

基于触摸屏与柔性导电材料的大 规模触摸交互技术研究

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

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摘要

目前基于感应电容的触摸屏交互已得到大规模应用，极大改变了人机交互模式，使人机交互更自然更、高效。然而，手机、平板电脑等电容屏设备的交互面积仍十分有限，很多情况下无法满足人们对更大规模的触摸交互需求，如桌面交互。如果电容屏过大，第一不方便携带，第二制造成本也会大幅上升。如何在不改变现有触摸屏设备的基础上增加交互面积，成为了当前人机交互领域的一个热点研究方向，而本文的工作则是研究如何利用基于以手机为代表的智能交互设备的计算能力和电容特性，以低成本的方式将人机交互的平面从屏幕表面解放出来，扩展至计算设备周围更大的平面，满足用户大规模交互需求。

本文提出了一种新的技术，使用廉价易得的导电材料即可在不改变交互设备本身的前提下大大增加交互面积，我们称为 *FlexTouch*。我们利用柔性导电材料如铜铂线，将触摸屏的边缘与交互平面通过定制化的 2D 纸电路相连接，从而实现大规模交互，这种交互技术无需对已有设备做任何改造。我们通过实验证明了 *FlexTouch* 可应用于多种导电材料，包括铜箔胶带（copper foil tape）、纳米银墨（silver nanoparticle ink）、氧化铟锡薄膜（ITO film）和碳涂料（carbon paint），同时也适用于多种制造工艺，包括剪切技术、表面涂层技术和油墨喷印技术。我们的一系列研究和实验表明，*FlexTouch* 可识别 4 米以内的人体触摸和 2 米以内的物体感知。最后，基于我们的识别原理和实验结果，我们展示了 *FlexTouch* 在不同场景下应用的可行性，例如可以在瑜伽垫上识别人体姿势，在桌面上检测人与水杯等物体的状态，以及在跑步机上检测人体的运动情况等。*Flextouch* 相比于之前的技术主要有以下优势：1) 交互设备无需外部供电，可直接利用手机等智能设备的电源；2) 改造简单，几乎无需改造交互平面，只需通过设计好的交互接口使手机/平板电脑与交互平面连接即可；3) 改造成本低，实验所使用的柔性导电材料廉价易得。4) 同时支持一维和二维交互，增加了有限面积内的感应密度。

本文重点研究了 1) 不同导电材料对电容信号的影响，给出了不同材料的交互面积上限，为应用设计给出了理论指导；2) 引入接地线后对电容感应信号的影响，进一步增强了信号识别率，为大范围交互提供了可能；3) 多种不同的大范围纸电路设计和相应的交互应用场景，为更多不同模态的交互模式提供了参考；4) 各种示例应用的在鲁棒性、准确性等方面的实际测试表现，证明了技术的可行性。

关键词：电容感应；交互接口；低成本制造；2D 电路设计；大规模交互

Abstract

Capacitive Touchscreen has been widely adopted in recent ten years, greatly improved the effectiveness of human-computer interaction, enabling more natural, more efficient interaction patterns. However, the interaction area of smartphone and tablet is still limited to the area of screen surface, which in many cases cannot meet the demands of large-scale interaction, such as table-based interaction. A straightforward solution to this issue is naively enlarge the area of touchscreen. However, there are at least two drawbacks: 1) Portability and 2) Cost Effectiveness. How to fully leverage existing smart device to enable large-scale interaction without modifications of smart device itself has become a popular research topic in Human-Computer Interaction.

In this paper, we present *FlexTouch*, a technique that enables large-scale interaction sensing beyond the spatial constraints of capacitive touchscreens using passive low-cost conductive materials. This is achieved by customizing 2D circuit-like patterns with an array of conductive strips that can be easily attached to the sensing nodes on the edge of the touchscreen. This retrofit requires no hardware modification to the device. *FlexTouch* is compatible with various conductive materials (copper foil tape, silver nanoparticle ink, ITO frame, and carbon paint), as well as fabrication methods (cutting, coating, and ink-jet printing). We demonstrate that *FlexTouch* can support long-range touch sensing for up to 4 meters and everyday object presence detection for up to 2 meters. Finally, we show the versatility and feasibility of *FlexTouch* through applications such as whole-body posture recognition, human-object interaction as well as enhanced fitness training experiences. *FlexTouch* has four advantages: 1) No need of external power source. 2) Simple fabrication. 3) Low cost. 4) 2D patterns that enables more sensing nodes in limited area.

Our major contributions are 1) Design-scope study of interaction with different materials. 2) Analysis of grounding strip effect. 3) Example applications and scenarios. 4) Evaluation on robustness and accuracy of different scenarios.

Key Words: Capacitive Sensing; Touch Interface; Low-cost Fabrication; 2D Circuit Pattern; Large-Scale Interaction

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Chapter 1 Introduction

1.1 Background

Capacitive touchscreens are one of the most profound interaction interfaces on modern devices. Thanks to the sensitivity and robustness of capacitive touchscreen, it is able to provide seamless, intuitive interaction between users and digital media. Furthermore, comparing with resistive touchscreen, the possibility of multitouch enabled by capacitive touchscreen as well as the unbreakable feature makes it a dominance in the touchscreen market. However, capacitive screen is still relatively expensive comparing with resistive touchscreen. Though manufacturers launched various different large-scale capacitive-screen products such as touchscreen wall, touchscreen table, touchscreen board, etc (Fig 1.1), the price of these products are unaffordable to ordinary people, due to the cost of capacitive touchscreen per unit area. As the most affordable touchscreen products, smartphone's touch interface is still limited to the area where touch sensors are embedded, constraining natural user interactions to the surfaces of these smart devices. Therefore, simply scaling touchscreens to large surfaces and everyday objects is expensive and challenging, which limits its wider adoption in the Internet of Things applications. How to scale the sensing capability of small capacitive touchscreen to larger area in a low-cost manner to enable large-scale touch interactions has become a popular research topic in the field of Human Computer Interaction.



Figure 1.1 Capacitive touchscreen products: iphone (A). multitouch arcade touchscreen game table (B) interactive whiteboard (C). touchscreen Wall (D).

Researchers have explored enabling touch interfaces on everyday surfaces or objects [1-7] with various sensing techniques. However, to recognize the touch events on every-

day objects such as toys, it requires different embedded sensors, such as resonate sensor, capacitive touch sensor, volatage sensor, and camera.

As we can see, these prior works require dedicated sensing platforms such as Arduino to power touch interfaces and to enable wireless communication with digital devices. These requirements prevent end-users from easily fabricating customizable touch interfaces. Users need to dedicate coporate the sensors with the touch interface and need to build companion computer program for event recognition, which significantly raise the barrier for fast prototyping.

As an alternative, in recent 5 years, researchers are trying to leverage the existing sensors that are available to everyone to empower everyday objects with sensing capability. Thanks to the ubiquity of capacitive touchscreen device such as smartphone, ipad and latop, researchers have proposed extending the capacitive sensing capability of these touchscreen devices to ambient surfaces through conductive strips. These systems can support interactions such as touch widgets [8-10], trackpad [11] as well as tangible interfaces [12-14]. However, though these systems is able to provide interaction beyond touchscreen surface, due to the lack of raw capacitance siganl, the smart device fail to distinguish the touch event between on-screen touch and off-screen touch, which will influence user's normal interaction on touchscreen such as click and slide. Additionally, these approaches can only support applications with very limited sensing range and fabrication materials. Furthermore, the feasibility of long-range capacitive sensing, the design scope, as well as the applications and user case haven't been fully explored.

Our work focuses on two parts: First, we study the feasibility of augmenting the interaction patterns of existing touchscreen device, such as backboard interaction, edge interaction, without disturbing user's on-screen interactions. We demonstrated that by capturing and analyzing the raw capaitance data of touchscreen device such as smartphone, we can configure a special capacitance threshold to accurately seperate on-screen touch event from off-screen touch event. Based on that, we proposed a series of applications to augment user's interaction experience with ambient surfaces of touchscreen devices (Fig 1.2). Second, we dive deeper into the study of large-scale capacitive sensing using existing capacitive touchscreen devices and conductive materials. Our study shows the possibility of large-scale capacitive sensing. We measured the sensing space of smartphone and proposed two major design patterns of touch interface. Furthermore, we presented example interactive applications of our large-scale sensing technique (Fig

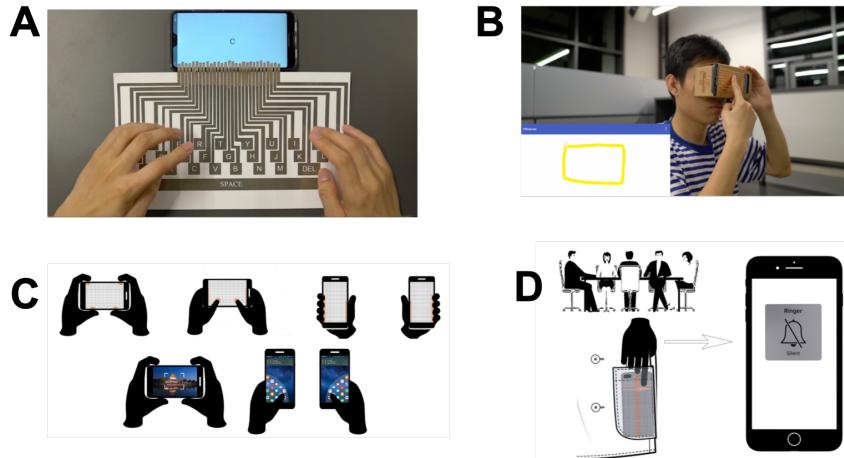


Figure 1.2 *FlexTouch* supports ambient interaction around touchscreen device surface. A: Full-size keyboard using silver nanoparticle ink-jet printing. B: Enhanced VR interaction of back of smartphone. C: Gesture sensing on edge of smartphone. D: Touch interaction on back of smartphone.

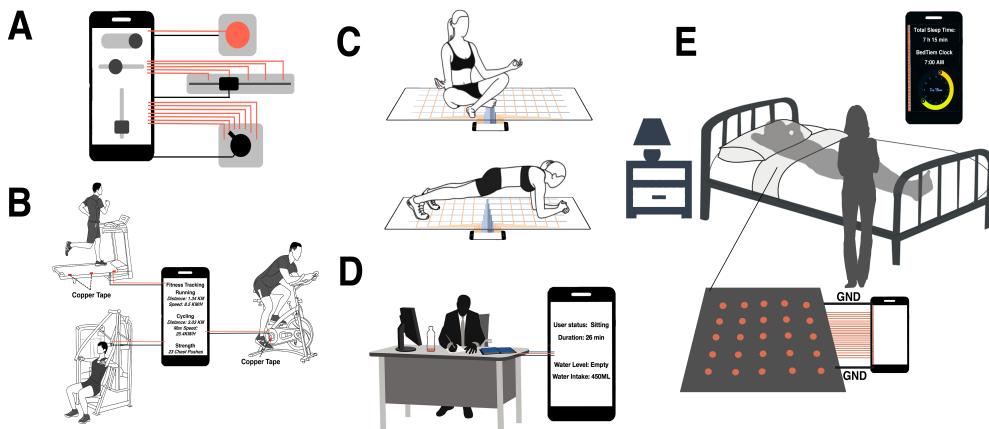


Figure 1.3 *FlexTouch* supports various large-scale applications with different configurations. A: Discrete and 1-dimension touch widgets sensing long-range touch events. B: Fitness tracking using designs in A for the count of repetitions, distance and speed measurement on a treadmill, cycling and chest exercise machine. C: Body posture detection on the yoga mat with a built-in capacitive sensing matrix in an X-Y layout. D: Smart desk application for object presence and user's state detection. E: Smart mattress for sleep monitoring with a one-on-one mapping node matrix from the touchscreen.

1.3), which is a good alternative of existing large-scale interaction devices such as touch table and touchboard.

1.2 Thesis Structure

In this paper, we present *FlexTouch*, a technique for distinguishing off-screen touch from on-screen touch as well as enabling long-range touch sensing interfaces beyond com-

mercial touchscreens by leveraging a variety of flexible conductive materials (Fig 1.2, Fig 1.3). *FlexTouch* utilizes simple fabrication techniques to create a variety of passive, conductive 2D-patterned touch interfaces that enable new health and wellness applications.

In chapter 2, we will introduce related work that is relevant to *FlexTouch*. First, we gathered the current literature aiming at enabling touch interaction on everyday surfaces and objects, including both small-scale and large-scale. We will introduce some techniques these papers applied such as capacitive sensing, volatage sensing, camera sensing, etc. Then we review some work specifically relevant to capacitive sensing beyond touchscreen surfaces. Finally, we discuss the limitation of prior work regarding capacitive sensing and room for innovation and improvement.

Chapter 3 lays out the theoretical principal of 2D capacitive sensing. We present equivalent circuit to explain the effect of attaching conductive materials on touchscreen as well as the effect of off-screen finger touch. Then we elaborate the reason why large-scale capacitive sensing is so difficult and why introducing local ground will amplify the capacitance signal. Based on the equivalent circuit, we give a reasonable assumption that the mutual capacitance scales with the area of extended conductive materials.

Chapter 4 first introduces the signal processing algorithm and procedures of recognizing touch event. Then, we propose several different conductive materials as well as fabrication methods for *FlexTouch* implementation. In particularly, we design a clip-on widget, which we called **plug and play** interface, that is able to connect the touchscreen with large interactive surface using copper foil tape.

Chapter 5 conducts a series of evalutaion of *FlexTouch*. The first experiment we conduct is observing the difference of signal pattern between on-screen and off-screen touch. Then we explore the relationship between sensing range and coverage area with different conductive materials, hardware and local ground. To step further into studying the effect of grounding strip, which includes the gap between grounding and signal strip, the width of grounding strip, and the conductivity of grounding strip. Finally, to explore the possibility of detecting the presence of everyday objects, we also evaluated the signal variance of touch event across different objects.

In chapter 6, we focus on real-word applications of *FlexTouch*. The applications of *FlexTouch* can be categorized into two different divisions. The first is what we called **touchscreen ambient interaction**, second is **larage-scale extendable interaction**. In

the first set of applications, we propose four different scenarios, that are direct augmentation of existing touch interactions around smartphones, such as hold-gesture sensing, backboard touch sensing, external plugin flexible keyboard and VR cardboard interaction. In the second part, we present also four common use cases including smart mattress, yoga mat fitness posture detection, fitness tracking, and smart desk. Additionally, we also conduct concrete user study and quantitative analysis on each application to guarantee the feasibility and robustness of *FlexTouch*.

As a summary of this paper, chapter 7 concludes our work on extending sensing capability of touchscreen surfaces and potential applications. Finally, it points out the future direction of our work from three perspectives.

1.3 Main Contributions

To summarize, some prior work focuses on enabling touch sensing on everyday objects with both regular and irregular shapes, while external sensors and computational board are necessary. Some other work attempts to leverage capacitive sensors embedded in modern smart devices to enable ambient interaction around touchscreens, but being aware of the fact that these ambient interactions only serve as augmentation or translation of existing on-screen touch, and the interaction area is constrained by the screen size.

Differing from prior work, we leverage the capacitive sensing capability of existing touchscreen to enable everyday-object sensing, off-screen event detection, and large-scale interaction. Our main contributions in this paper are as follow:

1. We differentiated the off-screen touch from on-screen touch, which enables recognizing user's off-screen touch event without disturbing normal on-screen touch event.
2. We created 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.
3. We enabled large-scale touch sensing up to 4 meters and objects' presence up to 2 meters away from the capacitive touchscreen to ambient surroundings by including the local ground in the external conductive pattern design.
4. We demonstrated that *FlexTouch* is easy to fabricate, assemble and use. The 2D circuit-like pattern is compatible with various conductive materials (copper foil tape, silver nanoparticle ink, ITO frames, and carbon paint), as well as fabrication methods (cutting, coating, and ink-jet printing). Furthermore, we proposed two easy attaching and

assembling approaches to connect the extension part to touchscreens.

5. We benchmarked the performance of *FlexTouch* through user studies. In particularly, we fully explored design variables such as materials, extension strips' width as well as gap distance between strips and evaluated their impact on the coverage distance of *FlexTouch*.

6. We demonstrated the versatility and feasibility of *FlexTouch* through multiple applications such as body posture sensing, object presence detection, enhanced fitness sensing applications, etc.

Chapter 2 Related Work

In this chapter, we first review a set of work that aims to enable touch interaction on everyday surfaces and objects. Then we dive deeper into prior work in the field of capacitive sensing closely related to *FlexTouch* to better position our work in the related literature.

2.1 Touch Interaction on Everyday Surfaces and Objects

Researchers have explored various methods and techniques to enable interactive interfaces on everyday surfaces and objects. One popular method to enable touch interactions, as shown in Fig. 2.1 is by projecting 2D user interfaces onto a surface and then recognize user interaction via computer vision technique [4,15-17]. For example, *WorldKit* system makes use of a paired projector and a depth camera to capture user's touch-based interaction on surfaces, enabling people to quickly instantiate any shapes of interface they like. To achieve this, the system also requires preconfiguration of functionality of different locations on the surface. Apparently, these solutions can support large-scale interactions which are suitable for fixed infrastructure. However, its power consumption and form factor still make it hard to fit into everyday mobile scenarios. Furthermore, the cost of the toolkit as well as the difficulty of setup also makes it far way from being popularized to the industry.

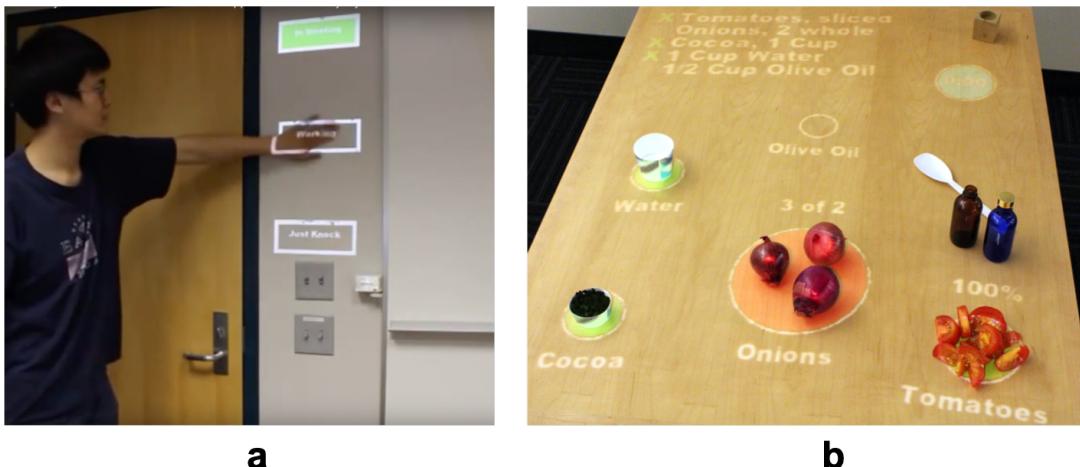


Figure 2.1 Example applications of vision-based large-scale interaction: a) notification message application. b) Kitchen application.

Touch interaction can also be supported by acoustic sensing. Ono's work is based on the difference of resonate properties of different objects [1]. As illustrated in Fig 2.2, by attaching a vibration speaker and a piezo-electric microphone, the system collects and amplify the vibration data and transmit it into a computational device. Then, by train a supervised pattern recognition model for recognizing different acoustic wave patterns, it is able to distinguish various touch events. Researchers have also explored recognizing a discrete set of touch events on everyday objects such as windows [18], desktops, and other surfaces [19]. However, these approaches can only be applied towards a small set of touch inputs like tapping or scratching on various materials. Last but not least, these approaches cannot live without dedicated sensing platforms to collect and transmit acoustic data from objects, which adds too much complexity to existing objects.

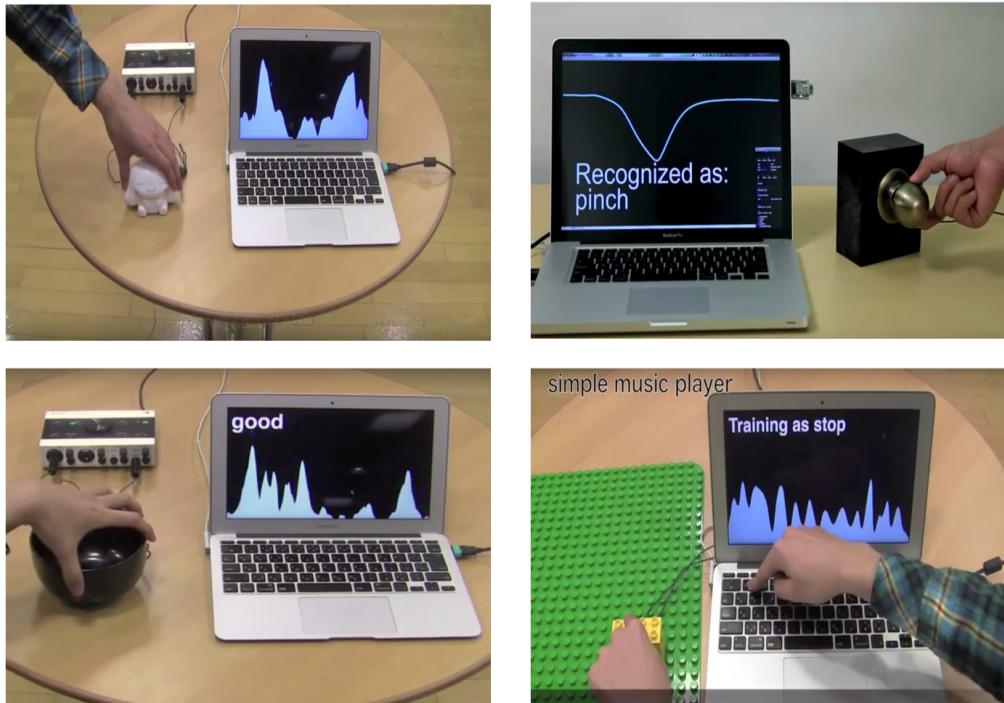


Figure 2.2 Touch and Activate: Adding interactivity of existing objects using active acoustic sensing

Another popular method is electromagnetic sensing. *SmartSkin* enabled multi-touch interaction on surfaces using a mesh-shaped capacitive sensor grid [5]. They make use of a capacitive sensor grid with size of 32×24 to detect touch events on a large-scale surface.

Electricick [7] and *Pulp Nonfiction* [20] enabled touch input on everyday surfaces and objects using Electric Field Tomography (EIT) with coated conductive materials on everyday surfaces and objects. As shown in Fig 2.4, by sensing the voltage difference

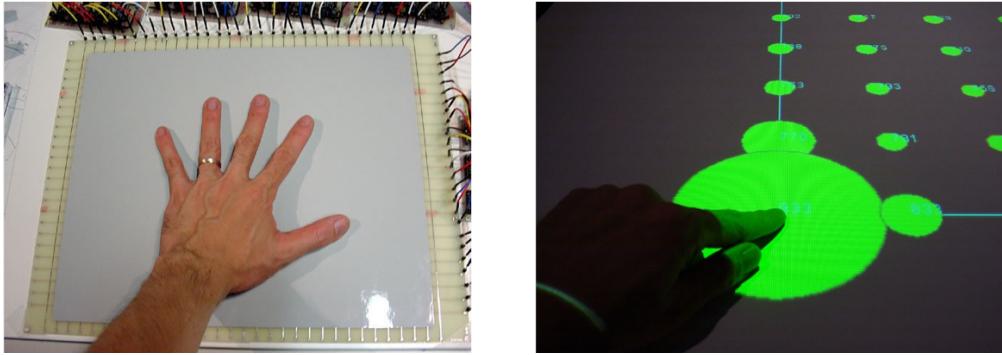


Figure 2.3 *SmartSkin* is embedded with dense capacitive sensors to achieve accurate touch sensing on flat surface.

between paired electrodes before and after touch, *Electrick* can accurately locate user's touch position as well as measuring the pressure of touch event.

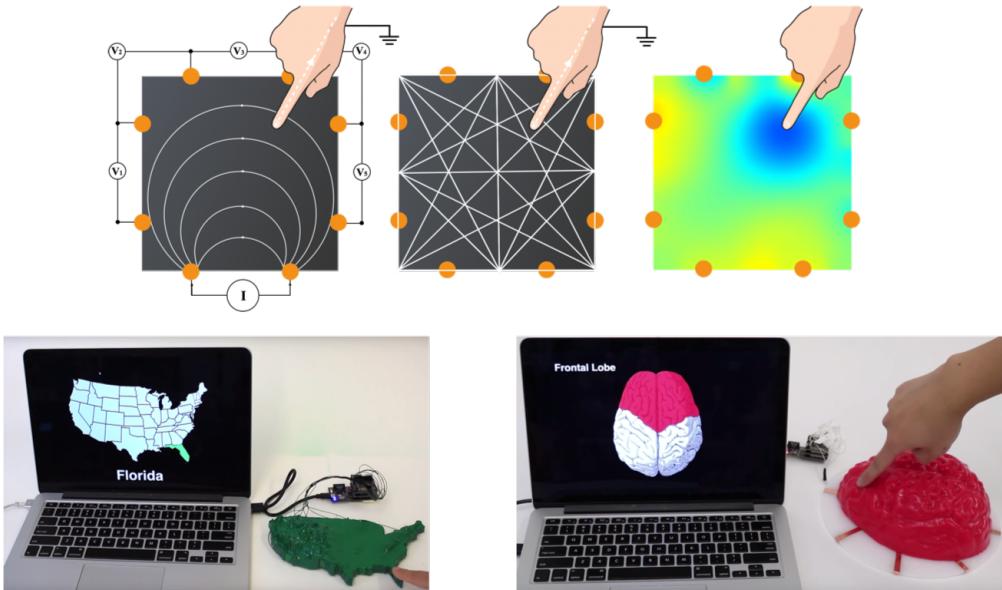


Figure 2.4 *Electrick*: Enabling low-cost touch sensing on any shapes of surfaces by using electric field tomography

Touche [3] enhances touch interface on the human body or everyday objects by measuring the electrical profiles with a frequency-sweep signal. *Midas* [21] fabricated customized capacitive touch sensors to prototyping interactive object with a circuit board milling machine. *Cutable* [6] goes a big step further in customization, which allows customizable shapes of sensor by cutting. *Wall++* [22] enabled large-scale touch interaction on the wall for activity recognition. Other prior work also explored printing custom-shaped capacitive sensors [23-26]. These prior works demonstrated very promising results, again however, they rely heavily on dedicated sensing platforms and customized embedded systems to provide power supply, external sensors, signal processing, and commu-

nication modules. These requirements create barriers for end-users to easily fabricate customized touch interfaces.

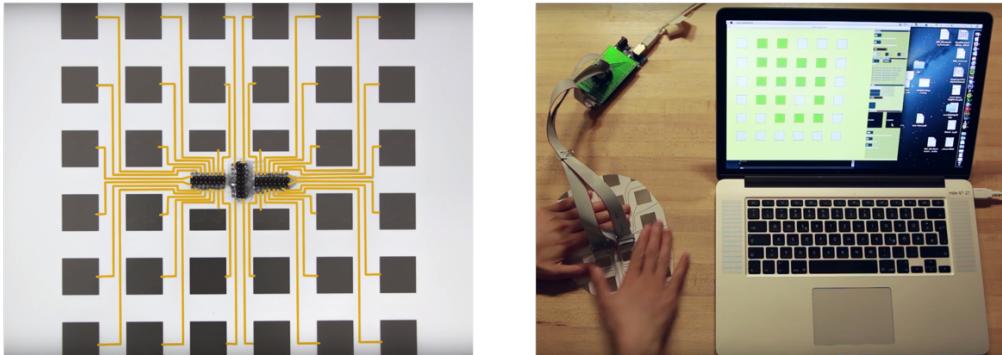


Figure 2.5 A cuttable multitouch sensor using tree topology electrodes and flexible materials.

2.2 Capacitive Touch Interaction Sensing beyond Touchscreens

Capacitive sensing was introduced into the field of HCI over two decades ago. Recently, Grosse-Puppendahl and his colleagues reviewed and summarized past researches related to capacitive sensing theories and techniques [27]. Among all the capacitive sensing methods, shunt mode sensing is the most widely spread approach in implementing 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 (Fig 2.6). Each node is a high-resolution continuous capacitance measurement sensor. Obtaining the low-level capacitive data from the touchscreen provides us with more capability beyond binary finger touch sensing.

Similar to our approach, *BodyPrint* [28] and *CapAuth* [29] (Fig 2.7) combined capacitive touchscreens with machine learning classifiers to provide authentication and even identification of users by recognizing different patterns of capacitance image on touchscreen. *PalmTouch* enabled the palm as an additional input modality to enhance mobile interaction [30]. Researchers also explored the potential of using the raw capacitive data of touchscreens to support sensing of tangible 3D-printed gadgets on top of the screen [12-14]. While these prior works share the same raw capacitance signal as our approach, we focus on fabricating conductive interfaces to support large-scale, flexible touch interfaces on the ambient surfaces connected to touchscreens.

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 have ex-

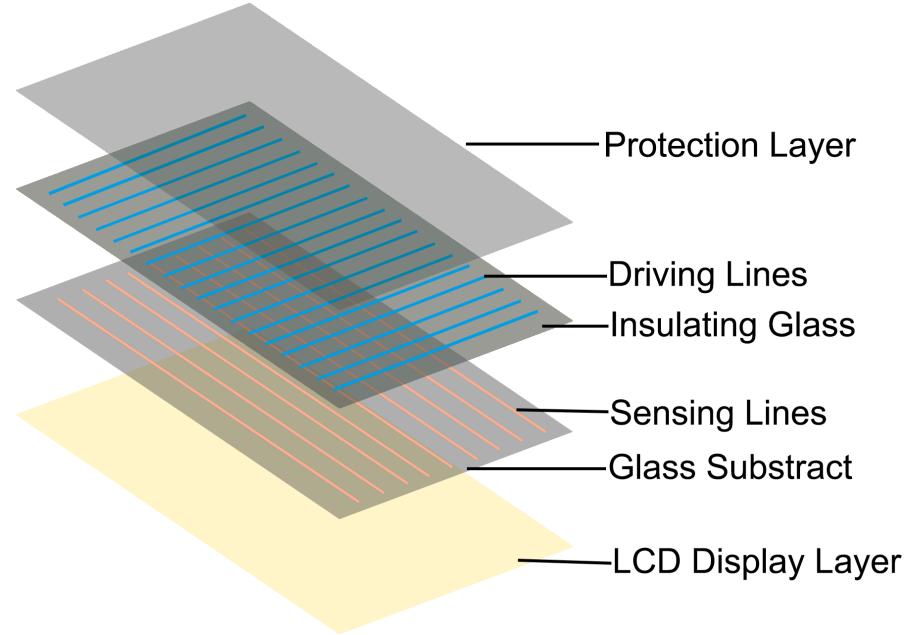


Figure 2.6 The multi-layer structure of mutual capacitance touchscreen.

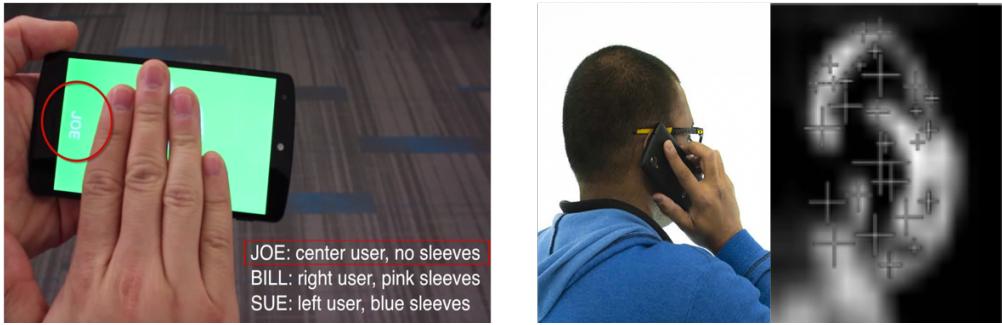


Figure 2.7 User authentications using capacitive sensors on touchscreen.

plored attaching capacitive sensors to mobile devices to enable interactive user applications. iGrasp^[31] and IrotateGrasp^[32] 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, the requirement of external sensors, power source and processing unit create barriers for massive adoption.

Researchers also explored leveraging the built-in sensors to enhance the interaction on or around the touchscreen. Acoustumrments^[33] 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^[34] enabled touch interface on surrounding surfaces using build-in proximity and ambient light sensors. Wang and colleagues presented a virtual keyboard technique on the surrounding surface of mobile devices through harnessing

multipath fading with multiple built-in microphones [35].

In close proximity to our work, researchers explored methods extending touch interaction from the touchscreen to ambient objects or surfaces with conductive materials. *Clip-on Gadgets* extended capacitive touchpoints on the phone to physical controllers via conductive materials [36]. Kato and his colleagues went a step further, fabricating 3D-printed conductive gadgets with haptic feedback patterns [10]. User interaction with these gadgets was detected via the capacitive screen when they were placed onto the phone. In addition, they also presented a technique named *ExtensionSticker* which allowed touch sensing to be transferred to ambient surfaces [8-9]. However, without accessing the raw capacitive data, *ExtensionSticker* could not support large-scale touch interfaces. Long-range conductive strips attached on touchscreens would be recognized by the built-in touch detector as finger touch events, which prevents the detection of real touches on the strip. As a result, these extension-sticker techniques only allow for near-range touch sensing interfaces. Recently, Gao and Ikematsu demonstrated the feasibility of using 1D conductive ink strips or ABS filament arrays sensing 2D finger positioning [11,37] through measuring the resistance introduced to the touchscreen’s sensing circuit. However, they only demonstrated short-range applications such as 2D finger tracking on phone-based VR headsets or 1D touch bar using a single sensor node. Though these work already provides diverse interaction surrounding smartphone, they are not able to differentiate off-screen touch and on-screen touch. In some cases when user is conducting on-screen touch, it is possible for the smart device to mistakenly recognize the event as off-screen touch due to the similarity of capacitive image pattern.

In contrast with prior work, *FlexTouch* can perfectly differentiate on-screen touch from off-screen touch based on our study of raw capacitance signal of these two interaction modes. More importantly, *FlexTouch* allows users to create large-scale, passive, flexible and customizable touch sensitive gadgets that can be easily attached to the mobile touchscreen for rapid prototyping of interactive applications. To further empower large-scale capacitive sensing, we leverage the local ground plane of the touchscreen to boost capacitance signal strength that enables touch-sensing coverage range up to 4 meters and objects’ presence sensing range up to 2 meters, which we think is a significant milestone in large-scale touchscreen-based capacitive sensing. This capability allows *FlexTouch* to support large-scale sensing applications such as touch sensitive yoga mats or bed mattresses with signal processing and machine learning techniques. These advancements

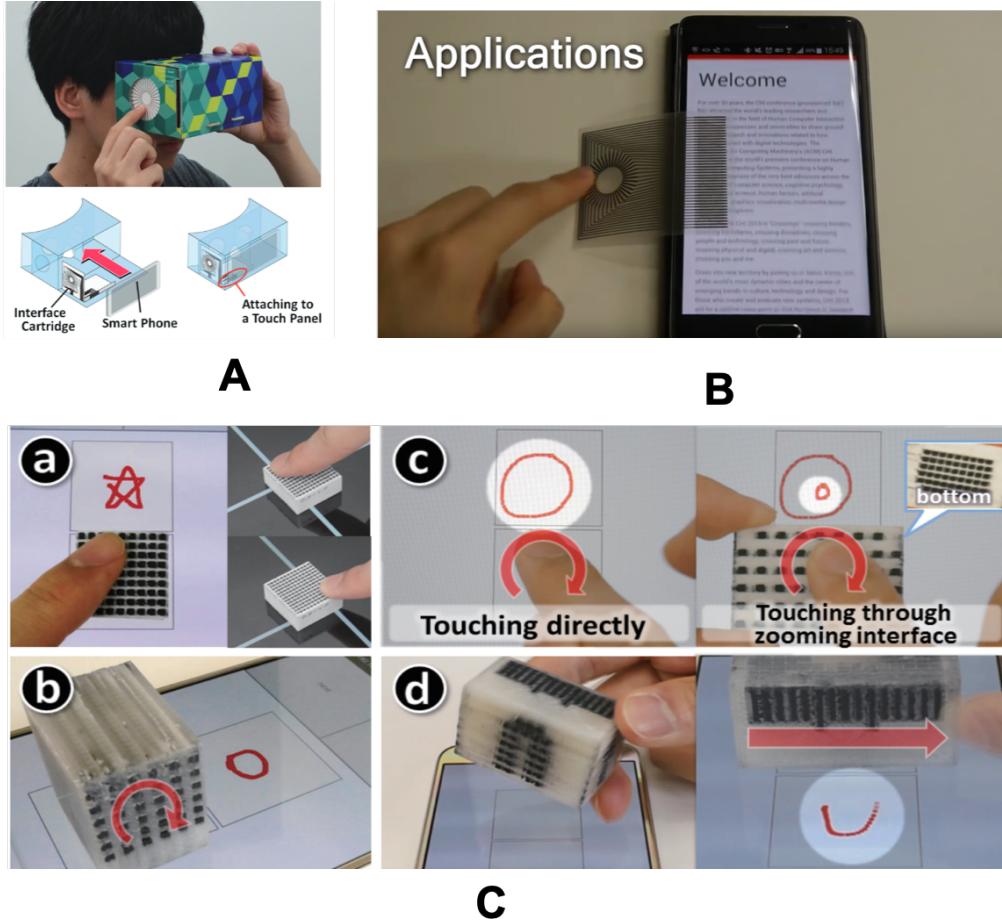


Figure 2.8 Extending touch interaction to ambient objects using strip-like conductive materials. A: Mobile head-mounted display with proprietary controller. B: Smartphone side-input controller. C: Conductive gadget that enables touching, zooming and sliding interaction.

provide *FlexTouch* with potentials to be applicable to a variety of new touch sensing applications beyond prior works.

2.3 Summary

In this chapter, we walked through the body of literature related to our work, and introduced several different touch sensing techniques, ranging from acoustic sensing, electromagnetic sensing to capacitive sensing, that are applied to augment the interactivity of everyday surfaces and objects. Some work already supports large-scale touch sensing, but dedicated sensing platform and external power are essential to these systems. Then we took a closer look at capacitive sensing beyond touchscreens. We introduced some work that innovatively leverage the embedded sensors in smartphone for user authentications. Coupled with smartphone, well-designed touch interface like *ExtentionSticker* and

conductive gadget make full use of touchscreen that provide user with a more natural and efficient way of basic interactions around smartphone. However, these interactions are only augmentation or a form of translation of on-screen touch, which heavily relies on existing touch events such as click, and does not allow user to define customizable off-screen interaction. Finally, we introduced our work *FlexTouch*, which specifically solve the off-screen detection problem as well as interaction scaling problem.

Chapter 3 FlexTouch Working Principles

3.1 Sensing Principle of Touchscreen

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 [38]. The touch panel consists of multiple layers above the display screen as demonstrated in Figure 2.6. 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.

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) [39]. 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 3.1 A) shows.

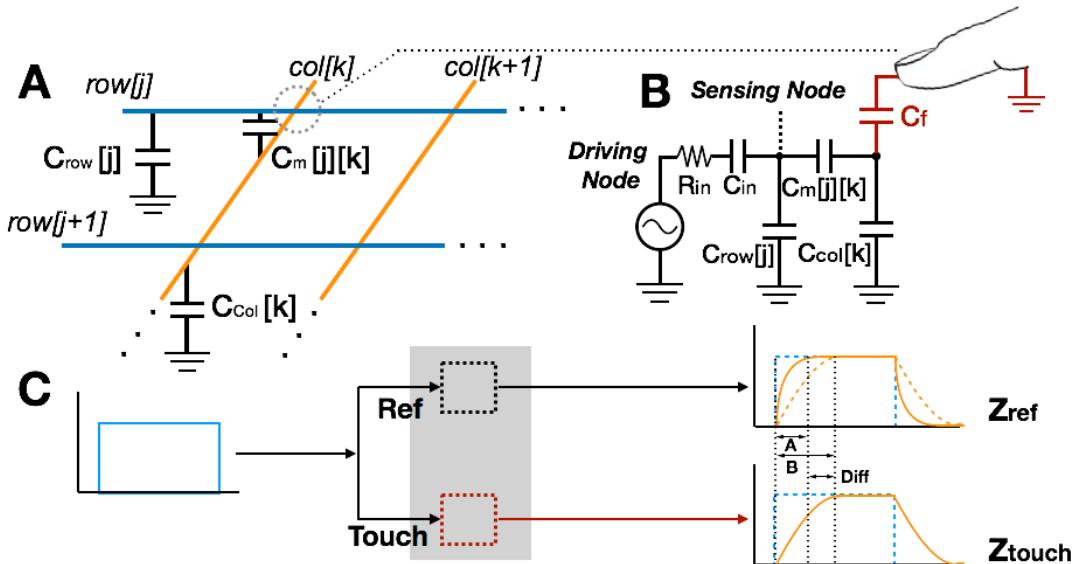


Figure 3.1 A: Representation of capacitive sensing row-column matrix structure B: Equivalent circuit of each junction. C: The measurement of capacitance of each junction.

The finger touch increases the mutual capacitance of the touched electrodes. To de-

tect 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 3.1 B) and C). The standard method to detect the mutual capacitance of each junction is to measure the charging time to reach a certain voltage threshold between the driving line and the sensing line.

3.2 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*.

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 3.2 ,the measurement output from each junction node is positively correlated to mutual capacitance. In Figure 3.2A, the measurement of junction #16 is 2 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 983. And when a user is pressing onto the thread, the measurement is further increased to 1090 accordingly. If user press on both signal strip and grounding strip, the signal significantly increase to 1453, which demonstrated the amplifying effect of grounding strip.

Any conductive object in contact with the touchscreen draws currents passing from the driving line (transmitting electrode) to the sensing line (receiving electrode) at each junction. The control IC of the touchscreen is designed to measure this leaking current to detect touch events. Prior work introduced an extension tape enlarging the transmitting electrode to boost the touch sensing distance [8-9,11,37]. In Kato's work, the signal transmitted into the conductive tape returns to the device through an environmental coupling path, called ***virtual ground***. To further extend the capacitive sensing distance, we intro-

duce the ground of the phone, the ***local ground***, into the extended circuit. Therefore, we can short this coupling path with another conductive tape directly passing the signal back to the touchscreen device. Although the local ground can be extended from the charging port, we use the back panel of the touchscreen device since it's easier to assemble as illustrated in Fig. 4.6 C. We can simplify the structure made of the attached conductive tape, the back panel, and the inner local ground circuit as one large capacitor. Here, we define two types of extension strips: 1) ***signal strip***, which is attached to the touchscreen sensor node, and 2) ***grounding strip*** which extends the local ground of the touchscreen.

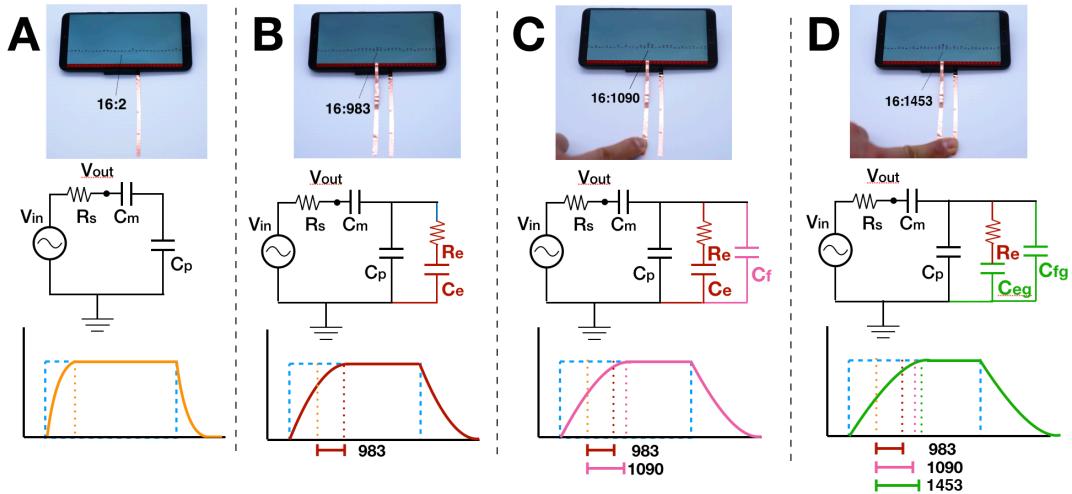


Figure 3.2 Four capacitive states and corresponding simplified equivalent circuits of *FlexTouch*. A: Idle state - original touchscreen sensing node. B: Attaching state - adding the signal strip on one touchscreen sensing node. C: Touching state - touch on the signal strip. D: Grounding state - touch both the signal strip and the grounding strip.

We present simplified equivalent circuits under each column in Fig. 3.2 with each capacitive sensor node treated as a RC circuit. R_s , C_m , C_p , C_e , C_f , C_{fg} , C_{eg} , R_e represent the inner resistance, mutual capacitance, parasitic capacitance, introduced capacitance between the extended element and local ground, touch introduced capacitance, introduced capacitance of touching both the signal and grounding strips, changed capacitance between the extended element and local ground as well as the extended element introduced resistance. Equation (1) shows the calculation of v_{out} ignoring the effect of R_e , using $C_{e(g)}$ representing either C_e or C_{eg} and $C_{f(g)}$ representing either C_f or C_{fg} .

$$V_{out} = v_{in}(1 - e^{-\frac{C_m + C_p + C_{e(g)} + C_{f(g)}}{R_s C_m (C_p + C_{e(g)} + C_{f(g)})} t}) \quad (3-1)$$

The touchscreen controller transmits a series of step voltage signals to scan through

each electrode and measures the charging time (time for V_{out} to reach a threshold) as raw capacitive values of the touchscreen. The charging time is linearly dependent on the Time Constant of the RC circuit, named τ , that is given as:

$$\tau = R_s \frac{C_m(C_p + C_{e(g)} + C_{f(g)})}{C_m + C_p + C_{e(g)} + C_{f(g)}} \quad (3-2)$$

We assume that C_m and 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 as well as the intersection effect between the extended elements. C_f typically varies from several to dozens of pF introduced by human touch.

Fully understanding the effect of C_e is the key to exploring the upper-limit of *FlexTouch*'s performance. In pursuit of testing this limit, we simply model the mutual capacitance between the extended material and the virtual ground with following formula.

$$C_e = \epsilon \frac{A}{d} = \epsilon \frac{L \times D}{d} \quad (3-3)$$

A represents the scale of dimensions of extension strips including length (L) and width (D), d represents the separation between the signal strip and the local ground, and ϵ represents the material's permittivity of extension strips. Therefore, to fully evaluate the sensing distance capability of *FlexTouch*, we need to study the effect of variable factors contained in the fabrication material along with the width and gap distance of the extension strips.

3.3 Summary

In this chapter, we introduced the sensing principles that related to *FlexTouch*. We first briefly talked about the capacitive sensing principle of modern touchscreen. Then we dived deeper into the sensing principle of *FlexTouch* by discussing the equivalent RC circuit in detail. Finally, we conducted a qualitative analysis of *FlexTouch* sensing based on the formulas we derived, which pointed out some factors needed to be studied to figure out the design space of *FlexTouch*.

Chapter 4 FlexTouch Implementation

In this chapter, 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's source code, we extracted the raw capacitive sensing data: $32 \times 16 = 512px$ 16-bit diff value image across a 5.8-inch surface at 100 fps for Huawei P20 phone, $28 \times 16 = 448px$, 16-bit diff value image across 5.1-inch surface area at 20 fps for Huawei P10 phone. We built an Android application that shows positions and raw capacitive values with corresponding update rates of chosen sensing nodes. The app also logs the raw capacitive image to a local server for later analysis.



Figure 4.1 Android Applications showing the raw capacitive data and positions of the sensing nodes.

4.1 FlexTouch Sensing Capabilities

We summarized the sensing capabilities of *FlexTouch* into four categories as shown in Figure 4.2.

- 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 [9]. But the other modalities are unique to *FlexTouch*.

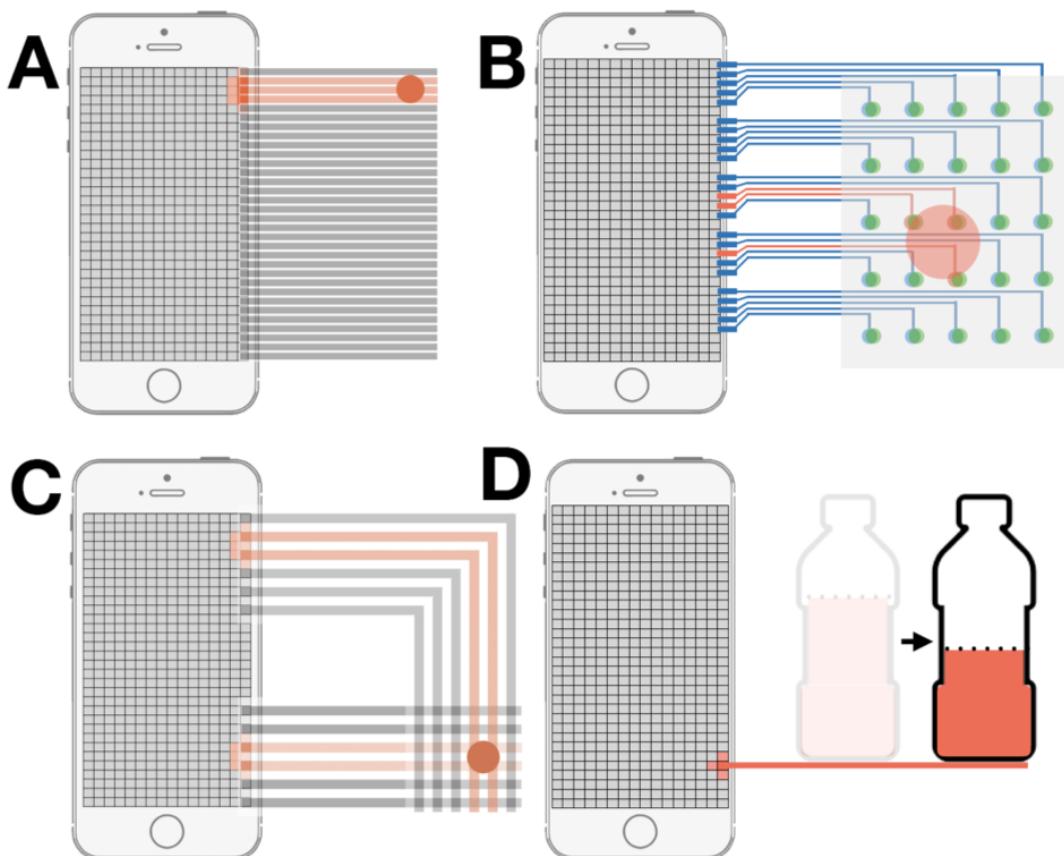


Figure 4.2 *FlexTouch* supports various applications with different sensing capabilities including A: 1D touch sensing, B: 2D continuous multi-touch tracking, C: 2D High resolution single touch tracking and D: Object presence and state sensing

4.2 Signal Processing for Touch Event Detection

In this section, we use the P20 phone as an example to present the signal processing and the touch event detection pipeline of *FlexTouch*.

Fig 4.3 demonstrates the signal processing procedure to detect the touch event on a 3-meter extension tape attached to the touchscreen. To filter out the high-frequency background noises, we applied a moving-average filter on the raw capacitive data using the unweighted mean of the previous 10 data points. During a touch event, a sharp signal

rise occurs. To detect these rising step events, we applied a sliding window that contains 20 data points on a low-pass filtered signal. The step event can be extracted by comparing the data samples in front of the sliding window queue and at the tail of the queue. Each data sample in the black line graph in Fig 4.3 is calculated using the following equation where S_i represents the filtered capacitive data.

$$S_{diff} = \frac{S_{16} + S_{17} + S_{18} + S_{19}}{4} - \frac{S_0 + S_1 + S_2 + S_3}{4} \quad (4-1)$$

Here we define the **signal-to-noise ratio (SNR)** representing the signal strength of the raw capacitive data. As shown in Fig 4.3, we define the **Noise** to be the difference between the maximum and minimum values of 100 data points for P20 before the touch event. The **Signal** is the S_{diff} . To extract the touch signal from the background noise effectively, the SNR should be greater than a predetermined threshold. In theory, if $SNR > 1$, we can detect touch events.

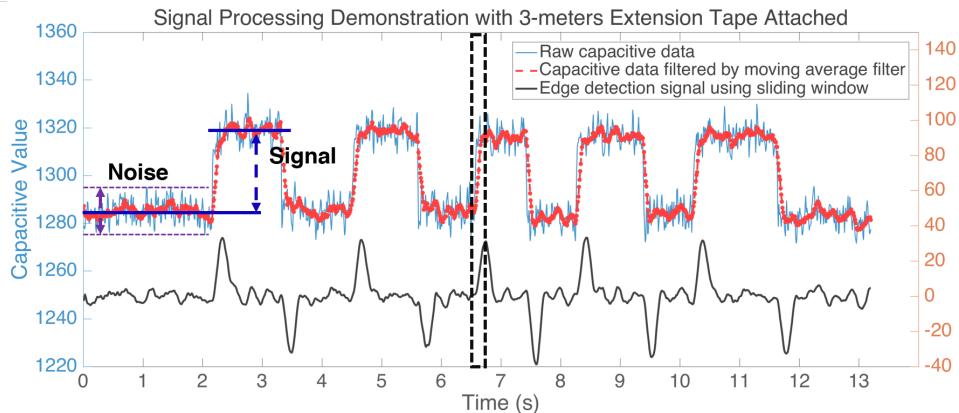


Figure 4.3 Signal processing demo detecting the touch event.

4.3 Differentiation Between On-screen and Off-screen Event

We collected raw capacitance data from P20 phone from both on-screen touch and off-screen touch event. Then we applied the moving-average based signal processing method to visualize and analyze our result. In our experiment, we use the copper strip with 5cm length attache to #16 joint point on the touchscreen and perform both on-screen touch and off-screen touch 5 times simultanously.

Fig 4.4 shows that there is a visual difference between on-screen and off-screen touch, with the signal of on-screen touch approximately 500 higher than off-screen touch,

which means that even simply choose a appropriate threshold can separate the two types of touch event fairly well.

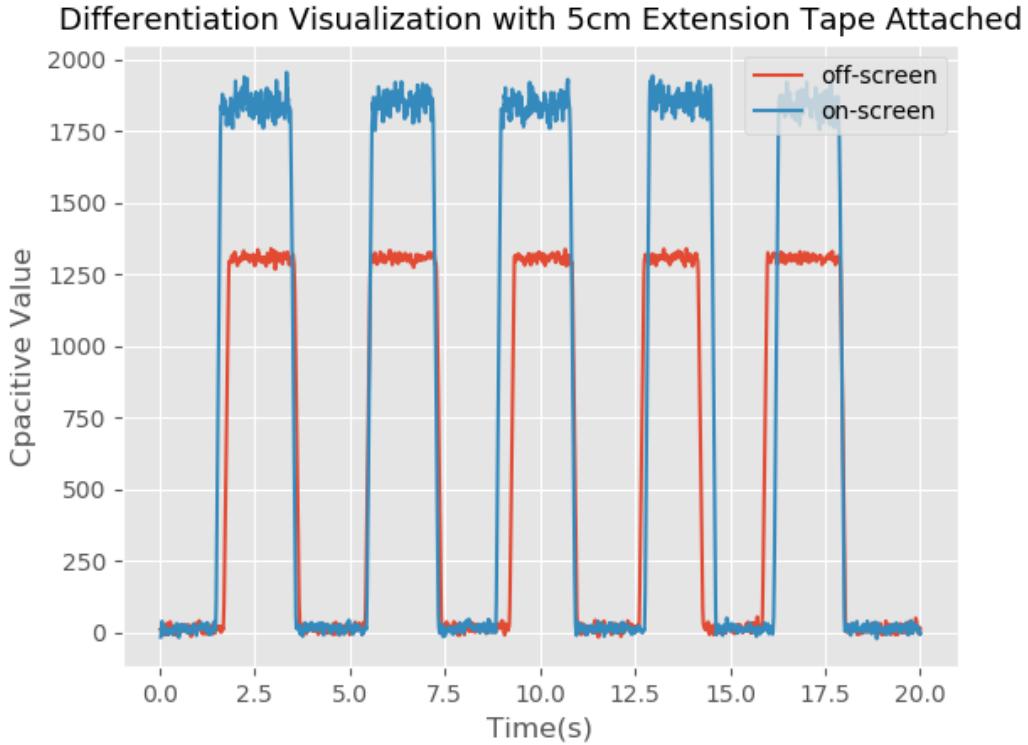


Figure 4.4 Signal processing demo detecting the touch event.

4.4 Fabrication

We identified materials that can be easily customized into everyday surfaces with properties including flexibility, conductivity, and commercial availability. We fabricated 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 leveraged the following materials to fabricate *FlexTouch* interfaces.

4.4.1 Conductive Tapes

Conductive adhesive tapes are widely used for electromagnetic shielding and transmission wiring (e.g. paper circuits). The most widely available conductive tape is an adhesive copper foil tape that can be found at most hardware, electronic or gardening stores (Fig. 4.5 A). It is \$2.50 per roll (6.3 mm x 20 m). The copper tape is highly conductive on both sides (0.05 Ω per square centimeter).

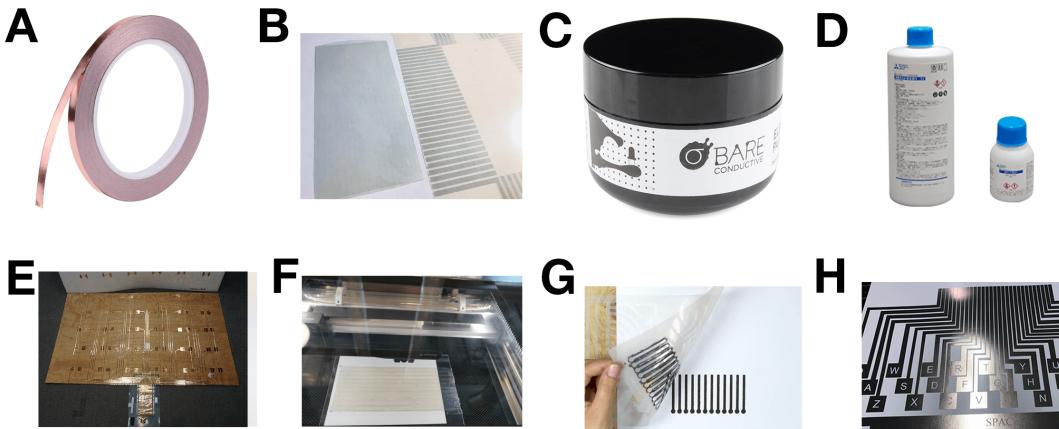


Figure 4.5 Commercially available materials. Copper foil tape (A) can be fixed to any surface (E). ITO PET Plastic film (B) can be fabricated to any 2D pattern using a laser cutter (F) or manually. Bare conductive carbon paint (C) and screen painting (G). Ink-jet circuit printer with Mitsubishi Silver nanoparticle ink (D) for printable conductive 2D layout (H).

End-users can manually arrange any layout on any surface using copper foil tapes (e.g., Fig 4.5 E) without any additional fabrication equipment. In addition, the conductive tape is more flexible and suitable for large-scale applications since it can easily adhere to everyday objects. However, the copper foil tape is not suitable for volume production since it is not compatible with current fabricating techniques such as laser cutting or printing.

4.4.2 Conductive Films

Film-like materials can be subtracted to 2D patterns using cutting or etching fabrication 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 [40] that is compatible with laser cutters. Furthermore, 2D custom layouts are also available by coating ITO materials on extremely thin (0.05mm) plastic film at a cost of \$30 per square foot (Fig. 4.5 B).

Since the ITO-coated PET plastic film is highly transparent, it can be attached to the touchscreen without occluding the display (Fig. 4.6 A). The ITO film can be customized as a screen protector for daily use with an array of ITO strips attached to the edges of the screen. This ITO strip array interface can be connected to the external application easily with a plug and play design as Fig 4.6 A and B show.

4.4.3 Conductive Coating

Liquid paint coating and ink printing are more versatile, as they can be added onto any surface in post-production. We identified two coating materials as examples. We use conductive carbon paint from Bare Conductive (Fig 4.5 C, \$280 per litter). This material can be painted on a flat surface such as a wooden board or cardboard, and then laser cut to engrave the layout on top of it. Another suitable coating material is printable ink. We identified Silver nanoparticle ink made by Mitsubishi (Fig 4.5 D, \$340 per 100 ML) as presented by Instant Inkjet Circuits [41]. We fabricated the inkjet printable circuit with a Brother MFC-J480DW model printer.

The conductive coating method is compatible with mass production due to its reproducibility. However, because of the limited size of each template or substrate, we need to further assemble the fabricated elements for large-scale application.

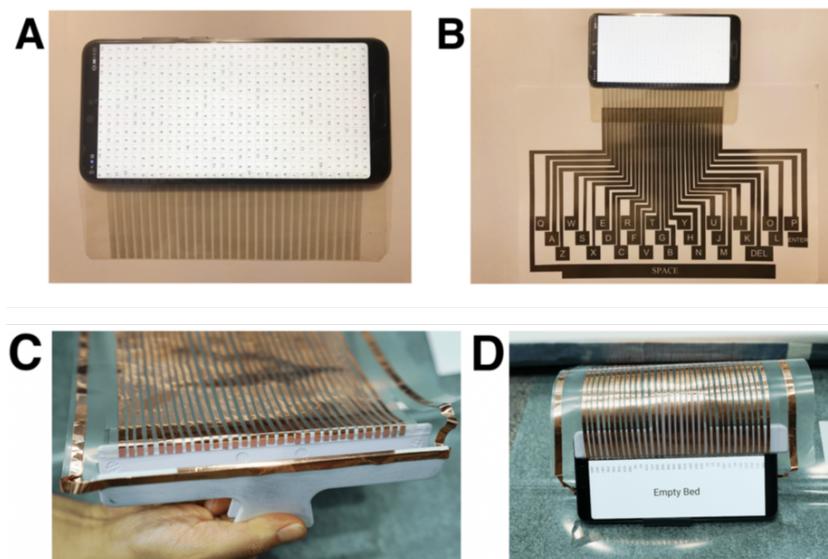


Figure 4.6 Demonstration of two assembly methods. The ITO strip array interface (A) can be stuck to a 2D-patterned application (B). The external application can be clipped onto the edge of the touchscreen (C and D).

4.5 Plug and Play

In this section, we present *FlexTouch*'s plug and play interface for daily use by proposing two assembly approaches as demonstrated in Fig 4.6.

- **Adhere the external application with an ITO array film.** The ITO film is suitable for being integrated into a screen protector with an ITO conductive array connected to the edge of the touchscreen. The adhesive ITO film can easily be attached or

detached to the external 2D patterned application.

- **Fix the external application on the phone’s edge with a clip.** The external application is connected with an array of conductive threads on one side of the clip while the electrodes on the 2D pattern representing the local ground are connected on the other side of the clip as shown in Fig 4.6 C. The customized part can be clipped onto the edge of the touchscreen as shown in Fig 4.6 D.

4.6 Summary

In this chapter, we implemented *FlexTouch* on two Android devices: Huawei P10 and Huawei P20. We first summarized the sensing capabilities of *FlexTouch* that supports both 1D and 2D interaction patterns. After that, we introduced the signal processing algorithm we used for touch event detection, and how to differentiate the off-screen touch from on-screen touch. Then we elaborated our the materials we used along with corresponding fabrication approaches.

Chapter 5 FlexTouch Sensing Capability Evaluation

In this chapter, we evaluate the sensing range of *FlexTouch* considering the effects of several factors including fabrication materials, the signal strip's dimension, sensing hardware and the configuration of the grounding strip.

5.1 Evaluating Sensing Range with Variable Fabrication Material, Hardware, and the Local Ground

Fig 5.1 illustrates our hardware setup for this study. Two strips are coming out from the phone. The signal strip is directly attached to the phone touch surface by a plastic clamp, while the grounding strip is connected to the back plate of the phone. In this study, we only look at the difference between using and not using the grounding strip. We discuss other variables pertaining to the grounding strip in a more thorough study in later parts of this section.



Figure 5.1 Experiment setup to evaluate the touch sensing coverage range.

To evaluate the effect of different materials, We fabricated four different 5-meter long signal strips using materials including copper foil tape (CFT), ITO PET film (IPF), carbon paint (CP), and silver nanoparticle ink (SNI) with a fixed width of 1.5mm. We set the grounding strip (5-meter long, 6mm-wide copper foil tape) 2cm away from the signal strip in this study. We recruited four participants for this experiment with an average age of 26.5 ($SD = 2.5$). The study lasted for 2 hours in total and we compensated each participant with a \$50 dollar gift card.

1) We attached the signal strip to the central position of the 8th sensing node on the touchscreen's left edge at the beginning of each session. In each session, we randomly selected two participants to perform a one-second finger touch on the far end of the signal

strip five times followed by a one-second finger touch on the far end of both the signal and the grounding strips (also five times). Then we attached the signal strip to the 18th sensing node and repeat above procedure.

- 2) We switched the phone hardware and repeated step 1).
- 3) We cut both signal and grounding strips to the next neighboring length following the order of 5m, 4m, 3m, 2.5m, 2m, 1.5m, 1m, 0.5m, 0.25m and 0.1m in sequence and repeated steps 1) and 2).
- 4) After completing the test on one material, we replaced it with another signal strip made of different material and repeated the experiment. Participants took a two-minute break between material switches.

Table 5.1 Average SNR versus extension distance under different configurations. (CFT: copper foil tape, IPF: ITO PET film, CP: carbon paint, SNI: silver nanoparticle ink)

Length[m]	0.10	0.25	0.50	1.00	1.50	2.00	2.50	3.00	4.00	5.00
P20, CFT	6.8	3.5	1.6	1.1	0.6	-	-	-	-	-
P20, IPF	6.6	3.4	1.4	0.9	0.5	-	-	-	-	-
P20, CP	6.5	3.1	1.9	0.8	-	-	-	-	-	-
P20, SNI	6.4	2.9	1.3	0.9	-	-	-	-	-	-
P20, CFT w/ GND	15.8	9.8	5.8	4.7	3.3	2.6	2.0	1.5	1.3	0.7
P20, IPF w/ GND	16.5	10.8	5.5	4.0	3.1	2.0	1.6	1.1	0.8	0.5
P20, CP w/ GND	15.4	10.1	6.0	3.7	2.2	1.7	1.0	0.8	-	-
P20, SNI w/ GND	15.3	9.8	5.4	3.1	2.2	1.7	1.4	1.2	0.9	0.5
P10, CFT	15.7	7.6	4.3	2.7	1.7	1.1	0.7	-	-	-
P10, IPF	14.2	7.5	3.9	2.9	1.4	1.0	0.5	-	-	-
P10, CP	14.4	6.8	3.2	1.6	0.8	0.5	-	-	-	-
P10, SNI	14.9	6.9	3.1	2.8	1.4	1.0	0.6	-	-	-
P10, CFT w/ GND	20.4	10.2	7.0	4.3	3.1	2.3	1.9	1.5	1.1	0.8
P10, IPF w/ GND	21.4	11.5	7.9	5.3	3.2	2.7	1.7	1.2	0.8	0.5
P10, CP w/ GND	20.1	12.4	8.1	4.3	2.8	2.1	1.2	0.7	-	-
P10, SNI w/ GND	19.4	11.2	8.6	4.1	2.8	2.0	1.6	1.2	0.8	0.5

5.1.1 Results

We summarize our results in Table 5.1, which outlines the signal strength illustrated by the SNR value of our system. There are a total of 16 different hardware/material/grounding strip's presence configurations and each of them has ten different signal strip length configurations. We highlight the following insights gained from this

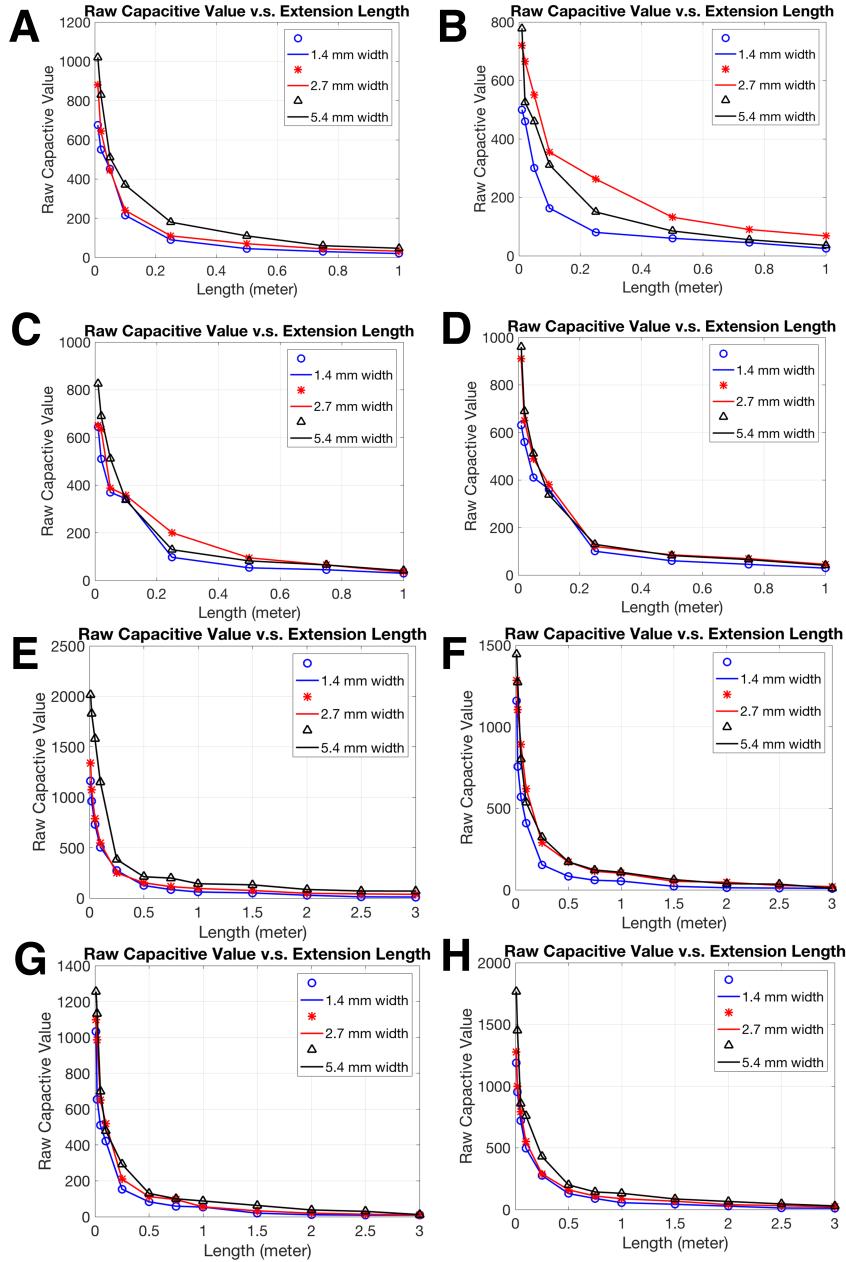


Figure 5.2 The curve between the increase of the raw capacitive value of the touchscreen and the lengths of the extension strip under different widths for Huawei P20 phone (A, B, C, D) and P10 phone (E, F, G, H). A/E: Copper foil tape. B/F: ITO plastic film. C/G: Carbon paint. D/H: silver nanoparticle ink.

evaluation study:

1. FlexTouch can support large-scale capacitive sensing applications with a coverage range of up to 4 meters. Using the threshold of $\text{SNR} > 1$, we observe that the minimum sensing distance supported by *FlexTouch* exceeded 0.5 meters regardless of the hardware, the material, and the grounding strip's presence. However, the grounding strip helps extend the sensing range significantly: Under the best conditions, with both the p10

and p20 hardware and CFT material, *Flextouch* could reach coverage distance of more than 4 meters.

2. *FlexTouch*'s sensing range is positively correlated with material conductivity.

Among the four materials, CFT achieved the longest sensing range, following by SNI and IPF, finally by CP. This ordering is consistent with the conductivity ordering of the 4 materials presented in Figure 5.3 B. We believe that materials with even better conductivity may be able to exceed the sensing range we observed in this study.

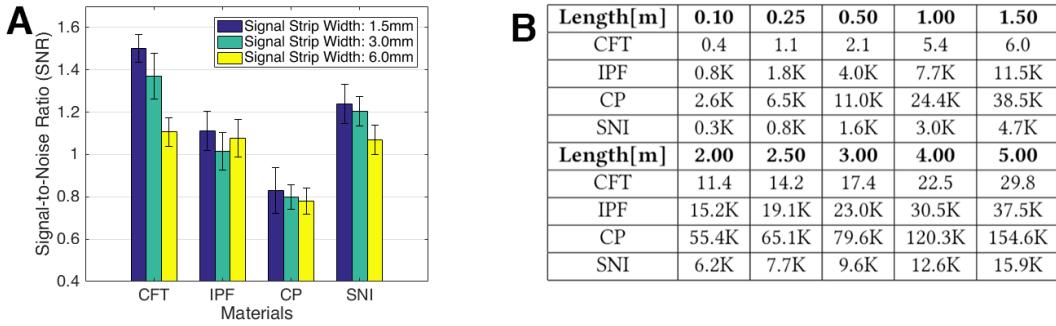


Figure 5.3 The SNR versus the signal strip width using four different materials (A). The table of material's resistance values (Ω) under different extension lengths (B).

3. The extension distance increases as the width of the signal strip decreases.

To better understand the effect of the width of the signal strip, we conducted a follow-up study changing the width of the signal strip made with 4 different materials with a fixed length of 3 meters. We recorded the SNR in Figure 5.3 A, which demonstrates that *FlexTouch* has the best performance with a 1.5mm-wide signal strip regardless of the fabrication material. We believe that even thinner strip will be able to support longer sensing ranges. However, since a thinner strip is less conductive, we believe that there's a lower limit on the strip's width.

4. *FlexTouch* can not differentiate touchpoints at different locations on the extension strip with the presence of the ground plane. We evaluated the touch resolution on a single pair of extension strips by touching on different positions with a 50cm-step using different materials. We did not observe that 2D touch input could be enabled with single-layer conductive materials as prior work [11,37] mentioned with the grounding strip's presence.

5. No significant difference in using different capacitive sensing hardware. The 2 different phones being employed in our study, Huawei p10 and P20 demonstrate moderate SNR difference when the same material is being deployed with a length below 1m. However, when the strip length continued to increase, the SNR demonstrated similar

results when all other variables are consistent. Given limited hardware resources, we were only able to evaluate these two phone models. Future studies that include capacitive touchscreens from different manufacturers will be necessary to fully understand the impact of capacitive touchscreens on the feasible sensing range of our system.

5.1.2 Study Results in Relation to the Proposed Working Principle

Results in Table 5.1 show that as the length of the sensing strip increases linearly, the touch signal strength decreases logarithmically. As presented in section *FlexTouch: Working Principles*, the finger touch introduces additional shunt circuit changing C_e to C_{eg} . We assume the values of C_f , C_m , C_p are 5 pF, 10 pF and 10 pF while $C_{eg} = 1.5 \times C_e$. Then Formula (2) can be presented as following.

Before the touch event:

$$\tau_b = a \frac{100 + 10C_e}{20 + C_e} \quad (5-1)$$

After the finger touch on the signal strip only as well as on both the signal strip and the grounding strip:

$$\tau_{af} = a \frac{150 + 10C_e}{25 + C_e}, \tau_{ag} = a \frac{150 + 15C_e}{25 + 1.5C_e} \quad (5-2)$$

The estimated capacitance value can be represented as:

$$\tau_{df} = \tau_{af} - \tau_b, \tau_{dg} = \tau_{ag} - \tau_b \quad (5-3)$$

We assume that $C_e = 100 \times L$ where L represents the length (meter) of the strip since the width is assumed to be static. The curve of how the estimated capacitive value along the strip length matches the measured raw data if a is assigned to 600. The pattern we see in our result matches with 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 5.5 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 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.

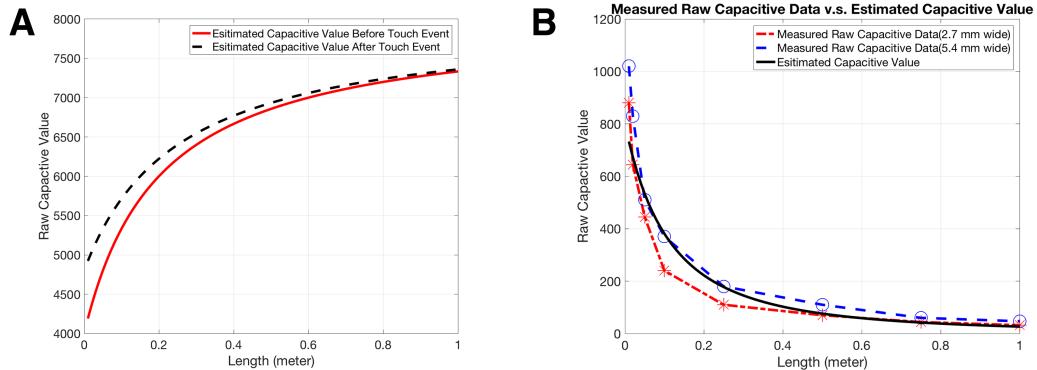


Figure 5.4 The Comparison between the measured raw capacitive data and estimated capacitive value.

5.2 Understanding the Effect of the Grounding Strip

The previous study shows the significant effect of introducing the grounding strip into the extension circuit design. There are additional variables such as the distance between the grounding strip and the signal strip, the width of the grounding strip as well as the material of the grounding strip that we would like to further evaluate to provide in-depth insights into designing touch sensing solutions with *FlexTouch* in this section.

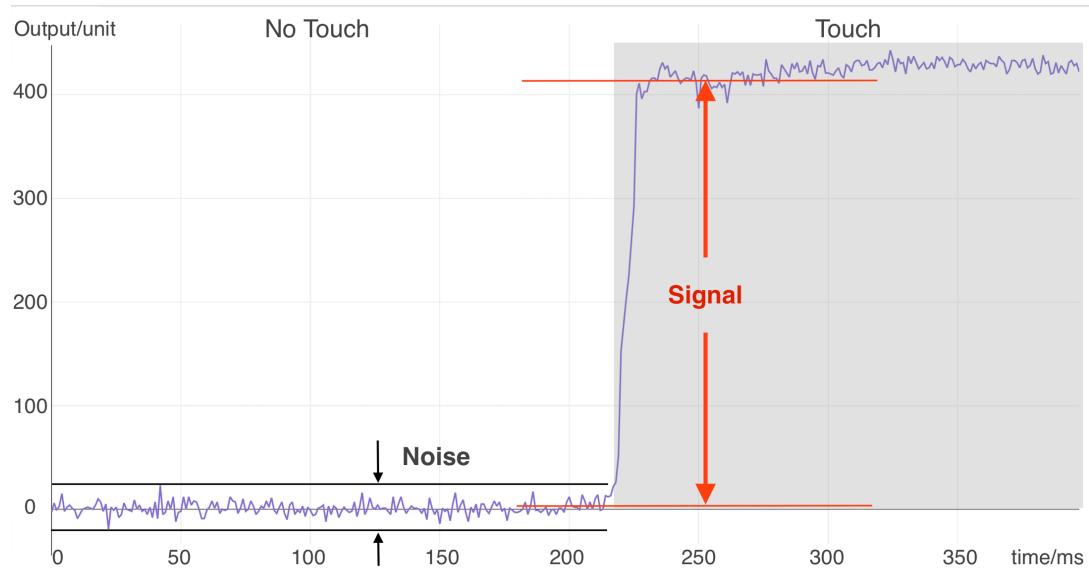


Figure 5.5 The calculation of SNR with raw capacitive value from a Huawei P20 phone.

5.2.1 Effect of the Gap Between Grounding and Signal Strips

We used copper foil tape as example material to examine the effect of the gap between the grounding strip and the signal strip on the maximum touch sensing distance. We set the grounding strip's width to be *6mm*. We measured the maximum coverage with the following variables. 1) Gap distance between the central lines between the signal and grounding strips: *0.5cm*, *1cm*, *2cm*, *3cm*, *5cm* and *10cm*. 2) Signal strip's width: *1.5mm* and *3.0mm*. 3) Touch postures: single index finger touch and dual index finger touch with two hands.

To measure the maximum touch sensing distance, we started with the maximum sensing distance measured in the previous study. In each session, we increased/decreased the extension distance by sticking/cutting additional *n* pieces of *10cm*-long copper foil tape at the far ends of both the grounding and signal strips. We recruited four participants for this study with an average age of 25.5 (SD = 1.5). They performed three touches with each touch posture at the far ends the extension strips. We repeated the above sessions until the SNR exceeded 1.0 for both single-finger and double-finger touches. We repeated the above procedure five times to obtain an average coverage distance for each condition.

1. The maximum touch sensing distance increases logarithmically as the gap distance between the grounding strip and signal strip increases. As shown in Figure 5.6, there exists an upper limit on the touching sensing coverage distance around 5 meters regarding the gap distance and the signal strip's width. However, although larger gap distance results in better sensing coverage distance, it limits the number of strips that can be deployed for any given space.

2. Touch posture has no significant effect on the coverage distance performance. There is no significant difference between touches with one finger or two fingers from two hands ($F_{1,89} = 0.32, p = 0.54$). We envision that future work could connect the local ground directly to users and not to the extension circuit, enabling longer sensing range and higher resolution design.

5.2.2 Effect of Grounding Strip Width

We used copper foil tape as example material to examine the effect of the grounding strip width on the touch sensing distance. We set the gap distance between extension strips to be *2cm* and the signal strip width to be *1.5mm*. We measured the signal strength on fixed extension distances (*1m* and *3m*) with different grounding strip's width: *1.5mm*, *3.0mm*

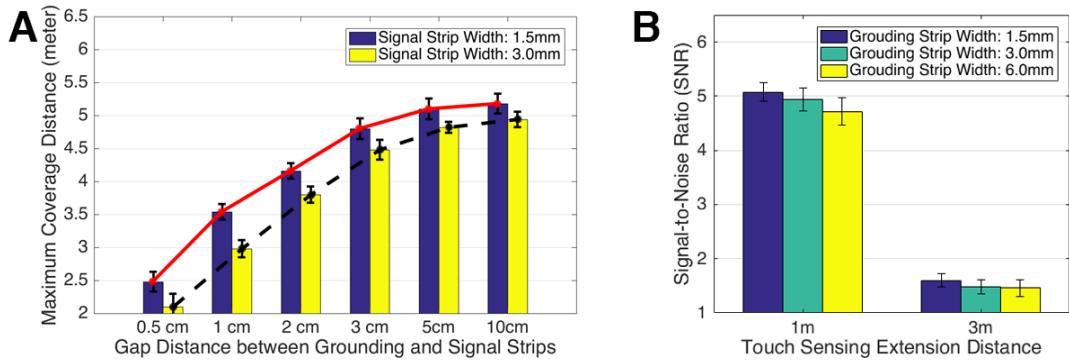


Figure 5.6 Maximum touch sensing distance versus the gap distance between signal and grounding strips (A). SNR versus the grounding strip width with different extension distances (B).

and 6mm. We recruited four users to touch the far ends of the paired extension strips three times for each condition. We repeated the above procedure five times to obtain an average measured SNR. We highlight the following insights gained from this evaluation study:

The touch sensing coverage distance is negatively correlated with the grounding strip's width. We recorded the SNR values in Figure 5.6 B, which demonstrates that *FlexTouch* has the best performance with the 1.5mm-wide signal strip. We recommend a thinner signal strip that can support better sensing range performance as well as higher resolution design. Combined with the result on the signal strip's width in Section 5.1.1, we believe that the sensing distance can be further extended if we adopt 1.5mm-wide or thinner copper foil tape for both the signal and grounding strips.

5.2.3 Effect of the Grounding Strip Material

In this study, we explored whether grounding strip material affects the sensing distance performance. We set the signal strip material to be copper foil tape, the gap distance between extension strips to be 2cm and the widths of both the signal strip and grounding strip to be 6.0mm. We measured the SNR values of 1-meter and 3-meters sensing distance with four different grounding strip's materials. The result is illustrated in Table 5.2.

Table 5.2 Average (standard deviation) SNR values with one strip made of CFT and the other made of one of the three materials.

Material	CFT	IPF		CP		SNI	
	Condition	reference	ground	signal	ground	signal	ground
1m sensing distance	1.14 (0.07)	1.06 (0.11)	1.07 (0.13)	0.88 (0.12)	0.86 (0.10)	1.11 (0.14)	1.09 (0.13)
3m sensing distance	3.40 (0.20)	3.31 (0.25)	3.35 (0.23)	3.22 (0.12)	3.20 (0.08)	3.42 (0.13)	3.37 (0.14)

1. *FlexTouch* sensing range is positively correlated with material conductivity

of the grounding strip in general. Similar to the results in Section 5.1.1, we found that the material conductivity has a positive effect on the sensing range performance.

Then we switched the grounding strip and the signal strip which are made of different materials and noticed that:

2. Signal strip and ground strip made of different materials are interchangeable when they have the same width. We found no significant difference in the signal strength when switched the two strips with the same width but different materials.

5.2.4 Study Results in Relation to the Proposed Working Principle

Section 5.1.2 explains the relationship between signal strength and the extension strip's length using the working principle hypotheses in Section 3. We explain the results we found in study 2 that pertain to the effect of separation - d as well as fabrication material - ϵ .

To enhance the effect introduced by touch, less capacitance between the signal strip and the grounding strip is preferred, which is represented as C_e . The sensing distance can be represented as:

$$L = \frac{C_e \times d}{\epsilon \times D} \quad (5-4)$$

Therefore, we conclude that smaller extension strip width (D), larger gap distance (d), more conductive material and more insulating material between strips (smaller ϵ) will help extend the sensing range, which is consistent with our study's results.

5.3 Evaluating Object Presence Sensing Capabilities

Given the capacitive nature of *FlexTouch*'s sensing principle, it can go beyond sensing touch events. Everyday objects that contain capacitance also draw electric current from the touchscreen and can be detected by *FlexTouch*. In this section, we evaluate the feasibility of detecting everyday objects' presence using *FlexTouch*.

5.3.1 Apparatus and Procedure

In this study, we used 3.0mm wide copper foil tape and a Huawei P20 phone. We explored a range of factors that may affect *FlexTouch*'s capability in sensing everyday objects' presence: the dielectric property and materials of different everyday objects, the

length of the extension strips as well as the presence of the local ground. We used the following procedure in the experiment:

- 1) We attached the signal strip to the central position of the 19th sensing node on the left edge of the touchscreen. Then we started the testing application on the phone sending the raw capacitive data to a local server running on a laptop for later analysis.
- 2) We placed 11 pre-selected objects in random order at the end of the signal strip without the grounding strip's presence for around 2 seconds then on both the signal and grounding strips for another 2 seconds. We picked up and re-placed the object five times, ensuring the object was in contact with the strips on each placement.
- 3) We trimmed the strips in order of the following lengths: 3m, 2m, 1.5m, 1m, 0.5m, 0.25m, 0.1m and repeated step 2).

5.3.2 Results

Table 5.3 presents the average SNR value with 22 configurations across everyday objects and the presence of the grounding strip.

As presented in Table 5.3, *FlexTouch* can sense the presence of everyday objects by detecting the current they draw via the extension strip. The second column in Table 5.3 illustrates that all the objects change the capacitive signal extended from the touchscreen on the phone. However, the sensing range varies with the object's material. Objects made of metal have the strongest signal strength. The coverage distance ranges from 50cm to 2m. Besides, pairing the local ground with the touch screen extension strip can dramatically enhance the object detection's sensing range.

5.4 Summary

In this chapter, we conducted a series of concrete evaluation of *FlexTouch* including fabrication materials, the signal strip's dimension, the sensing hardware and the configuration of grounding strip. We first took a look at the relationship between lengths and SNR under the condition of different devices, different material, with/without grounding strip. Our study shows that *FlexTouch* is capable of supporting large-scale capacitive sensing with coverage range of up to 4 meters. To step further, we jumped into the study of grounding strip including gap between strips, and strip width. Finally, we tested *FlexTouch*'s sensing ability of object presence, which demonstrated that *FlexTouch* can support a variety of objects.

Table 5.3 Average SNRs versus extension strips' lengths with different everyday objects. The table's X and Y values (X/Y) represents the SNR values of conditions with and without the grounding strip.

Length[m]	0.10	0.25	0.50	1.00	1.50	2.00	3.00
Finger Touch (reference)	15.8/6.8	9.8/3.5	5.8/1.6	4.7/1.1	3.3/0.6	2.6/-	1.5/-
5cm × 5cm Copper Foil Tape	15.3/3.2	9.5/1.9	5.5/0.8	4.6/-	3.0/-	2.3/-	1.3/-
Stainless Steel Water Cup	12.6/3.4	10.0/2.0	4.3/1.1	2.0/-	1.6/-	1.5/-	0.7/-
MacBook Pro 13'	5.4/2.4	3.7/1.7	1.2/0.6	0.6/-	-/-	-/-	-/-
Carving Knife	5.6/1.5	2.7/0.6	1.3/-	-/-	-/-	-/-	-/-
iPhone XR	4.6/2.5	2.5/2.0	1.2/0.5	0.7/-	-/-	-/-	-/-
550 ml Bottled Water	4.3/2.8	2.8/1.2	0.6/-	-/-	-/-	-/-	-/-
50 ml Bottled Water	3.1/1.3	2.0/0.7	-/-	-/-	-/-	-/-	-/-
Glass Cup	2.7/0.6	1.0/-	-/-	-/-	-/-	-/-	-/-
Notebook	0.9/0.8	-/-	-/-	-/-	-/-	-/-	-/-
Cardboard Box	0.5/0.6	-/-	-/-	-/-	-/-	-/-	-/-
Mouse	0.5/0.5	-/-	-/-	-/-	-/-	-/-	-/-

Chapter 6 Example Applications

In this chapter, we present two sets of example applications to demonstrate the versatility of *Flextouch*, including both ambient interaction and large-scale interaction. For ambient interaction, we preset four examples including hand gesture recognition, off-screen touch interaction, full-size keyboard and VR trackpad. For large-scale interactions, our examples include body posture recognition, 2D large-scale continuous touch tracking, fitness speed tracking as well as sensing the presence of everyday objects. More particularly, as large-scale interactions to be our focus, we conduct concrete user study and evaluation on our large-scale interaction examples. These applications demonstrate the possibility of new interaction methods and the sensing potential of *FlexTouch*.

6.1 Enhancement of Ambient Interactions

6.1.1 Gesture Sensing on the Edge of Smartphone

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 1.2.C. 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 6.1 Gesture sensing on edge of smartphone.

6.1.2 Touch Interaction on the Back of Smartphone

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 1.2.D, 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 implementation and study results.

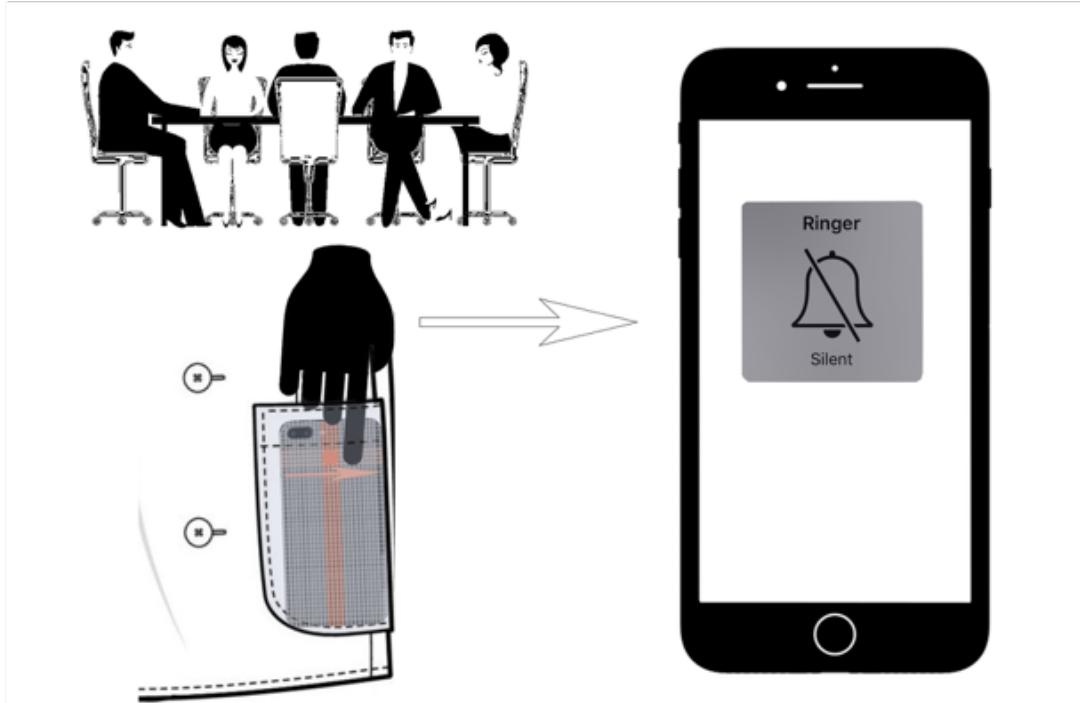


Figure 6.2 Touch interaction on back of smartphone.

6.1.3 Full-size Foldable Keyboard

In Figure 1.2.A, 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.

6.1.4 Head-mounted VR Trackpad

Phone based VR platform like the Google cardboard project mounts phones onto cheap and disposable cardboards for VR/AR applications. Such approach greatly low-

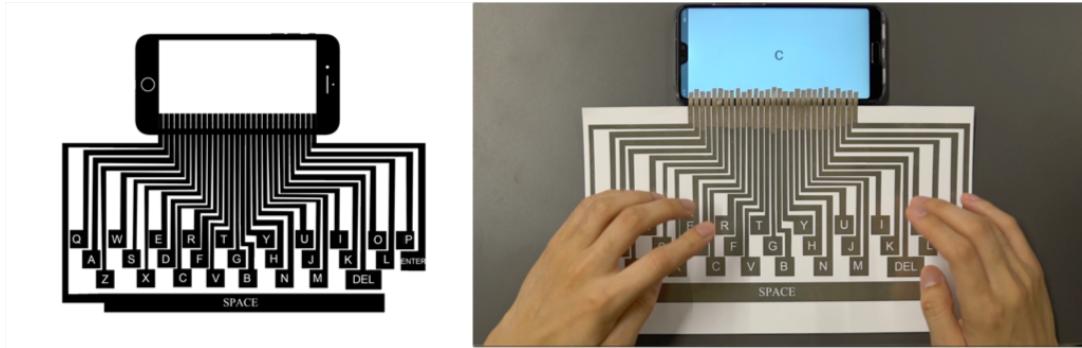


Figure 6.3 Full-size keyboard using silver nanoparticulate ink-jet printing.

erred 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 1.2.B 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.

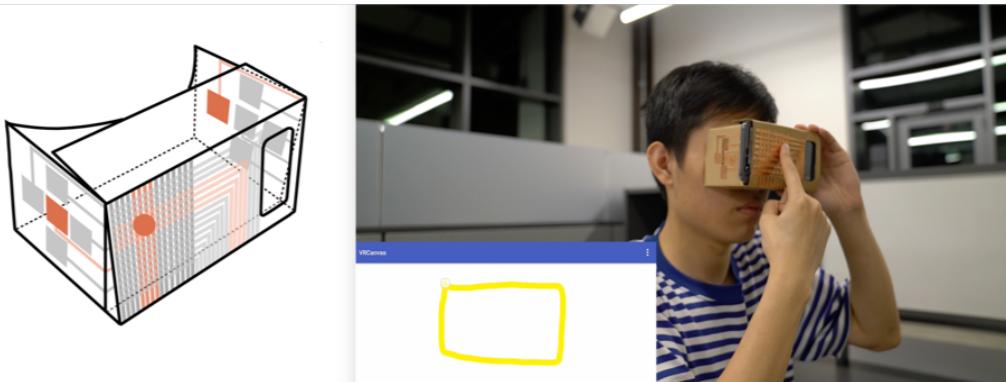


Figure 6.4 Enhanced VR interaction of back of smartphone.

6.2 Large-scale Interactions

6.2.1 Smart Mattress for Sleep Monitoring

As *FlexTouch*'s sensing range can reach up to 4 meters, we can leverage this long-range capability to detect users' behaviors while they're in bed. This is achieved by fabricating a three-layer structure with $5 \times 6 = 30$ sensing nodes as presented in Fig 6.5 A - C. Each sensing node on the top layer is formed with a signal and a grounding electrode (Fig 6.5 B). All electrode pairs are connected to electrodes on the bottom layer. We placed a mattress on a wooden board and affixed a copper-tape circuit (Fig 6.5 C) with its electrodes connected with the electrodes on the bottom layer of the mattress. We activated the

application by plugging in the touchscreen phone using a clip with an array of copper foil tapes attached (Fig. 6.5 E to I). The material cost of this application was 10 USD.

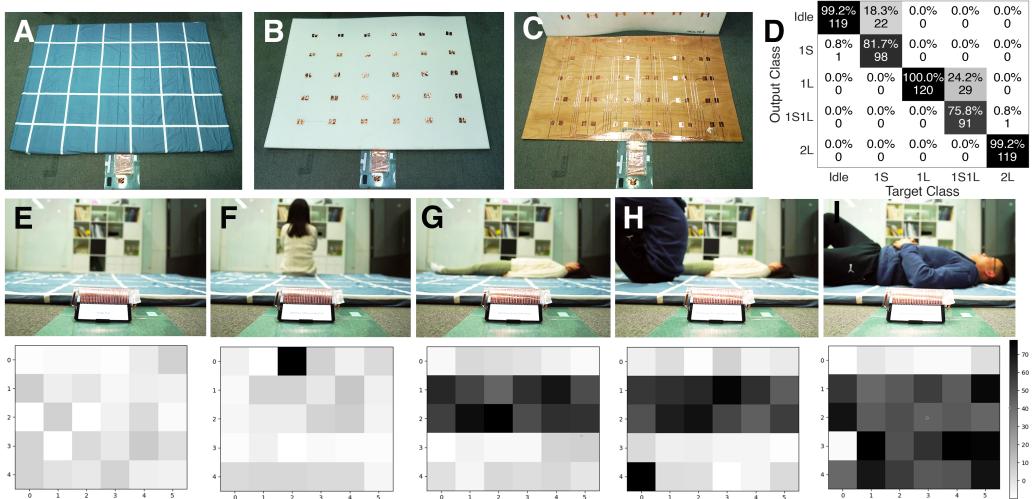


Figure 6.5 The structure of the smart mattress (A - C), the classification confusion matrix (D) and the five detected states (E - I) with corresponding scenarios and raw sensing data visualization

6.2.1.1 User Evaluation

To evaluate the performance of the smart mattress, we recruited eight pairs of participants (10 males) with an average age of 25.6 (SD = 2.2) and an average height of 170 cm (SD = 5.3) who we compensated with a \$20 gift card for a 30-minute test. There was one practice session followed by three data collection sessions. For each session, the paired participants followed the instruction of *single user sitting on the bed, single user lying on the bed, one user sitting and one user lying on the bed, two users lying on the bed* in order. The paired participants repeated the above procedure in each session five times and kept each posture for approximately 4 seconds. We logged the raw capacitive data with a Huawei P20 phone and logged the procedure with a camera for labeling.

6.2.1.2 Result

All samples were manually labeled according to the video. We picked frames out of the series of data for each state. The dataset contains 120 data samples per posture across participants and each data sample includes 30 raw capacitive data points. The dataset was randomly split into 2 subsets (96 training samples and 24 testing samples). We conducted 5-fold cross-validation using the LibSVM classifier and achieved an average accuracy of 91.2% across 5 states. We believe that the low resolution causes low recognition when

users are sitting on the mattress, as Fig 6.5 D indicates. We discuss this result and future design recommendations in the later discussion section.

6.2.2 Smart Yoga Mat for Fitness Posture Detection

The sensing range of *FlexTouch* allows us to enable large-scale sensing applications such as a yoga mat. *FlexTouch* can detect and classify different user poses based on their capacitive profiles when working out on the yoga mat. Leveraging this functionality, smart home applications can adjust the surrounding environment based on users' physical activities. For instance, it could adjust ambient light, temperature, and music according to the user's activity on the yoga mat. The materials we used to build the touch-sensitive yoga mat cost just 8 USD.

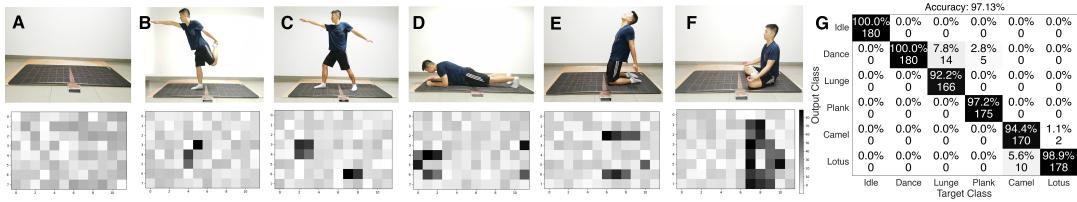


Figure 6.6 Recognizing user's posture on the yoga mat built by *FlexTouch* with raw sensing image data

As shown in figure 6.6, we built a 2D-patterned matrix ($8 \times 11 = 88$ sensing nodes) on a regular yoga mat using ITO strips, which can classify five different yoga poses (lord of the dance pose, plank, high lunge variation, camel pose and lotus pose).

6.2.2.1 User Evaluation

User Evaluation. We recruited 12 participants (6 males, 6 females, average age 27.7 (SD = 3.4), average height 171.2 cm (SD = 9.8). Each participant received \$10 for participating in this study, which included 1 practice session followed by three data collection sessions. Before each data collection session, the five postures were randomized. Then the participant performed each posture five times with a duration of 3 seconds. We logged the raw capacitive data with a Huawei P20 phone and logged the procedure with a camera for ground truth labeling.

6.2.2.2 Results

All samples were manually labeled according to the video. We picked the middle frame out of the series of data when the pose was performed. The dataset contains 180

data samples in total and each data sample includes 32 frames of raw capacitive data. We performed 5-fold cross-validation on the dataset (144 training samples and 36 testing samples for each iteration) using the LightGBM classifier and achieved an average accuracy of 97.1% across 6 classes (five body postures and no action).

6.2.3 Fitness Tracking on Count of Repetition, Speed and Distance

In this example, we demonstrate fitness tracking applications when deploying *FlexTouch* on a treadmill, cycling machine, and chest-press machine as shown in Figure 6.7. Even though some recent commercial fitness machines have the function of sharing data to personal mobile devices, many machines are not embedded with this function such as chest press machine, lat pull-down gym machine, etc. Since these machines have similar periodic patterns, we propose these applications to inspire future designs by identifying the position where the sensing node is placed to sense states, state-changing events, and state-changing speed. We designed a binary sensor using a pair of 1.5m-long, 3mm-wide copper foil tapes. Since the update rate of the Huawei P20 phone is 100 fps, the button sensor can detect not only the binary touch event but also how fast it changes. By counting the touch event frequency, we can calculate the distance or speed. This allows users to track their fitness behavior across devices at home or in the gym by simply plugging their phones into a customized passive module. Based on the tracking data, the application can customize fitness plans for individuals. This design cost 0.3 USD.

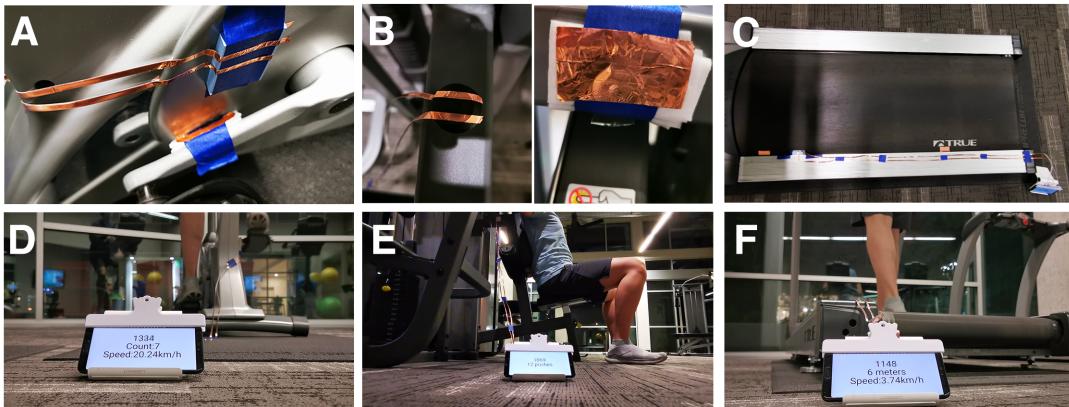


Figure 6.7 Fitness tracking using *FlexTouch*. A and D: speed tracking on a cycling machine. B and E: push counter on a chest-press machine. C and F: distance and speed tracking on a treadmill.

6.2.3.1 User Study

To evaluate the tracking accuracy, we recruited six users (3 females, average age of 24.7 (SD = 0.8)). Each user finished three rounds of testing. For each round, users ran on the treadmill for 2 minutes with a maximum speed of 12KM/H , rode the cycling machine for 2 minutes with a maximum speed of 25KM/H , and, finally, finished the round with ten chest presses. The study lasted for 20 minutes and we compensated each participant with a \$20 dollar gift card. We used a camera attached on the display panel to record the speed and distance data from the fitness machine for ground truth annotation.

6.2.3.2 Results

We measured the maximum riding speed from the cycling machine, the maximum running speed and distance resolution from the treadmill as well as repeat counts from the chest-press machine. Since the signal processing algorithm stated in Section 4.4 requires a minimum of 10 valid data to detect a touch event, there's an upper limit of the build button sensor's working frequency under 10 fps. Results indicate that *FlexTouch* had an accuracy of 98.9% on tracking the running and cycling speed and 100% on tracking the chest-press count. Since the touch event happens once every cycle, our distance tracking resolution for the treadmill is 1.5 meter for the model that we tested.

6.2.4 Smart Desk Reminder Application

Given the flexible and passive nature of *FlexTouch*, we recognize the potential to integrate it into large surfaces such as tables or desks to detect interaction with humans or everyday objects (Fig. 6.8). In this example, we placed three sensing nodes 40cm away from the touchscreen to sense the user's body contact as well as one sensing node with 20cm distance to sense the cup's water status (i.e. the amount of water remaining in the cup). When the user is working, instead of placing the phone on the desk, the user uses *FlexTouch* to activate the smart desk application. It can remind users to take a break or stay hydrated by drinking water while they work continuously for a while. This is achieved by extending the touch sensing node to the desk where users lay their arm and place the water cup. The material cost for building this application was 0.30 USD.



Figure 6.8 Smart desk example detecting user and object’s presence and status

6.2.4.1 User Study

To evaluate the sensing performance on the presence and status of the user and the water cup, we conducted a user study in which six users (2 females, 4 males, average age of 25.0 (SD = 0.9)) participated. For each round, users read a book with his or her arms laying on the table for 20 seconds and then replaced the thin plastic water cup filled with $250ml$ water with another water cup filled with $50ml$ water. Finally, the user left the desk for 10 seconds and came back to repeat the session five times in total.

6.2.4.2 Results

We obtained a dataset containing 16 minutes of user’s behavior data ($96.5K$ data frames). We manually labeled the data to extract 60 data points on user presence status and 90 data points on the cup status. We measured the detection accuracy by whether the user was present as well as the cup’s water status (not present, $50ml$ and $250ml$ water inside). Results show that *FlexTouch* can achieve an accuracy of 98.3% on in detecting the user presence at the desk, an accuracy of 92.2% on the cup water status (see the confusion matrix in Figure 6.8 C).

6.3 Summary

In this chapter, we proposed a set of different applications that *FlexTouch* can be easily applied. First, we showed four example applications of smartphone ambient interaction under common user scenarios. Different from prior work, based on the signal processing technique we described in chapter 4, we are able to provide a broader range of ambient interactions without any disturbance of user’s usual on-screen interactions. Then we presented several large-scale interaction examples along with concrete user study and result analysis. The results demonstrated the feasibility and robustness of *FlexTouch* in large-scale settings.

Chapter 7 Discussion and Future Work

FlexTouch enables large-scale interaction sensing beyond the spatial constraints of capacitive touchscreens by introducing the local ground into the extension circuit design. We show that our technique is compatible with a variety of conductive materials as well as fabrication methods. *FlexTouch* supports posture recognition, human-object interaction as well as enhanced fitness training experiences with a large coverage range of up to 4 meters. In this section, we discuss our findings, design guidelines, and future work.

7.1 Lower Development Barriers Using *FlexTouch*

Since *FlexTouch* requires no external or internal hardware modifications, our technique allows end-users to design and develop varied, low-cost capacitive sensing applications easily with a single touchscreen device. In addition, they can fabricate the customized low-cost interface with various commercially available materials and fabrication methods.

7.2 Effectiveness and Limitation of Introducing the Local Ground to Boost the Sensing Range

FlexTouch enables long-range capacitive sensing of up to 4 meters by introducing the local ground of the touchscreen to the extension circuit design. Through a series of studies, we proved the effectiveness of this approach. In addition, we found some insightful results that may benefit future designs. We recommend thinner, more conductive material to make extension strips and wider gap distances between grounding and signal strips to achieve a better sensing performance.

However, the limitation of this "local ground" method is the low spatial resolution and the effort to avoid overlays between the signal and grounding strips. Designers can choose to increase the resolution by shortening the gap distance and reducing the sensing range. We recommend a multi-layer design to avoid the intersection between signal and grounding strips as Section 6.1 and 6.2 shows. One potential solution to this limitation is connecting users or objects to the local ground directly with conductive threads. Another possible solution is connecting the local ground to the earth ground through a

charging line. Therefore, the environmental virtual ground couples the human body and earth ground to the local ground of touchscreen devices.

7.3 Fabrication and Assembly

We demonstrated that *FlexTouch* is compatible with four commercially available fabrication materials as well as a variety of fabrication methods. The current fabrication of our system is primarily based on hand-made prototypes. Additional machine-based approaches are expected for volume production with better quality control. We propose several potential directions for fabrication such as conductive inkjet printing, laser cutting with conductive frames, or printing robots that can enable large-scale circuit design on a wall^①. Programmable sewing machines can extend *FlexTouch* applications to touch interface widgets on a sleeve for quick access to a phone placed in a pocket.

In addition to our existing plug and play approaches mentioned in chapter 4, we expect additional approaches to further extend this idea. For instance, future design can enable an electrode base where users can lay their phone with the touchscreen facing downward to connect to *FlexTouch* interfaces. Furthermore, since the conductive strip increases the raw capacitive value when it's attached to the touchscreen, we can connect different applications with a patterned strip array. *FlexTouch* can detect the signal pattern caused by the patterned strip to serve as a short for launching applications when users attach the extension circuit to the touchscreen.

We recommend future fabrication designs considering the layout and spatial resolution when placing sensing nodes. An improper design leads to low recognition accuracy result as section 6.1 (smart mattress) demonstrates. The distance between sensing nodes is approximately 30 cm. As a result, it is hard for this application sensing users' sitting posture when they sit in the gap between electrodes or on the edge of the mattress. We believe that a higher resolution will improve accuracy significantly. In addition, we observed the negative effect of cloths on the signal strength especially with the presence of the sheet. Therefore, future designs should also consider the object/cover placed between human bodies and the extension surface.

① <https://scribit.design/>

7.4 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 resistance introduced by the material will have a significant effect on the signal strength once it reaches to kilos Ω according to prior work [11]. We will explore the feasibility of utilizing both the capacitance and resistance introduced by the extension of conductive 2D patterns in the future.

7.5 Enabling More Sensing Nodes

Currently, only the sensing nodes on the edge of the touchscreen have been used (94 nodes for the P20 phone and 88 nodes for the P10 phone). In the future, we can extend more nodes with a cover (Fig 7.1) that can be attached to the touchscreens. Multiple layers can be attached to different columns of the touchscreen with isolated materials between layers. By activating more sensing nodes, we can increase the resolution and range of our applications, which provide us with more possibilities. Another solution to enable more sensing nodes is designing the extension layout in an X-Y matrix configuration as shown in Section 6.3. To minimize the effect between neighboring sensing electrodes, we suggest a gap between attached strips larger than $2mm$ on the touchscreen. We also suggest an isolation gap between layers into which we inserted a $4mm$ isolated rubber in each joint node.

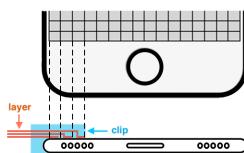


Figure 7.1 Possible design for more sensing nodes.

7.6 Conclusion

FlexTouch enables large-scale, passive, and low-cost interaction sensing interfaces by extending the capacitive sensing capability of touchscreens into the ambient environment. It can support a variety of large-scale interaction applications by attaching cus-

tomized conductive strips to the edge of the touchscreen. We demonstrated that our technique allows for easy fabrication of touch interfaces via a variety of commercially available conductive materials and fabrication approaches. Through a series of evaluation studies, we showed that *FlexTouch* supports long-range touch interaction sensing for up to 4 meters as well as everyday object presence detection for up to 2 meters. Then we demonstrated the versatility and feasibility of *FlexTouch* by implementing and evaluating applications in the domain of body posture recognition, activity detection, object presence detection, and enhanced fitness tracking experiences.

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声 明

本人郑重声明：所呈交的学位论文，是本人在导师指导下，独立进行研究工作所取得的成果。尽我所知，除文中已经注明引用的内容外，本学位论文的研究成果不包含任何他人享有著作权的内容。对本论文所涉及的研究工作做出贡献的其他个人和集体，均已在文中以明确方式标明。

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Publications

- [1] Yuntao Wang, **Jianyu Zhou**, Hanchuan Li, Tengxiang Zhang, Minxuan Gao, Zhuolin Cheng, Chun Yu, Shwetak Patel, and Yuanchun Shi. 2019. FlexTouch: Enabling Large-Scale Interaction Sensing Beyond Touchscreens Using Flexible and Conductive Materials. Proc. ACM Interact. Mob. Wearable Ubiquitous Technol. 3, 3, Article 109 (September 2019), 20 pages. (IMWUT’19)

Awards

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- [3] 2017 Mathematical Contest in Modeling, Meritorious Winner.