and WorldKit [Xiao et al. 2013]. the authors used projectors displaying the user interface on everyday surfaces and uses RGB or depth camera to sense user touch interactions on everyday surfaces. The camera based solutions are suitable for fixed infrastructure, but its size and form factor is still challenging for mobile scenarios.

Acoustic is another popular way to sense touch interaction. Researchers explored recognizing a discrete set of touch events on everyday objects by passing a frequency-sweep signal through a pair of piezoelectric transducers [Ono et al. 2013, Ono et al. 2014]. Other methods support acoustic sensing on various objects such as window [Paradiso et al. 2002], desktop and other surfaces [Harrison and Hudson 2008].

Another common method is through electromagnetic sensing. Electrick [Zhang et al. 2017] and Pulp Nonfiction [Zhang and Harrison 2018] enable touch input on everyday surface or object using Electric Field Tomography (EIT) with coated conductive materials on everyday surfaces and objects. Touche [Sato et al. 2012] enhances touch interface on the human body or everyday objects through measuring the electrical profiles with a frequency-sweep signal. Midas [Savage et al. 2012] fabricated customized capacitive touch sensors to prototyping interactive object with a circuit board milling machine.

However, all the acoustic or electrical solutions relay heavily on dedicated sensing platforms and customized embedded systems to provide power supply, external sensors, signal processing and communication modules. These requirements create barriers for end users to easily fabricate customizable touch interfaces. Researchers are seeking easy sensing and fabrication methods to achieve low-cost touch-sensitive interfaces.

### Capacitive Sensing

Capacitive sensing has been introduced to the HCI field for more than two decades. Recently, Grosse-Puppendahl and colleagues provided an analysis and review of past research related to capacitive sensing theories and techniques [Grosse-Puppendahl et al. 2017]. Among all the capacitive sensing methods, shunt mode sensing is the most widely spread approach which are ubiquitous in modern capacitive touchscreens. The touch panel consists of multiple layers above the display screen with all the sensing nodes oriented in a row-column matrix. Obtaining the low-level capacitive data from the touchscreen provide us more capability beyond finger multi-touch sensing. Similar to our approach, *BodyPrint* extracted the raw capacitive data of the touch panel for Biometric User Identification [Holz et al. 2015]. Using 2d capacitive touchscreen data, *CapAuth* combined with machine learning classifiers to provide authentication and even identification of users [Guo et al. 2015]. Researchers also explored the potential of using the raw capacitive data of the touchscreen to support sensing of tangible 3D printed gadgets on top of the screen [Schmitz et al. 2017, Schmitz et al. 2018]. These prior work shares the same raw capacitance signal as our approach in this work. Yet we have a different focus on fabricating conductive interfaces to support large-scale thin and flexible 2D touch interfaces in the ambient surfaces.

### Enhancing Interaction around Mobile Devices

Modern mobile devices are embedded with rich sensors and actuators. Researchers have explored approaches and techniques enhancing the interaction around mobile devices with customized sensors via active and passive techniques.

Researchers has explored attaching active sensor to mobile devices to enable interactive user applications. SideSight [Butler et al. 2008], in particular, added a sensor board with multiple linear arrays of discrete infrared (IR) proximity sensors on the edge of the mobile device to extend the touch interaction to the surface around the device. Toffee [Xiao et al. 2014] enables around device interaction through acoustic time-of-arrival correlation method with piezoelectric transducers. iGrasp [Cheng et al. 2013b] and IrotateGrasp [Cheng et al. 2013a] used capacitive touch sensors on the edge and back of the mobile device to recognize the hold postures for adaptive keyboard layout and screen rotation. These approaches demonstrate promising applications space, however, adding external sensors requires power source and processing unit which create scalability barriers for adoption.

As an alternative, researchers explored leveraging the built-in sensors to enhance the interaction on or around the touchscreen. Acoustruments [Laput et al. 2015] constructed various sensing units that can detect hand interaction around mobile devices such as touch, proximity and rotation by measuring the acoustic signal transmitted in an enclosed, pipe-like pathway from the speaker to the microphone. UbiTouch [Wen et al. 2016] enabled touch interface on surrounding surfaces using build-in proximity and ambient light sensors. Wang and colleagues presented a virtual keyboard tehcnique on the surround surface of mobile devices through harnessing multipath fading with multiple build-in microphones [Wang et al. 2014].

Capacitive touch sensing panel provides a high-resolution method for sensing user hand interactions. Related work explored enhancing tangible interaction on the touch scree via Clip-on Gadgets, which extends capacitive touch points on the phone to physical controllers via conductive materials [Yu et al. 2011]. This approach provides haptic feedback via the controllers while allowing for interactive applications via phone capacitive touch screen. In close proximity to our work, Kato and his colleagues took one step further to fabricate 3D printed conductive gadgets with haptic feedback patterns [Kato and Miyashita 2016]. User interaction with these gadgets can be sensed via the capacitive screen when they are placed onto the phone. In addition, they also presented an technique named ExtensionSticker which allows input sensing to be transferred to ambient surfaces [Kato and Miyashita 2015c]. They also discussed an VR application where this techniques is utilized to enable interactive VR applications [Kato and Miyashita 2015b]. The challenges here is these prior work usually blocks out a area of the screen for attaching conductive tapes which limits user's natural interaction with the digital contents. In addition, These techniques using extension stickers only allow for 1 dimensional touch sensing on the areas connected to the touch screen.

In this paper, we present FlexTouch, a techniques that allows users to create flexible and customizable touch sensitive gadgets that can be easily attached onto the phone for rapid prototyping of interactive applications. Different from prior work which partially block the mobile phone display, we combine transparent materials such as ITO which can be easily attached onto the phone in an unobtrusive way. In addition, we apply signal processing and machine learning directly to the raw value of the capacitive sensor to enable 2 dimensional continuous finger localization on ambient surfaces. This advancement from prior work dramatically enhances the expressiveness of user interactions.

## SENSING PRINCIPLES OF TOUCH SCREEN

Most touch screens today are based on either self or mutual capacitive touch sensing. The mutual capacitive touch sensing method is widely adopted in industry due to its robustness in sensing multiple touch points simultaneously [Ye et al. 2015]. The touch panel consists of multiple layers above the display screen as demonstrated in Figure 2. A substrate glass etched with the sensing lines is attached. Then a layer of insulating material etched with the driving lines is placed on top. Finally, a bonding layer and a protective layer are placed on the top of the stack.

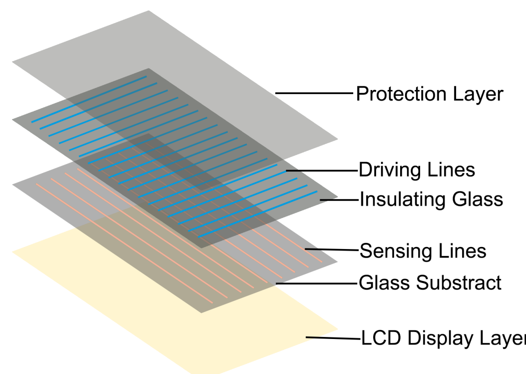


**Figure 2. The multi-layered structure of mutual capacitive touch panel.**

The driving and sensing lines are made by a highly transparent conductive material named Indium Tin Oxide (ITO). They are oriented in a row-column matrix. A thin insulating layer between the driving lines and sensing lines forms a gap, the coupling mutual capacitance is formed at each junction (intersection between the driving and sensing lines) [Barrett and Omote 2010]. Dedicated IC drives each driving line (row) and scans all the the sensing lines (columns) to measure the capacitance value at each row-column intersection. This procedure is repeated for all the driving lines as one entire cycle as Figure 3 a) shows.

The finger touch increases the mutual capacitance of the touched electrodes. To detect the touch events, the driver IC measures the capacitance of each electrode intersection by comparing the source signal injected to the driving line and returned signal from the sensing line. The equivalent circuit and measuring method are illustrated in Figure 3 b) and c). The standard method to detect the mutual capacitance of each junction is to measure the charging time to reach a certain

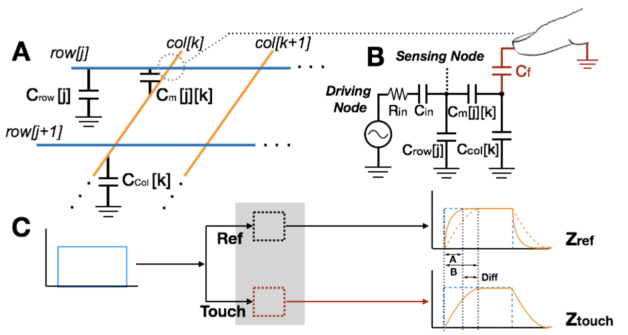


**Figure 3. A: Representation of capacitive sensing row-column matrix structure B: Equivalent circuit of each junction. C: The measurement of capacitance of each junction.**

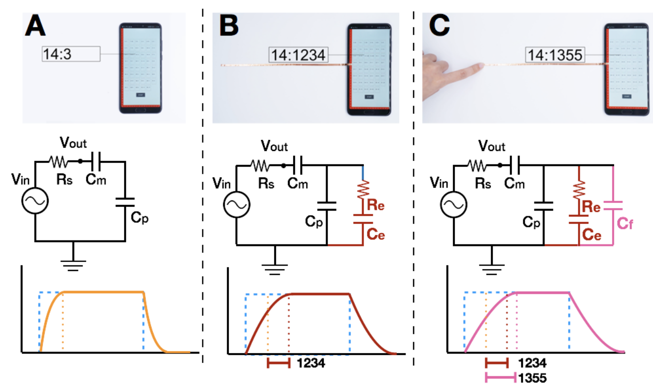


**Figure 4. Simplified equivalent circuits of *FlexTouch*. A Original touch capacitive sensing junction. B: Adding a conductive strip on the touch-screen. C: Touch on the conductive strip attached on the touch screen.**

voltage threshold between the driving line and the sensing line.

## FLEXTOUCH

*FlexTouch* extends the capacitive sensing method of commercially available touch screen to surrounding areas through a single conductive thread or frame attached on each sensing electrode. The attached conductive material, changes the electric field around the capacitive sensing junction. In this section, we explain the working principle, implementation and various of design configurations of *FlexTouch*.

### Working Principle

The conductive thread attached onto the touch screen draws currents passing from the driving line around the corresponding junctions. As a result, it takes more time to charge both the inner circuit and the attached conductive thread. In other words, any attached conductive material increases the mutual capacitance of the capacitive sensing node. Consider another case when people touch on the conductive thread, human body draws additional currents from the touch screen that further increases the mutual capacitance. In Figure 4 ,the measurement output from each junction node is positively correlated to mutual capacitance. In Figure 4a, the measurement of junction #14 is 3 when no finger touch is present and now conductive thread is attached. When we connect an copper conductive thread onto the sensing node, the measurement jumped up to 1234. And when a user is pressing onto the thread, the measurement is further increased to 1355 accordingly.

We also present simplified equivalent circuits under each column in Figure 4. We simplified the circuit for each capacitive sensing touch node as a RC circuit. $C_m$, $C_p$, $C_e$, $C_f$, $R_e$ represent the mutual capacitance, parasitic capacitance, introduced capacitance between the extended element and virtual ground, touch introduced capacitance and extended element introduced resistance. Equation (1) shows the calculation of the measured $v_{out}$ ignoring the tiny effect of $R_e$.

$$V_{out} = v_{in}(1 - e^{-\frac{C_m+C_p+C_e+C_f}{R_s C_m (C_p+C_e+C_f)}t}) \tag{1}$$

The touchscreen controller transmits a series of step voltage signal to scan through each electrode, and measures the capacitance through the charging time (time for $V_{out}$ to reach a threshold) as the raw value of the touch screen. The charging time is linearly dependent on the Time Constant of the RC circuit, named $\tau$, that is given as:

$$\tau = R_s \frac{C_m(C_p + C_e + C_f)}{C_m + C_p + C_e + C_f} \tag{2}$$

We assume that $C_m$, $C_p$ are static with value around $10pF$. The value of $C_e$ depends on the characteristics of the extended surfaces such as conductivity of the material, length and width of each extended element as well as the intersection effect between the extended elements. Depending on different of touches on the extended surface, $C_f$ typically varies from several to dozens of $pF$. Fully understand the effect of $C_e$ towards the circuit is the key to explore the upper performance limit of *FlexTouch*. To achieve such goal, we modeled the mutual capacitance between the extended material and the virtual ground according to following formula.

$$C_e = \varepsilon \frac{A}{d} \tag{3}$$

Since the the separation $d$ between the extending material and the virtual ground is nearly static, the capacitance scales with the area $A$ of the extended element and the dielectric constant of the material $\varepsilon$ that is given as:

$$C_e \propto \varepsilon A \tag{4}$$

To validate above assumptions, we designed a study to explore the effect of the length, width and different type of materials that we present in the coverage area evaluation section.

### Implementation

To validate the feasibility of our approach across different Android devices, We implemented *FlexTouch* on a Huawei P20 and a Huawei P10 phone. By rooting the Android operating system and modifying the driver of the touch screen controller IC in the kernel source code, we extracted the raw capacitive sensing data: 32 by 16 px 16-bit diff value image across a 5.8 inches surface at 100 fps for Huawei P20, 28 by 16 px, 16-bit diff value image across 5.1 inches surface area at 20 fps for Huawei P10. We built an Android application showing positions and raw capacitive values with corresponding update rates of all the sensing nodes (Figure 5 a) and c)). Each junction capacitive sensing point covers an area of 4 mm width an 4.16 mm height on the Huawei P20 and 3.75 mm width and 4.16 mm height on the Huawei P10 phone.


**Figure 5. Android Applications showing the raw capacitive data and positions of the sensing nodes.**

### FlexTouch Sensing Capabilities

We summarized the sensing capabilities of *FlexTouch* into four categories as shown in Figure 6.

a) 1D touch interfaces enable tangible discrete touchable buttons, 1D touch gesture widgets.

b) 2D continuous multi-touch tracking enables large-scale multi-touch tracking or hand/body activity detection.

c) 2D High resolution single-touch tracking via extending ($N$) capacitive sensing junctions into X-Y matrix configuration that enables $N^2/4$ capacitive sensing nodes.

d) Everyday object state sensing includes object presence detection and object state sensing based on capacitance measurement.

Note that sensing capability a) has been discussed in prior work [Kato and Miyashita 2015c]. but the other modalities are unique to FlexTouch.

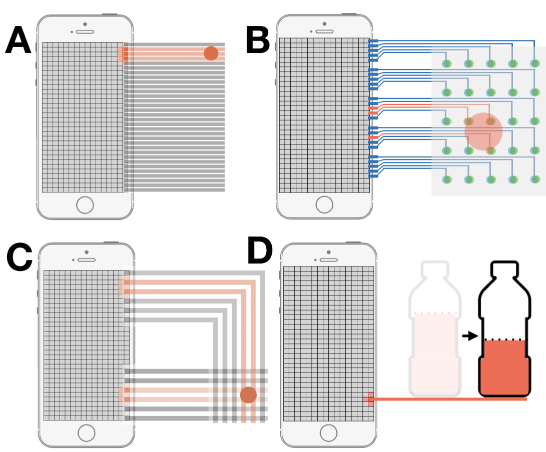


**Figure 6. *FlexTouch* supports various applications with different sensing capabilities including A: 1D touch sensing, B:2D continuous multi-touch tracking, C: 2D High resolution single touch tracking and D: Object presence and state sensing**

## FABRICATION MATERIALS AND METHODS

We identified materials that can be easily customized into paper-like surfaces with properties including nontoxic, flexible, conductive and commercially available. We fabricate interfaces using these materials through various processes, including adhering, cutting (e.g., manual cutting, laser cutting) and coating methods (e.g., ink-jet printing, brush painting). We leverage the following materials to fabricate *FlexTouch* interfaces.

### Conductive tapes

Conductive adhesive tapes are widely used for electromagnetic shielding and transmission wiring such as building paper circuits.

The most widely available example conductive tape is the adhesive copper foil tape that can be found easily at most hardware, electronic or gardening stores (Figure 7A). It is $2.50 per roll (6.3 mm x 20 m). The copper tape is highly conductive (0.05 Ω per square centimeters). We can manually arrange any 2D layout on any surface using copper foil tape (e.g., Figure 16). However, the copper foil tape does not work well for applications that can requires fabricating techniques such as the laser cutting or 3D printing.

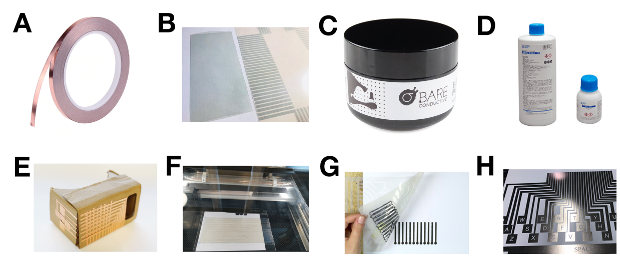


**Figure 7. Example commercially available materials. Copper foil tap (A) can be sticked to any surface such as the cardboard (E). ITO PET Plastic film (B) can be cut to any 2D pattern with laser cutter (F) or manually . Bare conductive carbon paint (C) and related painting fabrication method (G). We built ink-jet circuit printer with Mitsubishi Silver nanoparticle ink (D) for printable conductive 2D layout (H).**

### Conductive Films

Film-like materials can be subtracted to 2D patterns with proper cutting or etching fabricating methods. One example material is the flexible Indium Tin Oxide (ITO) coated PET plastic film that is semi-transparent and conductive. We use the commercially available ITO coated PET film manufactured by HNXCKJ [Technology 2018]. The film is compatible with laser cutter. Further more, 2D custom layout is available by coating ITO materials on the plastic film that is extremely thin (0.05$mm$) at a cost of $30 per square feet (Figure 7B)

Since the ITO coated PET plastic film is highly transparent, it can be attached to the touchscreen without blocking the display of the screen (Figure 8A). So we used the custom film as a screen protector with an array of ITO strips attached to the edges of the screen to extend capacitive sensing space of the phone. This ITO strip array interface can be connected to the application easily through matching the designs of the application (Figure 8B).

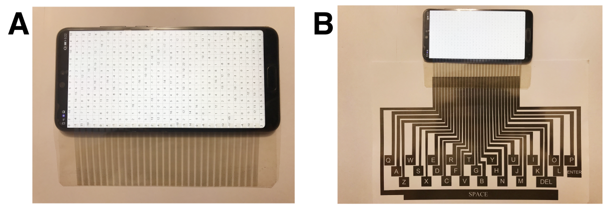

**Figure 8. The ITO strip array interface (A) can connect the 2D pattern application with the touchscreen easily (B).**

### Conductive Coating

Liquid paint coating or ink printing are more versatile, as they can be added onto any surfaces in a post-production manner. We identified two example coating materials. We use conductive carbon paint from Bare Conductive (Figure 7C, ($280 per litter. With this material, We painted on a flat surface(wooden board, cardboard, etc.) and used laser cutter to engrave the layout on top of it.

Another suitable coating material is printable ink. We identified Silver nanoparticle ink made by Mitsubishi (Figure 7D, $340 per 100 ML). We fabricate the inkjet printable circuit [Kawahara et al. 2013] with a Brother MFC-J480DW model printer.

## EVALUATION

### Touch Sensing Coverage Area

Exploring the coverage limit of *FlexTouch* is essential towards quantifying design space and interaction possibilities. We illustrated in *Working Principle* section that the material's type and surface area have major effect on the capacitance of the extension strip. Therefore, in this section, we evaluate *FlexTouch*'s maximum coverage area as a function of materials, touch interface dimensions and touch point configuration of the conductive strip attached to the touchscreen.

#### *Apparatus and Procedure*

There are a range of factors that affect the performance of *FlexTouch*: the conductivity of different materials, lengths and the widths of the extension strips, as well as the hardware. We described the particular conditions and apparatus of our experiments as:

**Material.** We tested four kinds of commercially available materials including *copper foil tape, ITO PET plastic film, carbon paint, and silver nanoparticle ink*.

**Length.** Through some qualitative experiments, we found the distance between the touch point and phone edges effects the signal strength significantly and the signal strength of Huawei P10 phone is stronger than that of Huawei P20 phone. To understand the lower bound for sensing range, we tested different lengths for the P20 (0.01m, 0.02m, 0.05 m, 0.10m, 0.25m, 0.50m, 0.75m, 1.00m, 1.25m, 1.50m) and P10 (0.01m, 0.02m, 0.05 m, 0.10m, 0.25m, 0.50m, 0.75m, 1.00m, 1.50m, 2.00m, 2.50m).

**Width.** ($1.4, 2.7, 5.4mm$ which are 0.5, 1 and 2 times of the actual width of the sensing node) . The conductive strips are attached to the capacitive sensing node on the edge of the touchscreen.

**Hardware.** We evaluated the coverage range performance on two kinds of touchscreen phones that are Huawei P10 and Huawei P20.

We implemented an Android app for the testing (Figure 5B, D) guiding us through the locations of the sensing nodes on the left and bottom edges of the touchscreen. The app logs the raw capacitive image ($32 \times 16 = 512px$ for Huawei P20 and $28 \times 16 = 448px$ for Huawei P10). To filter out environmental noises, we locate the touchscreen phone on a rubber sheet. Then we fabricated twelve 1.5 meters long strips (4 kinds of materials $\times$ 3 kinds of width). The evaluation procedure is as follow:

1) Attach the strip to the central positions of the sensing nodes (node 2, 8, 14, 20 and 26 on the touchscreen's left edge as Figure 5 shows). For each round, we log the raw data for later analysis by clicking the start button. Then we perform a two second touch on the other end of the strip for 5 times.

2) We cut the strip to next shorter level of length ( for Huawei P20, we followed the order of 1.5, 1, 0.5, 0.25, 0.05, 0.02 and 0.01 meter) in sequence and repeat step 1).

To filter out the high-frequency background noises, we applied a simple moving average low-pass filter with the unweighted mean of previous 5 frames of data. We measure the touch signal strength as the differential on the raw mutual capacitive measurements on the phone. This is achieved by calculating the difference between the average values (100 data points average for P20 phone, 40 data points average for the P10 phone) before and after the touch events.

#### *Result*

In this section, we explain and analyze the signal behavior with the capacitive model we built in *Working Principle* Section. Then we provide the maximum coverage range of *FlexTouch* through the SNR (Signal Noice Ratio) measurement. Finally, we explore the effects of stripe width and material qualitatively.

Figure 9 shows the effect of the extension strip's length on the touch signal strength change with different widths and materials of both P10 and P20 phones. As the length grow linearly, the touch signal strength decreases in a log scale.

Guided by the working principle of FlexTouch, we explain the reason of the log scale decrease of the touch signal strength in Figure 9. As illustrated in section *Working Principle*, the raw data we extracted from the touch screen phone is relevant to the *Time Constant* of the RC circuit, named $\tau$ (Formula (2)). We assume that $C_f$, $C_m$, $C_p$ are static values of approximate 5 pF, 10 pF and 10 pF. Then Formula (2) can be simplified as:

Before the finger touch:

$$\tau_{before} = a\frac{100 + 10C_e}{20 + C_e} \tag{5}$$

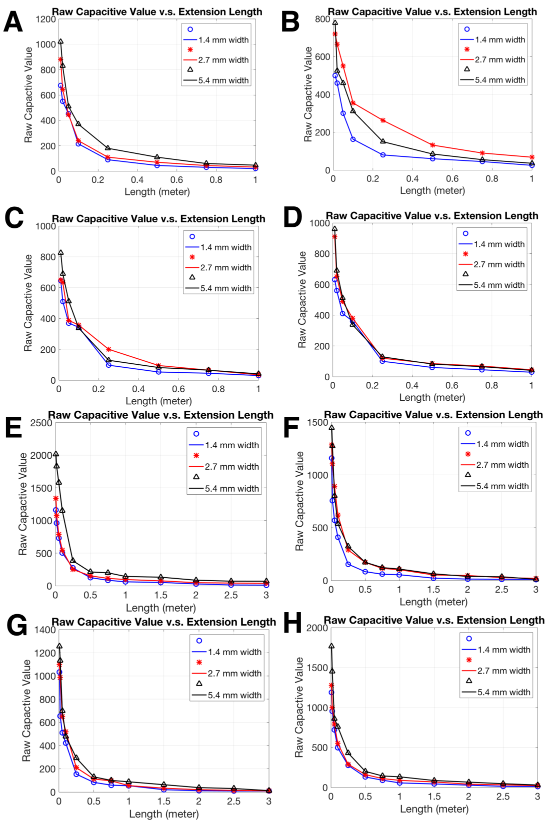


**Figure 9. The curve between the increase of the raw capacitive value of the touchscreen and the lengths of the extension strip under different widths for Huawei P20 phone (A, B, C, D) and P10 phone (E, F, G, H). A/E: Copper foil tape. B/F: ITO plastic film. C/G: Carbon paint. D/H: silver nanoparticle ink.**

After the finger touch:

$$\tau_{after} = a\frac{150+10C_e}{25+C_e} \tag{6}$$

The estimated capacitive value is:

$$\tau_{diff} = \tau_{after} - \tau_{before} \tag{7}$$

$C_e$ linearly depends on the length of the extension strip since the width is static. Figure 10 illustrates the curve between estimated capacitive value and extension strip's length if $a$ is assigned to 1000 as well as the comparison between the measured and estimated value. The similarity curve proves the correction of the model we built for explaining *FlexTouch*'s working principle.

We measured the *SNR* value by calculating the extremum of 100 data points (P20 phone, 40 data for P10 phone) without touching as the *Noise* and the difference between the average of touching and non-touching as the *Signal*. For instance, Figure 11 shows a sample of real data from the Huawei P20 phone with a 0.05m long, 2.7mm wide copper foil tape attached. Note that the noise baseline established from many measurements of parasitic capacitance is converted into digital

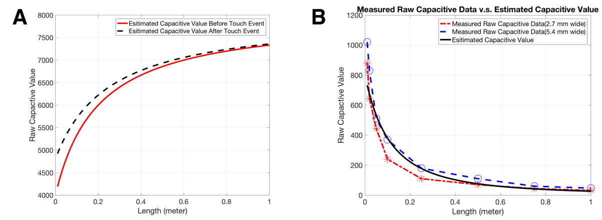


**Figure 10. The Compare between the measured raw capacitive data and estimated capacitive value.**

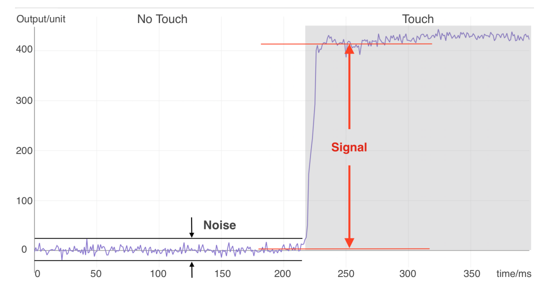


**Figure 11. The calculation of SNR with raw capacitive value from a Huawei P20 phone.**

counts. Similarly, when a finger is present, the system continues to measure the capacitance in order to establish an average value for the "touch" signal. In this case, the SNR is 18.1:1.

Table 1 shows the P20 SNR value of the 4 materials at different length with the same width of 2.7 mm. To extract the touch signal from the background noise effectively, the SNR should be greater than an SNR threshold (1.0 in our case). In general, the effective coverage range reaches to 1 meter for a Huawei P20 phone despite different materials.

| Length[m] | 0.02 | 0.05 | 0.25 | 0.50 | 0.75 | 1.00 | 1.25 |
|---|---|---|---|---|---|---|---|
| Copper Tape | 23.6 | 18.1 | 10.5 | 5.5 | 3.2 | 2.1 | 1.0 |
| ITO Film | 22.2 | 17.7 | 9.7 | 3.7 | 2.3 | 1.5 | 0.4 |
| Carbon Paint | 26.4 | 17.6 | 8.0 | 2.7 | 2.1 | 1.3 | 0.3 |
| Silver Ink | 25.5 | 18.4 | 9.0 | 2.9 | 2.4 | 1.7 | 0.7 |

**Table 1. P20 SNR value of the 4 materials at different length.**

Table 2 shows the P10 SNR value of the 4 materials at different length with the width of 2.7 mm. We set the SNR threshold as 1.0. Thus, P10 phone works effectively in a larger distance than P20 phone, which is 2 meters despite different materials. Except for exploring the effect of the length on the signal strength, we show that attached strip's width has significant effect on the touch signal strength ($F_{(3,132)} = 189, p < .001$). Shown in Figure 9 and Table 3, the signal strength increases as the attached strip goes wider. Considering the resolution (amount of sensing nodes) and the effectiveness of the signal strength, we recommend of the single node's effective width that is 2.7 mm.

Despite the effect of length and width on the signal strength, we proved that all the four commercially available materials work for *FlexTouch*. In the meanwhile, our approach can be

| Length[m] | 0.05 | 0.25 | 0.50 | 1.00 | 1.50 | 2.00 | 2.50 |
|---|---|---|---|---|---|---|---|
| Copper Tape | 32.5 | 7.0 | 6.0 | 2.6 | 1.9 | 1.2 | 1.3 |
| ITO Film | 28.6 | 6.6 | 6.1 | 2.4 | 1.7 | 1.2 | 0.7 |
| Carbon Paint | 24.1 | 5.2 | 4.4 | 2.2 | 1.5 | 1.1 | 0.6 |
| Silver Ink | 27.6 | 7.1 | 5.7 | 3.0 | 1.9 | 1.5 | 1.0 |

**Table 2. P10 SNR value of the 4 materials at different length.**

| width[mm]/length[m] | 1.4/1 | 2.7/1 | 5.4/1 |
|---|---|---|---|
| Copper Tape | 20 | 32 | 47 |
| ITO Film | 25 | 68 | 36 |
| Carbon Paint | 30 | 35 | 41 |
| Silver Ink | 29 | 45 | 41 |

**Table 3. The signal Strength of the P20 touchscreen increases as the extension strip's width increases.**

applied to different kinds of phones embedded with various of touchscreens.

### Detecting Everyday Objects' Presence

Not only the human body, but also everyday objects contain capacitance that can draw electric current from the touchscreen. In this section, we explore and prove the feasibility of detecting everyday objects' presence with *FlexTouch*.

#### *Evaluation*

We attached a $5cm \times 5cm$ square copper foil tape connected with a $20cm$ long $2.7mm$ wide copper strip to the P20 phone that is placed on a rubber sheet. We evaluated the signal strength (the change of the raw capacitive data of the touchscreen) when different objects are presented on the square. We selected 13 different kinds of example everyday objects made of metal, glass, plastic, paper or rubber et.al. The testing procedure is as follow:

1) We log the raw data for later analysis by clicking the start button.

2) We placed the randomly selected object on the square copper foil tape for 5 seconds. We picked up and re-placed the object for 5 times. Then we stopped the logging function.

3) We changed to next randomly selected object and repeat step 2) until we collected 5 data-set containing at least 5 seconds raw data for each object.

4) We repeat step 1) to 3) for 3 times.

#### *Result*

Figure 12 shows the signal strength of the presence of the selected 13 example everyday objects. We draw the conclusion that *FlexTouch* can detect everyday object's touch/contact event through the change of the capacitve relevant value of the sensing node on the touchscreen.

Besides the presence of the object, *FlexTouch* reports the capacitive signature of the object with mutual capacitance measurements. This provides us the possibility of distinguishing different object states. For instance, the capacitance can reflect the different amount of water contained in plastic cup, which we can utilized to monitor liquid level. We demonstrate related application in the next section.

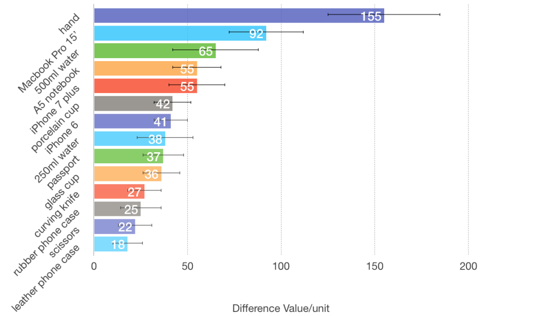


**Figure 12. The signal strength varies when placing different everyday object on the extended sensing node.**

## EXAMPLE APPLICATIONS

### Gesture sensing on the edge of the phone

*FlexTouch* extends the capacitive touch sensing capabilities to around the phone edge to enable hand gesture sensing. This extend interactive sensing area without blocking the digital contents. We support sensing 4 different hand gestures as represented in Figure 13. We also demonstrate an example where *FlexTouch* detects specific hand gestures to trigger applications such as photo apps. In addition, *FlexTouch* can sense and differentiate between left and right hands of users to naturally arrange type interfaces.

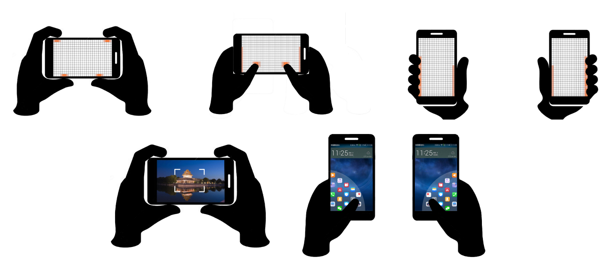

**Figure 13. *FlexTouch*åžŤçŤÍçd'žä¿ŃâĂŤâĂŤæĽŃæŁŞåğ£åŁ£çŽĎæčĂæţŃ**

#### *User Evaluation*

To evaluate the classification accuracy, we recruited 8 participants (4 females, average age 27) who were compensated \$10 for the user testing. They participated in 1 practice session and 5 data collection sessions. The whole procedure takes around 20 minutes. The order of the grasp gestures is randomized in each session. In each session, the participant is asked to pick the phone up from the desk and perform the asked grasp gesture for 5 times. We logged the raw capacitive data of the Huawei P20's touchscreen for offline analysis and classification.

#### *Result*

In total, we collected 200 sets of data cross 8 users for each of the 5 grasp gestures (including placing the phone on the table). Each set of data contains a certain time period of the raw image data ($32 \times 16 = 512px$).The data used for the machine learning is averaged with randomly selected 0.5-second of the raw image data when a certain posture is performed. The learning parameters are set with a 10 fold cross-validation using LIBSVM to classify the grasping gesture. The average classification accuracy for 5 grasp gestures (placing on the table, left-handed grasping, right-handed grasping, two-hand horizontally grasping and photo app launching gesture) reaches to 95.6%.

### Touch interaction on the back of the phone

*FlexTouch* can also extend the capacitive sensing capabilities to the back of the phone. This allows user to interact with a phone while it is placed in the pocket. In Figure 14, we demonstrate an application where users can silence their phone during meetings leveraging capacitive touch enabled by *FlexTouch* on the back of the phone. Please refer to the evaluation section for detailed implemention and study results.

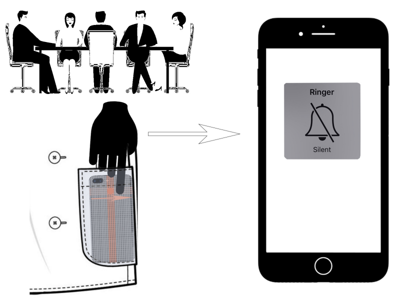


**Figure 14. Touch Interaction on the back of the phone while placed inside the pocket to silence phone during meetings**

### Full Size Keyboard

In Figure 15. we designed a 29-key keyboard layout including character 'A'-'Z', *Space, Enter,* and *Backspace*. We fabricated three keyboards with different printed materials (carbon ink, ITO, silver ink) based on the designed layout. We utilized 29 pixels out of 32 along the edge of Huawei P20, and every key is linked to one sensing node on the screen. This allow us to enable full scale keyboard which can be easily attached onto the phone.

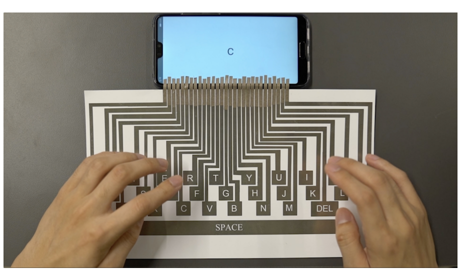


**Figure 15. Inkject printed full size keyboard that can be easily attached to the phone**

### Phone based VR/AR touch interactions

Phone based VR platform like the Google cardboard project mounts phones onto cheap and disposable cardboards for VR/AR applications. Such approach greatly lowered the barrier for VR hardware and allows easy access for developers to test out their VR/AR ideas. However, given the design of the cardboard approach, the touch screen is completely covered by the case and there is no easy way for user to interact with digital contents. Figure 16 demonstrates an example where *FlexTouch* wires out touch screen of phone to allow for touch interaction for phone based VR by allowing touch interaction on the cardboard surfaces on the back of the phone.

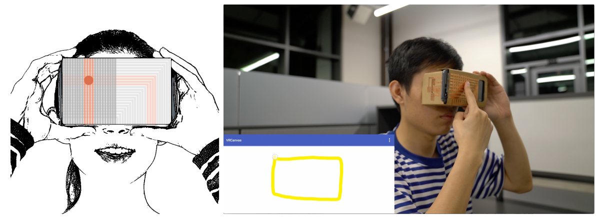

**Figure 16. Enhancing Phone VR applications with 2D touch sensing area on the back of the phone**

### Yoga Mat

The sensing range of *FlexTouch* allows it to extend to larger sensing areas (>1m) such as the yoga mat. Based on users capacitive profile when doing working out on the mat, *FlexTouch* can detect and classify different user postures. Based on this functionality, we can build application to track users fine-grain physical activities. In addition, other ambient platforms can leverage this data to create smart applications. For example, smart home systems can adjust ambient lighting, temperature and music volume according to user's activity on the yoga mat. As shown in figure17, we built a $5 \times 10$ 2D cover on a standard yoga mat with ITO strips, which is able to classify 5 different yoga postures (lord of the dance pose, plank, high lunge variation, camel pose, lotus pose).

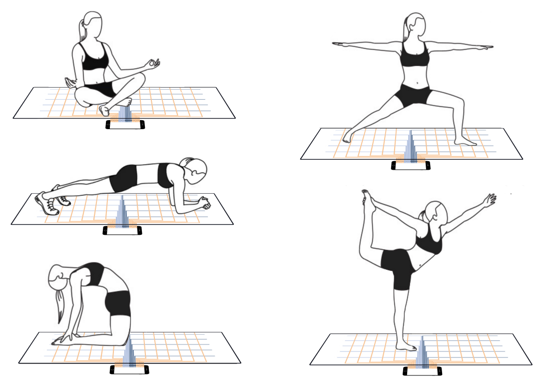

**Figure 17. Recognizing user's posture on the yoga mat built by *FlexTouch*.**

#### *User Evaluation*

We recruited 4 participants (all males, age around 24, height around 25) who were compensated $20 for the user testing to repeat 5 postures (lord of the dance pose, plank, high lunge variation, camel pose, lotus pose) 25 times each. In the whole session, each participant was asked to perform one posture out of five randomly and keep the posture for 5 seconds. We logged the raw capacitive data from huawei P20 touchscreen and collected 25 data points for each posture from each participant.

#### *Result*

The whole dataset contains 100 data points for each posture and each data point consists of 32 raw capacitive data (the left-most column of the screen). The dataset was randomly splitted into 2 subsets (80% for training and 20% for testing). All data was labeled manually and was trained on a LightGBM classifier using the training data. Finally we achieved an average accuracy of 71.7% across 5 postures on our test set.

### Smart Desk

Given the flexible and passive nature of FlexTouch, we envision it to be integrated into other large surfaces such as table and desk surfaces to detect the objects being places onto these surfaces as well as human interaction with these objects (Figure 18). In addition, we can detect the specific state of objects via its capacitive signature. For example, we can detect how much water is left in the bottle by sensing mutual capacitance variations caused by changes in the liquid volume. Please refer to the evaluation section for detailed implementation and study results.


**Figure 18. Detecting objects on 2d surfaces as well as user interaction with these objects**

## DISCUSSION AND FUTURE WORK

*FlexTouch* enables large-scale interaction sensing beyond the spatial constraints of capacitive touchscreens using a passive low-cost conductive film. We show that our technique is compatible with various conductive materials as well as fabrication methods. *FlexTouch* supports 2D continuous touch interaction and activity detection with a large coverage range (>1 meter) as well as object presence and state sensing. In this section, we address some findings, design guidelines and future works.

### Gap between conductive strips

To minimize the effect between sensing electrodes, we suggest a gap larger than 1 mm between strips on the strip array film that is attached on the touchscreen. In the meanwhile, we used the 2D high resolution single-touch tracking listed in Figure 6, we suggest a gap between the upper and bottom layers. We used 1 mm thin paper to isolate the two crossed strips.

### Coding the Application with Patterned Strip Array

The conductive strip will increase the raw capacitive value of the attached sensing nodes. Leveraging different strip pattern design, *FlexTouch* can distinguish different applications once the circuit-like 2D patterns are attached on the screen. We will explore the feasibility in the future work.

### The Effect of Ground

To better filter the background noise, modern touch screen phones usually embed one layer of local ground on the back of the phone. When the user hold the phone with one hand contacting with the back of the phone, the coupling capacitance between the finger and the touchscreen become stronger. Our tests showed that the signal strength increases significantly when the user has direct contact with the back of the touchscreen phone. Similarly, the signal strength increases when the local ground is connected to the ground through a charging line. Therefore, we can extend the coverage range further away leveraging the design of the local ground.

### The Effect of Resistance of the Extended Material

We identified four kinds of materials for *FlexTouch* including copper foil tape, ITO PET plastic film, carbon paint and silver nanoparticle ink. The resistance of these materials varies from 0.2Ω per square centimeter to several kilos Ω per square centimeter. We did not discuss the effect of the material's resistance in the *Working Principle* section. However, the capacitance introduced by the material will have significant effect on the signal strength once it reaches to kilos Ω according to the simulation we conducted. We will explore the feasibility of utilizing both the capacitance and resistance introduced by the extension conductive 2D patterns in the future.

### Extending more Sensing Nodes

Currently only the sensing nodes on the edge of the touchscreen have been used (94 nodes for P20 phone and 88 nodes for P10 phone). In the future, We can extend more nodes by deploying a 3D layout (Figure19). Multiple layers can be attached to different columns of the touchscreen with some isolating materials. By activating more sensing nodes, we can increase the resolution and range of our applications, which provide us with more possibilities.

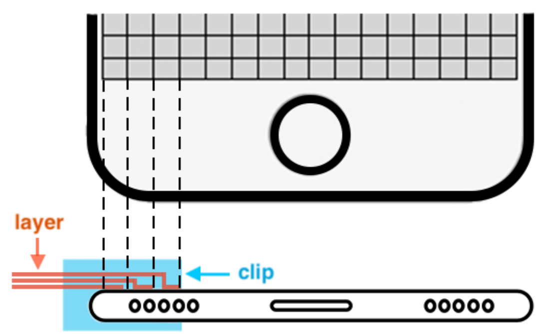


**Figure 19. Possible design with more layers.**

## CONCLUSION

*FlexTouch* enables passive and light-weight interaction interfaces by extending the sensing capability of the capacitive touchscreen to ambient surfaces. It can support a variety of interaction possibilities by attaching custom conductive 2D circuit-like film to the touchscreen. We demonstrate that our technique allows for easy fabrication of interfaces via a variety of commercially available conductive materials. *FlexTouch* can not only support continuous 1D or 2D touch interaction, but also recognize human postures and presence of every-day objects and its states. We evaluated the maximum covering area (> 1 meter) through series of user studies. Then we demonstrate the versatility and feasibility of *FlexTouch* by implementing and evaluating applications in the domain of hand/body posture sensing, object and activity detection as well as enhanced VR/AR .

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