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Shuo Gao , Arokia Nathan
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1 Human–Machine Interaction–Related Technologies in Interactive Displays

Visual display of information is greatly required in today's highly digital world and constitutes a powerful means of conveying complex information, which cannot conveniently be described in text. Visualizing information is based on the ability of the human eye and brain to perceive and process vast quantities of data in parallel. Its history can be traced to the ancient era, when our ancestors carved images on cave walls and monuments (around 30,000 BC [1]). Mosaic art forms emerged in the third millennium BC [2], with small pieces of glass, stone, or other materials used in combination to display information. These pieces are a counterpart to the pixels in modern electronic display. The electronic display has become the primary human–machine interface in most applications, ranging from mobile phones, tablets, laptops, and desktops to televisions, signage, and domestic electrical appliances, not to mention industrial and analytical equipment.

User interaction with the electronic display has progressed significantly. Through sophisticated hand gestures [3]–[11], the display has evolved to become a highly efficient information exchange device. While interactive displays are currently very popular in mobile electronic devices such as smart phones and tablets, the development of large-area, flexible electronics offers great opportunities for interactive technologies on an even larger scale. Indeed, technologies that were once considered science fiction are now becoming a reality, the transparent display and associated smart surface being a case in point. These technologically significant developments beg the question, "What will be the development trend of interactive technology?" This section reviews current mainstream interactivity techniques and predicts what we believe will be future interactive technologies.

Human–machine interactivity can be categorized based on touch or touch-free gestures. The former is employed primarily in the small- and medium-scale panels used in smart phones and tablets, while the latter is more popular in larger displays [12]. Various techniques for interactivity have been developed. Currently these are based mainly on resistive, capacitive, surface acoustic wave, acoustic pulse recognition, and infrared schemes [3]. Recently, touch-free (e.g., gesture recognition by optical imaging) and force-touch technologies have emerged and are now in commercial devices. These advanced features bring human–machine interactivity to a new level of user experience.

1.1 Touch Interactivity Architectures

A variety of techniques have been proposed and implemented for touch panels, including resistive-, capacitive-, acoustic-, and infrared-based architectures.

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Among them, the capacitive-based touch panel has dominated the market in recent years, in view of its excellent optical clarity, high accuracy, and multi-touch support. Other techniques have obvious drawbacks that limit their successful use in commercial interactive displays. For example, resistive-based techniques cannot support multi-touch events; acoustic-based techniques have non-touch areas in the presence of solid contaminants; and infrared-based touch interfaces are prone to low detection accuracy in the presence of strong sunlight. We first review all of the foregoing techniques along with a comparison table that summarizes their merits and drawbacks.

The first generation of touch panels employed resistive-based architectures [4]–[8], in which two transparent electrically resistive layers are separated by spacer dots and connected to conductive bars in the horizontal (x-axis) and the vertical (y-axis) sides, respectively. A voltage applied on one layer can be sensed by the other layer, and vice versa. When the user touches the panel, the two layers are connected at the touch point and work as voltage dividers, and the touch location is then calculated. These first-generation devices were limited to locating a single point, restricting their use for complex gestures.

In capacitive-based touch panels, electrodes are arranged as rows and columns and are separated by an insulating material such as glass or thin film dielectric. When a conductive object comes in contact with the panel surface, the electric field is perturbed, hence changing the capacitance between electrodes [9]–[15]. Capacitive touch panels are most commonly used in smart phones because they support multi-touch sensing without altering the visibility and transparency of the display.

In surface acoustic wave and acoustic pulse recognition interactivity schemes, the touch position is detected by acoustic waves [16]–[21]. In the former, ultrasonic waves are transmitted and reflected in the x- and y-directions. By measuring the touch-induced absorption of the waves, the location can be determined. In acoustic pulse recognition, transducers are fitted at the edges of the touch panel. A touch action on the panel surface generates a sound wave that is then detected by the transducers, digitalized, and subsequently processed to determine the touch position.

In the infrared-based architecture, two adjacent sides of a touch panel are equipped with light-emitting diodes, which face photodetectors on the opposite sides, forming an infrared grid pattern [22]–[26]. The touch object (e.g., finger or stylus) disrupts the grid pattern, from which the touch location is determined.

The techniques described in the preceding paragraphs detect two-dimensional single- or multi-touch, i.e., touch locations on an x–y plane. Table 1.1 summarizes their main pros and cons. Commercial products recently released by Apple support force sensing, expanding touch interactivity to three dimensions

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Table 1.1 Comparison of mainstream contact touch technologies

Working Principle	Multi-touch?	Glove Touch?	Hover Touch	Optical Clarity	Outdoor Operability
Resistive	No	Yes	No	Medium	Good
Capacitive	Yes	No	Yes (but very short distance)	Good	No in rain
Acoustic	No	Yes	No	Good	Good
Infrared	Yes	Yes	No	Excellent	No under strong sunlight

[27]–[29]. Here, panel deflection, and hence the corresponding change in capacitance, serves as a measure of the extent of applied force, which is then augmented with a haptic response.

1.2 Touch-Free Interactivity Architecture

While a variety of touch technologies are currently in use in products, touch-free gesture recognition has emerged recently. One current technique relies on locating discrete infrared sources and detectors at different positions on the display edges to construct the touch event. However, imaging is not possible because of the discrete nature of the sensors. The pixelated approach reported recently employs an image sensor integrated at every display pixel, thereby making it possible for the display to view the underlying gestures of the user. Alternately, the event can be remotely triggered by a light pen [30]–[35]. The interactive display can be transparent using, e.g., oxide semiconductor technology, and be able to carry out invisible image capture. This development has the potential for a high technological impact in human interfaces.

Voice recognition is another technique for remote interactivity [36]–[40]. Tremendous progress has been made in this area, with very impressive results. Existing commercial products include Siri and Echo from Apple and Amazon respectively. Even so, challenges remain in voice signal processing and machine limitations of speech perception, particularly with differently spelled but similar-sounding words, and signal recognition in a noisy acoustic background. These problems can be eventually overcome with the use of much faster processers and more memory to bring into consideration contextual information.

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1.3 Future Human–Machine Interface

Current mainstream human–machine interactive (HMI) technology–touch panel (TP) has two shortcomings. First, recently developed TPs employ a single sensing technique to detect one certain type of physical signal (one-dimensional sensing), as explained earlier and illustrated in Fig. 1.1a–f. Thus, multiple discrete devices with different sensing capabilities must be embedded into a single system to allow multi-dimensional sensing. For example, optical, temperature, and force sensors are integrated into commercial mobile phones to provide multi-dimensional signal detection functions for customers. However, this results in increased component costs, circuitry complexity, and power consumption. Second, although the energy cost is very small for the individual touch sensors in a TP, their total energy consumption is huge, considering numerous touch panels are intensively used worldwide. Besides optimizing the product design to reduce power consumption,

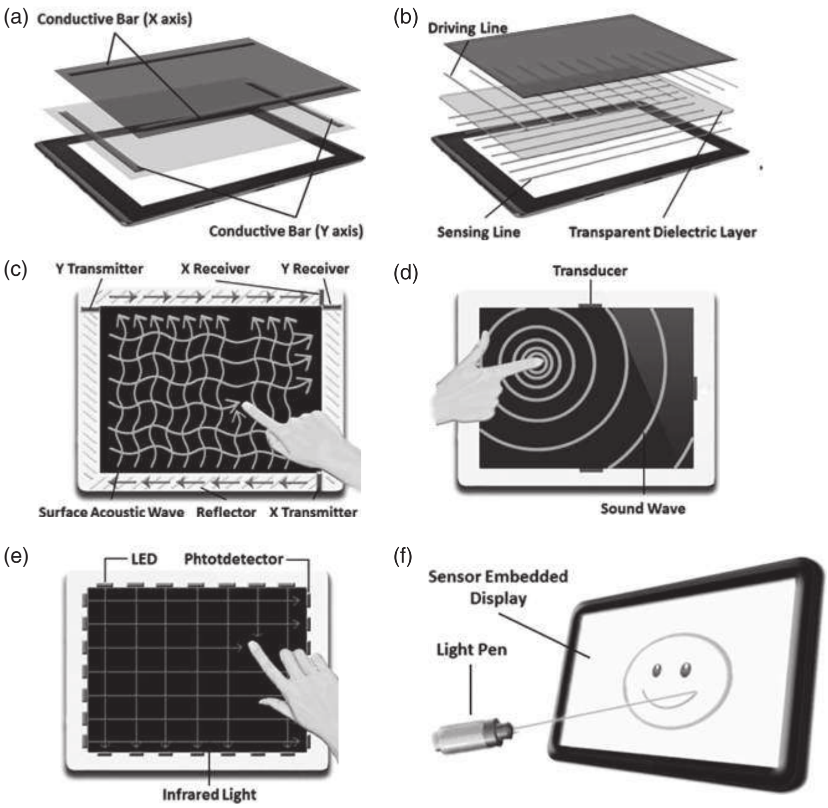

Figure 1.1 Interactivity based on (a) resistive, (b) capacitive, (c) surface acoustic wave, (d) acoustic pulse recognition, and (e) infrared touch architectures, and (f) touch-free interactive display based on image sensor.

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which approaches the limits of current technology, harvesting the environmental energy is essential to enhance the lifetime of the battery.

Thus, in the foreseeable future, the key task is to design and implement a multi-functional TP for multi-dimensional sensing along with possible applications to energy harvesting. First, multi-dimensional signals must be detected concurrently, providing customers with a user experience similar to that afforded using multiple mono-dimensional sensors. Second, because TP is a highly commercialized product, the proposed technique should fit well with existing TP techniques to avoid or reduce changes to production lines. Third, potential issues of the proposed technique need to be analysed and addressed. Last but not least, flexibility is a very important attribute for TPs, with the potential to enable and enhance a variety of applications to bring customers novel and advanced experiences.

To achieve these objectives, first, flexible functional materials are expected to be employed, owing to their inherent capabilities for flexibility and response to external stimuli. Specifically, in line with this work, piezoelectric materials will be used to assemble a prototype for demonstrating the authors' strategy, because of their intrinsic ability to convert mechanical stress to electric charges, providing the functions of force touch detection and energy harvesting. Second, the piezoelectric materials will be combined with capacitive touch panels, which dominate the TP market [41]–[43]. Third, algorithms on how to interpret these two signals will be developed.

1.4 Outline of this Element

This Element charts the authors' work on the understanding of capacitive TP and piezoelectric materials and the development of a multi-functional touch panel from theoretical analysis to touch panel fabrication and algorithm design. Section 2 provides literature reviews on capacitive touch panel and piezoelectric materials. The multi-functional touch panel for concurrently sensing force and capacitive stimuli is proposed at the end of this section. In Section 3, a theoretical analysis of the proposed technique is provided in mechanical and electrical terms, followed by a description of preliminary experiments for the purpose of validating the concept. The proposed multi-functional touch panel is fabricated and measured in Section 4. The experimental results demonstrate its good mechanical and electric response to touch events. Section 5 focuses on design and implementation of the algorithm for interpreting the force touch signal. Two practical issues facing force touch sensing are first addressed with the help of the capacitive touch signal: static force touch detection and stress propagation. Next, an algorithm is developed to achieve concurrent force touch

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detection and energy harvesting. Finally, the conclusions and technological outlook are described in Section 6.

2 Reviews on Capacitive Touch Panel– and Piezoelectric–Related Technologies

In the previous section, the need for a simple-structured multi-functional touch panel was explained, along with the design requirements for the multi-functional touch panel. To develop a piezoelectric material–based capacitive touch panel, it is necessary to gain an understanding of the capacitive touch panel and piezoelectric materials.

In this section, brief literature reviews are provided, first in terms of the working principles of projected capacitive touch panels and piezoelectric materials. Next, the design considerations of embedding piezoelectric material into capacitive touch panels are given through theoretical analysis and practical experiments. Finally, a multi-layered stack-up is proposed to achieve multi-functionality.

2.1 A Brief Overview of the Projected Capacitance Touch Panel

2.1.1 Working Principle and Panel Architecture

A projected capacitance touch panel system detects capacitance variations at electrodes to recognize the touch event [4], [9]. When a conductive object (e.g., human finger) is in close proximity to or in contact with the touch panel, the surrounding electromagnetic field is perturbed, altering the capacitance between electrodes. This is sensed and the signal is then digitalized and sent to the microcontroller (MCU) to determine the potential touch event and corresponding location. Two architectures broadly used are based on modulation of the self-capacitance and mutual capacitance.

In self-capacitance TP, the capacitance between electrodes to ground is measured [9], [44]–[46]. When a conductive object is approaching the electrode (electrodes are normally protected by a layer of dielectric cover, e.g., glass, and therefore cannot be contacted), the capacitance from the electrode to the ground is increased, and hence a touch event is detected. Two types of self-capacitance are constructed – multi-pad and row-and-column [9] – as shown in Fig. 2.1. In a multi-pad structure, each pad is connected with the controller individually; thus multi-touch is supported. In a row-and-column structure, each of the rows and columns is an electrode, instead of a pad as in a multi-pad structure, and individually connected with the processor. Although each intersection of rows and columns indicates a unique location on the touch panel, it cannot support multi-touch sensing because each electrode is measured, instead of each

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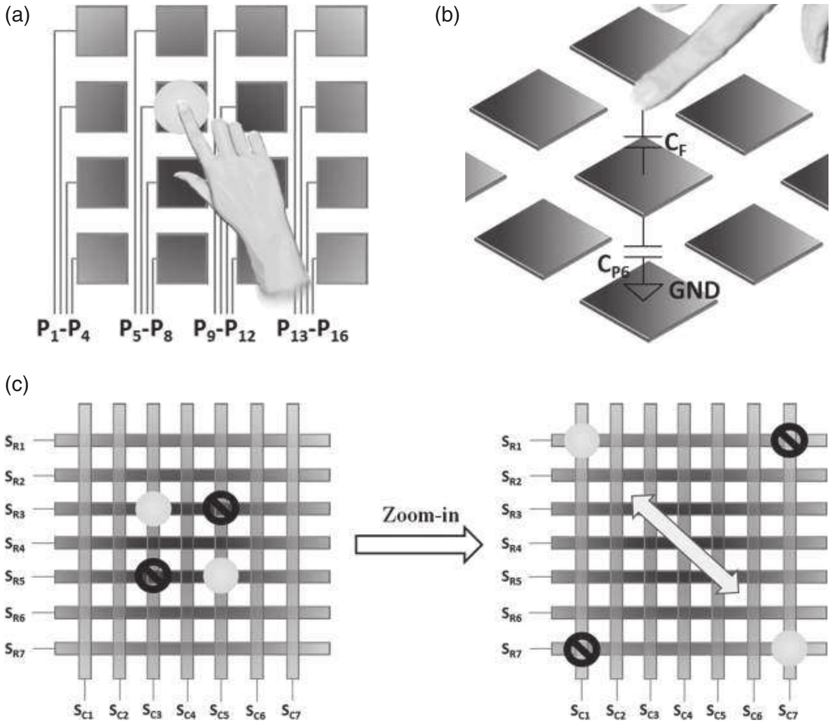

Figure 2.1 (a) Multi-pad structure in self-capacitance TP; P_1 to P_{16} indicate the number of the touch pads. The yellow point represents the touch location. (b) Working principle of multi-pad structured self-capacitance TP. CP_6 is the capacitance between touch-pad P_6 to ground and C_F is the finger touch induced capacitance. (c) Ghost points in row-and-column structured self-capacitance. SR_1 to SR_7 and SC_1 to SC_7 indicate the row and column sensing electrode 1 to 7, respectively. The yellow points and black block signs are the real touch locations and ghost point locations.

intersection. Thus when multi-touch is performed, ghost points are made as illustrated in Fig. 2.1c.

However, the zoom-in/zoom-out function still works, as the distances between the interpreted touch locations are calculated by software. When the distance increases, a zoom-in action can be interpreted. In contrast, a decrement of distance between registered touch locations indicates a zoom-out action. One advantage of the self-capacitance structure is its ability to detect hover touch and glove touch, as long-distance field projection is normally used [46].

Alternatively, in mutual-capacitance TP, the mutual capacitance between two electrodes is measured [46], [47]. In mutual-capacitance–based techniques, row-and-column structured electrodes are normally employed [47].

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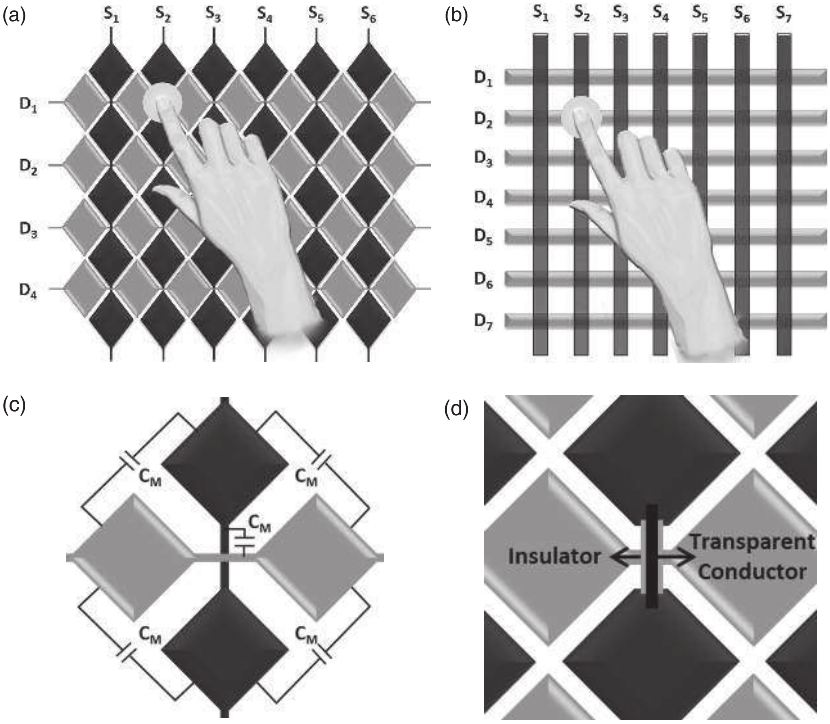

Figure 2.2 (a), (b) Mutual-capacitance diamond structure and bar structure. The yellow points indicate the touch locations. (c), (d) Working principle of mutual-capacitance structure.

Electrodes in rows function as driving lines and electrodes in columns work as sensing lines, or vice versa. Each intersection of rows and columns indicates a unique location (each location can be treated as a pixel; hence many image-related techniques are used to process touch signals), and each intersection will be sensed individually. By periodically scanning electrode intersections, multi-touch detection is supported. As shown in Fig. 2.2, electrodes in rows are arranged from D_0 to D_N, which are powered separately. The capacitance values of intersections with the sensing lines from S_1 to S_M will be detected in sequence to achieve multi-touch detection. When a conductive object contacts the panel cover, the mutual capacitance is decreased because charges are taken by the human finger, as conceptually shown in Fig. 2.3. Compared to the self-capacitance architecture TP, one major disadvantage of mutual-capacitance TP is considerable scanning time for a full-panel measurement. State-of-the-art commercial products have a sensing rate from 20 Hz to 200 Hz [9], while some laboratory-used and -developed touch panels can achieve a higher sensing rate, up to 6,400 Hz[3], [14], [46]–[54].

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Table 2.1 Main distinctions between self-capacitance and mutual-capacitance structures

Characteristic	Self-Capacitance	Mutual- Capacitance
Electrode type	Sensing	Driving and sensing
Number of layers	1 or 2	1 or 2
Electrode design	Multi-pad/row-and–column	Unique electrode intersections
Scanning method	Each electrode	Each electrode intersection
Whole panel scanning time	⧗	⧗ ⧗
Measured capacitance	Capacitance of electrode to ground	Capacitance between electrodes
Ghost point	Yes for row-and-column structure	No
EMI robustness	Bad	Good

EMI, electro-magnetic interference.
Modified from [2]–[6].

The main distinctions between self-capacitance and mutual-capacitance structures are summarized in Table 2.1.

2.1.2 Touch Panel Construction

Almost all the projected capacitive touch panels share two basic features in their construction [46]. First, the touch surface is above the sensing circuits; second, all the components are fixed, which means there are no moving parts. A typical two-layer projected capacitance construction concept is shown in Fig. 2.4. Two transparent thin-film ITO conductors are separated by a thin-film insulator (normally glass or polyethylene terephthalate [PET]), and a touch surface is set on top of them.

The sheet resistance and line widths of the patterned indium tin oxide (ITO) layer are normally 150 Ω/γ and 20 µm when glass is used as substrate [9]. In contrast, when PET is employed as a substrate, the line widths are typically 100 to 200 µm [9], due to the reduced flatness compared to glass. For glass substrate–related ITO patterning, photolithographic methods are widely used. As to the PET substrate, more techniques can be applied for ITO patterning, such as panel printing [9]. Although the sheet resistance and line widths of the PET substrate–based patterning are higher and larger than those of the glass substrate–based patterning, the advantage of using a PET substrate is its thinness. The thickness of a PET substrate

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is usually 50 μm to 100 μm [9], [44], [55], [56]. Alternatively, the thickness of a glass substrate is 0.2 mm to 0.4 mm [9], [44]. A detailed comparison of a PET substrate versus glass substrate is given in Table 2.2. Optical clearance adhesive (OCA) is widely used to glue the multi-layered structure [9], [46].

Table 2.2 Main distinctions between self-capacitance and mutual-capacitance structures

Characteristic	PET	Glass
Glass transition Temperature	70°C	570°C
Aging effects	Yellowing, curling, surface deformation	No known effect
Transparency	85%	≥90%
Resolution	10–30 μm	1 μm
Stack-up	Thinner	Thicker
Weight	Lighter	Heavier
Lamination yield	Excellent	Good
Cost	$$ (was less than for glass)	$

Modified from [2], [3].

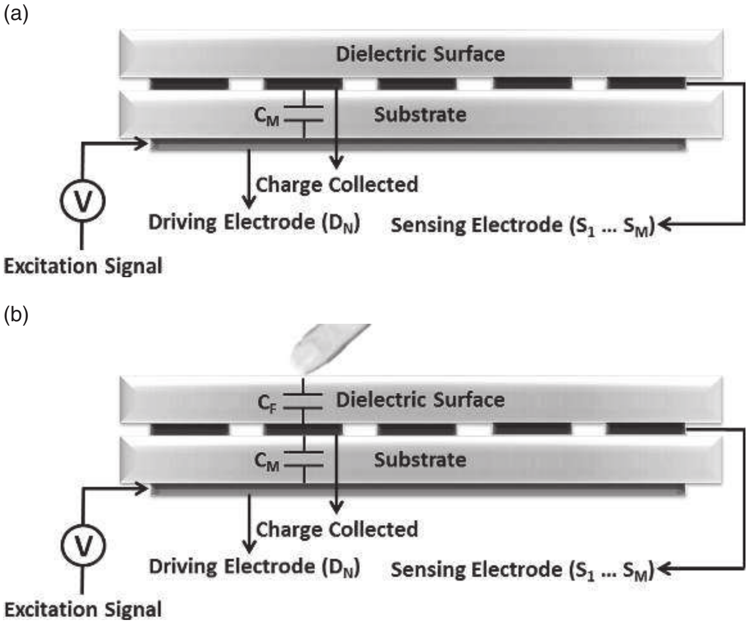

Figure 2.3 Working principle of mutual-capacitance structure (a) without and (b) with a finger touch.

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