A review of technologies for sensing contact location on the surface of a display

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Abstract — Touchscreen interactive devices have become increasingly important in both consumer and commercial applications. This paper provides a broad overview of all touchscreen technologies in use today, organized into 13 categories with 38 variations. The 13 categories are projected capacitive, analog resistive, surface capacitive, surface acoustic wave, infrared, camera-based optical, liquid crystal display in-cell, bending wave, force sensing, planar scatter detection, vision-based, electromagnetic resonance, and combinations of technologies. The information provided on each touchscreen technology includes a little history, some basic theory of operation, the most common applications, the key advantages and disadvantages, a few current issues or trends, and the author's opinion of the future outlook for the technology. Because of its dominance, this paper begins with projected capacitive; more information is provided on this technology than on any of the other touch technologies that are discussed. This paper covers only technologies that operate by contact with a display screen; this excludes technologies such as 3D gesture recognition, touch on opaque devices such as interactive whiteboards, and proximity sensing. This is not a highly technical paper; it sacrifices depth of information on any one technology for breadth of information on multiple technologies.

Keywords — touch technologies; touchscreen; touch panel; projected capacitive; in-cell; on-cell.

DOI # 10.1002/jsid.100

1 Introduction

Touchscreen interactive devices have become increasingly important in both consumer and commercial applications, with over one billion touchscreens shipped in 2011.[1] This paper provides a broad overview of all touchscreen technologies in use today, organized into 13 categories with a total of 38 variations. The information provided on each touch technology includes a little history, some basic theory of operation, the most common applications, the key advantages and disadvantages, a few current issues or trends, and the author's opinion of the future outlook for the technology. This paper covers only technologies that operate by contact with a display screen; this excludes technologies such as three-dimensional (3D) gesture recognition, touch on opaque devices such as interactive whiteboards, and proximity sensing. This is not a highly technical paper; it sacrifices depth of technical information on any one technology for breadth of information on multiple technologies. In this paper (and throughout this issue of Journal of the Society for Information Display), the terms "touchscreen" and "touch panel" are synonymous; both refer to a module consisting of a touch sensor and a touch controller (the former term is more commonly used in the West, whereas the latter term is more commonly used in Asia). Also in this paper, projected capacitive touch technology is often abbreviated as "p-cap." The touch industry has not yet settled on a single term for p-cap technology; it is also called "Pro-Cap," "PCT" (p-cap touch [or] technology), and increasingly, just "capacitive," as surface-capacitive technology becomes ever less relevant.

1.1 Context

As shown in Fig. 1, analog resistive and p-cap touch technologies dominate the touch landscape today. Together they accounted for more than 80% of revenue and 95% of units shipped in 2011. Resistive was historically always the largest technology in both revenue and units, but p-cap overtook resistive in revenue in 2010 and in units in 2011 [1]. Because of this dominance, this paper begins with p-cap; more information is provided on this technology than on any of the other touch technologies that are discussed.

2 Projected capacitive (p-cap)

Worldwide sales of p-cap were less than $20m in 2006, growing to over $7b in 2011. More than 95% of the $7b was in the consumer electronics market, with more than 75% in smartphones and tablets. Contrary to popular belief, Apple did not invent p-cap (or multi-touch!). The history of p-cap is less clear than that of many other touch technologies. The basic concept of sensing touch by measuring a change in capacitance has been known since at least the 1960s. In fact, the first transparent touchscreen, invented in 1965 for use on air-traffic system-control terminals in the UK, used a form of capacitive sensing.[2] Surface-capacitance touch technology (with an unpatterned sensor) was commercialized by MicroTouch Systems around 1985. During the mid-1990s, several US companies developed transparent capacitive touchscreens

Received 05/15/12; accepted 06/27/12.
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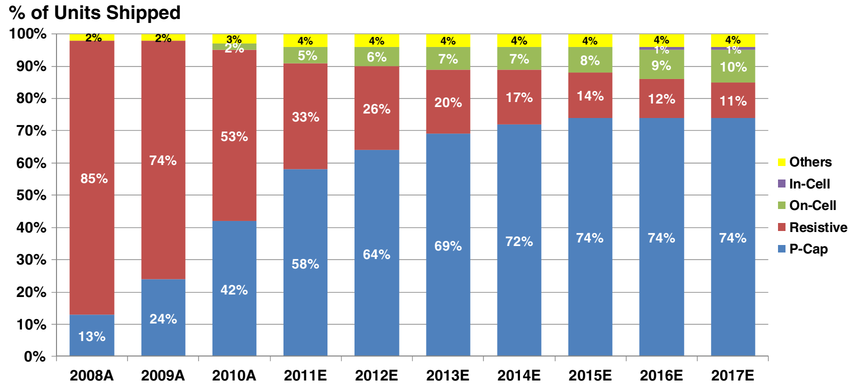


FIGURE 1 — The touch world is already well into a transition from analog resistive (red) to projected capacitive (blue) as the dominant touch technology. The figure combines the opinions of an Asian investment bank (Guoxin Securities), the world's largest touchscreen supplier (TPK) and world's number one touch market research firm (DisplaySearch). Source: Guoxin Securities, TPK, and DisplaySearch.

with patterned sensors by using indium tin oxide (ITO, the foundation of today's p-cap). Two of these were Dynapro Thin Films and MicroTouch Systems; both of which were later acquired by 3M (in 2000 and 2001, respectively) to form 3M Touch Systems. Dynapro Thin Films' p-cap touchscreen technology, known as "Near-Field Imaging," became 3M's first p-cap product in 2001. Also in 1994, an individual inventor in the UK named Ronald Peter Binstead developed a form of p-cap by using microfine (25 micron) wire as the sensing electrode.[3] He licensed the technology to two UK companies: Zytronic in 1998 and Visual Planet in 2003; both are still selling it today.

P-cap remained a little-known niche technology until Apple used it in the first iPhone in 2007. Apple's engaging and immersive user interface was an instant hit, causing most other smartphone manufacturers to immediately adopt the technology. Over the next 5 years, p-cap sets a new standard for the desirable characteristics of touch in the minds of more than one billion consumers, as follows:

- Multiple simultaneous touches ("multi-touch" for zoom)
- Extremely light touch with flick/swipe gestures (no pressure required)
- Flush touch surface ("zero bezel")
- Excellent optical performance
- Extremely smooth and fast scrolling
- Reliable and durable
- Fully integrated into the device user experience so that using it is effortless and fun

2.1 P-cap fundamentals

There are two basic kinds of p-cap: self-capacitance and mutual capacitance. Both are illustrated in Fig. 2. Self-capacitance is based on measuring the capacitance of a "single" electrode with respect to ground. When a finger is near the electrode, the capacitance of the human body increases the self-capacitance of the electrode with respect to ground. In contrast, mutual capacitance is based on measuring the capacitance between a "pair" of electrodes. When a finger is near the pair of electrodes, the capacitance of the human body to ground "steals" some of the charge between two electrodes, thus reducing the capacitance between the electrodes.[4]

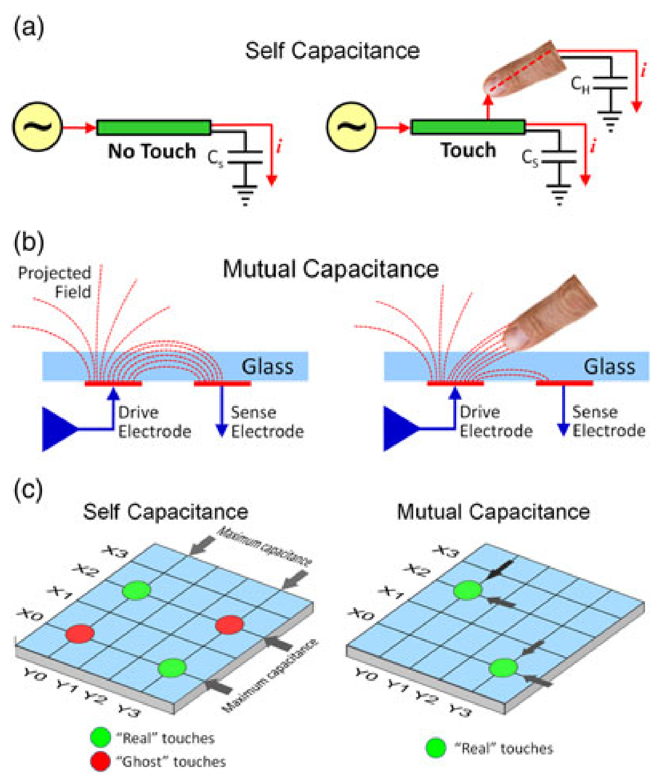


FIGURE 2 — Self-capacitance (a) is the capacitance of a single electrode to ground. When a finger is near the electrode, human body capacitance to ground "increases" the total self-capacitance of the electrode. Mutual capacitance (b) is the capacitance between two electrodes. When a finger is near the electrodes, it "steals" some charge from the drive electrode, "reducing" the mutual capacitance between the two electrodes. In an X–Y self-capacitance grid (c, left), each row and column electrode is scanned individually. If the sensor is touched with two fingers that are diagonally separated, the controller sees two maximums on each axis, but cannot tell which pair of maximums is the real touch points. In an X–Y mutual-capacitance grid (c, right), each electrode intersection is scanned individually, allowing multiple touch points to be unambiguously identified. Source: 3M and Touch International; redrawn by the author.

Although it seems that the difference between self and mutual capacitance could be determined by the number of electrodes, the key difference is actually in how the electrodes are measured. Regardless of how they are configured, the electrodes in a self-capacitance touchscreen are measured individually, one at a time. For example, even if the electrodes are configured in a two-layer X–Y matrix, all the X-electrodes are measured, and then all the Y-electrodes are measured in sequence. If a single finger is touching the screen, the result is that the nearest X-electrode and the nearest Y-electrode will both be detected as having maximum capacitance. However, as shown in Fig. 2(c), if the screen is touched with two or more fingers that are diagonally separated, there will be multiple maximums on each axis, and "ghost" touch points will be detected as well as "real" touch points (ghost points are false touches positionally related to real touches). Note that this disadvantage does not eliminate the possibility of using two-finger gestures on a self-capacitive touchscreen. Rather than using the ambiguous "location" of the reported points, software can use the "direction of movement" of the points. In this situation, it does not matter that four points resulted from two touches; as long as pairs are moving toward or away from each other (for example), a zoom gesture can be recognized. For this reason and because self-capacitance can be of lower cost than mutual capacitance, the former is often used on lower-capability mobile phones.

In contrast, in a mutual-capacitive touchscreen, each electrode "intersection" is measured individually. Generally, this is accomplished by driving a single X-electrode, measuring each Y (intersecting) electrode, and then repeating the process until all the X-electrodes have been driven. This measurement methodology allows the controller to unambiguously identify every touch point on the touchscreen. Because of its ability to correctly process multiple touch points (moving or not), mutual capacitance is used in preference to self-capacitance in most smartphones and tablets today.

2.2 P-cap controllers

In every case, the measurement of electrode capacitance is accomplished by a touch controller. Figure 3 illustrates the basic structure of a controller for a mutual-capacitance touchscreen. A sensor driver excites each X-electrode one at a time. An analog front-end measures the capacitance at the intersection of each Y-electrode and the excited X-electrode; the analog values are converted to digital by an analog-to-

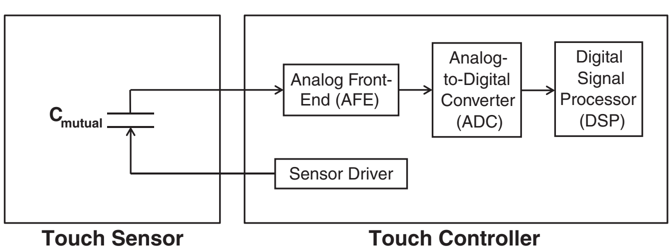


FIGURE 3 — A projected capacitive touch controller consists of only four main elements: a sensor driver to excite the drive electrodes, an analog front-end (AFE) to read the sense electrodes, an analog-to-digital converter (ADC), and a digital signal processor (DSP). Source: Maxim Integrated Products.

digital converter. A digital signal processor runs highly sophisticated algorithms to process the array of digital capacitance data and convert it into touch locations and areas, along with a variety of related processing such as "grip suppression" (the elimination of undesired touches near the edge of the screen resulting from holding a device) and "palm rejection" (the elimination of unintended touches resulting from the edge or base of your palm contacting the screen in the process of touching with a finger). A p-cap touch controller is an example of an application-specific integrated circuit (ASIC).[5]

Controllers are where most of the innovation is happening in p-cap today, although the geometry of the sensor pattern is also an ongoing contributor to performance improvement. The top three controller suppliers (Atmel, Cypress, and Synaptics, who together accounted for more than half of the p-cap controller unit shipments in 2011) are all US-based companies.[6] This could be taken as a sign of the relative youth of the p-cap controller industry because most system-level ASICs eventually become commoditized with suppliers based in Asia. An example of recent p-cap controller innovation is the significant increase in touch system signal-to-noise ratio (SNR) that has occurred during the last 18 months. The value of this innovation is that is allows p-cap touchscreens to support an active or passive stylus with a 1-mm tip, rather than just a human finger. Multiple p-cap controller suppliers have demonstrated or talked about this capability with regard to their latest controllers, although there has not been enough time for it to show up in consumer electronic products on the shelf yet.[4,7]

A fine-tipped stylus adds a large amount of value to a smartphone or tablet. It allows the user to "create" data (drawings, notes, etc.) rather than just "consume" media. In Asia, it is highly desirable to write Kanji characters on a smartphone, and finger writing is impractical because the tip of your finger obscures what you are writing. A fine-tipped stylus is also excellent as a pointing device for use with software that was not designed for touch (e.g., legacy Windows applications running on a Windows 8 tablet in "desktop" mode).

2.3 P-cap sensors

A p-cap sensor is at heart a set of transparent conductive electrodes used by the controller to determine touch locations. In self-capacitance touchscreens, transparent conductors are patterned into spatially separated electrodes in either a single layer or two layers. When the electrodes are in a single layer, each electrode represents a different touch coordinate pair and is connected individually to a controller. When the electrodes are in two layers, they are usually arranged in a layer of rows and a layer of columns. The intersection of each row and column represents unique touch coordinate pairs; however, as noted in the previous section, in self-capacitance, each electrode is measured individually rather than measuring each intersection with other electrodes, so the multi-touch capability of this configuration is limited.

In a mutual-capacitance touchscreen, there are almost always two sets of spatially separated electrodes. In higher-performance touchscreens (such as that in the iPhone), the electrodes are usually arranged in a rectilinear grid of rows and columns, spatially separated by an insulating layer or a film or glass substrate. In contrast, the most commonly used electrode pattern is an interlocking diamond consisting of squares on a 45° angle, connected at two corners via a small bridge. When this pattern is used on two spatially separated layers, the processing of each layer is straightforward. However, this pattern is often applied in a single "coplanar" layer to achieve the thinnest possible touchscreen. In this case, the bridges require additional processing steps to (1) insulate the first ITO bridge before depositing the second (intersecting) ITO bridge or (2) omit the second ITO bridge during deposition and replace it with a metal "microcrossover" bridge.

Figure 4 illustrates the stack-up of a typical mutual-capacitance touchscreen. To keep this and all similar drawings in this paper as easy to understand as possible, several simplifications have been made, as follows. (1) The electrode pattern shown (rows 3 and 5) is a rectilinear grid rather than the more common interlocking diamond; row 3 shows the end views of the Y-electrodes, whereas row 5 shows a side view of one X-electrode. (2) The common use of optically clear adhesive has been omitted; for example, the space between rows 2 and 3 is typically filled with optically clear adhesive. (3) The touchscreen is shown using a glass substrate; in lower-end mobile phones, the substrate is often two layers of polyethylene terephthalate (PET) film, one for each set of electrodes. (4) All the layers below the thin film transistor (TFT)-array glass in the liquid crystal display (LCD) (e.g., bottom polarizer, brightness enhancement films, and backlight) have been omitted.

One of the key points made in Fig. 4 is that the touchscreen adds a fourth sheet of glass to the stack-up. All LCDs use two sheets of glass, and essentially, every mobile device adds a third sheet of glass (or Poly(methyl methacrylate) (PMMA)) as a protective and decorative covering over the LCD. Adding a fourth sheet of glass is generally considered to be undesirable because it adds weight, thickness, and cost to the mobile device. There are two basic methods of eliminating the fourth sheet of glass: (1) the method used by the touchscreen industry, called "one-glass solution," "sensor on lens," or a variety of company-specific names, and (2) the method used by the LCD industry, called "on-cell touch." These methods are in direct competition.

Figure 5 illustrates the one-glass solution, in which the touchscreen electrodes are moved to the underside of the decorated cover glass ("lens").[8] In this solution, the touchscreen manufacturer either purchases the decorated cover glass from an appropriate supplier or vertically integrates and acquires the equipment and skills necessary to manufacture the cover glass. The touchscreen manufacturer then builds the touch module (sensor plus controller) by using the decorated cover glass as a substrate and sells the entire assembly to a mobile device Original Equipment Manufacturer/Original Design Manufacturer (OEM/ODM) (as is often the case, the touchscreen manufacturer may also obtain the LCD on consignment from the device OEM/ODM and integrate the touchscreen module with the LCD). The advantage of the one-glass solution to the end user is that the mobile device is lighter and thinner because of the elimination of the fourth piece of glass. The advantage of the one-glass solution to the touchscreen manufacturer is that they continue to derive revenue from the production of touchscreens instead of forfeiting revenue to the LCD industry.

Figure 6 illustrates the on-cell touch solution, in which the fourth piece of glass is eliminated by moving the touchscreen

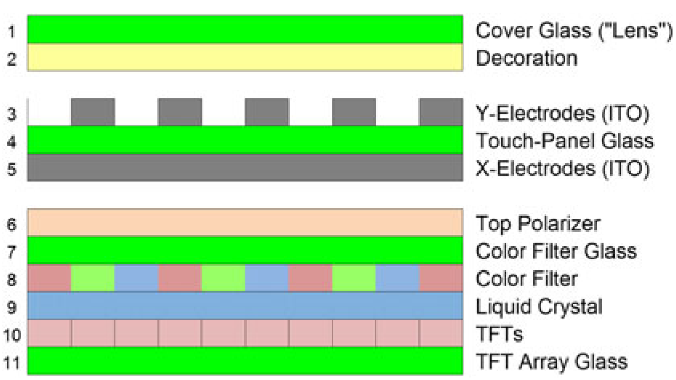


FIGURE 4 — All smartphones and tablets use some form of "decorated covering" (rows 1 and 2) to protect the LCD (rows 6–11) from damage. When a projected capacitive touchscreen is added, most commonly, the electrodes are located on a fourth piece of glass (rows 3–5). ITO, indium tin oxide; TFT, thin film transistor. Source: the author.

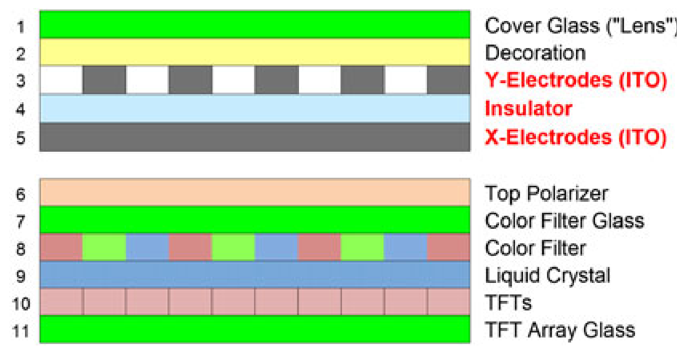


FIGURE 5 — This figure depicts the p-cap "one-glass solution" (also called "sensor on lens") configuration used by the touchscreen industry. To eliminate the fourth piece of glass, the p-cap electrodes are moved to the bottom surface of the decorated cover glass (rows 3–5). ITO, indium tin oxide; TFT, thin film transistor. Source: the author.

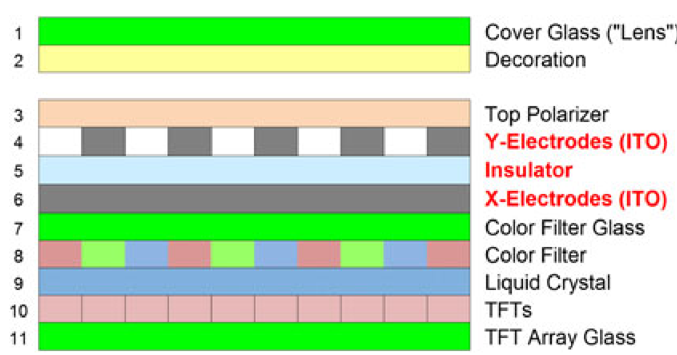


FIGURE 6 — In the on-cell touch sensor configuration used by the liquid crystal display industry, the fourth piece of glass is eliminated by moving the p-cap electrodes to the top of the color filter glass, underneath the top polarizer (rows 4–6). The touch functionality is exactly the same as in Figure 5. ITO, indium tin oxide; TFT, thin film transistor. Source: the author.

electrodes to the top of the color filter glass, underneath the LCD's top polarizer. Note that an on-cell configuration is standard p-cap with exactly the same functionality as in Figs. 3 and 4; only the location of the electrodes is different. The advantage of the on-cell solution to the end user is exactly the same as the one-glass solution—the mobile device is lighter and thinner because of the elimination of the fourth piece of glass. The advantage of the on-cell solution to the LCD manufacturer is that it increases their revenue because of the added value of touch functionality (but the touchscreen manufacturer loses revenue).

One other factor in on-cell's favor is that with the touch sensor integrated into the LCD, it makes sense to consider integrating the touch controller and the display driver together into a single ASIC or at least establishing a direct connection between the two chips to enable cooperation. Manufacturing yield can be more of an issue with on-cell because depositing the electrodes on the top surface of the color filter glass substantially increases the value of that one piece of glass; if either the color filter or the touch electrode deposition is defective, both must be discarded. Product-line management is also an issue for the LCD manufacturer—for example, should every LCD be designed with on-cell touch included or only some models? Should there be two versions of a high-volume LCD, one with on-cell and one without?

It should be clear from the aforementioned that on-cell touch is not necessarily an automatically better solution than one-glass. There are factors to be considered on both sides, and some of those factors are more business-related and operational-related than technical. Competition between touch module manufacturers and LCD manufacturers will remain a major factor in the progression of on-cell. The author believes that on-cell will achieve only limited success in the next 5 years, accounting for no more than 10%–15% of all p-cap touch in consumer electronics applications and much less (if any) in commercial applications.

2.4 ITO-replacement materials for p-cap sensors

ITO-replacement materials eliminate the need for vacuum sputtering; patterning of ITO-replacement materials can be carried out at room temperature in a normal atmosphere without the need for an expensive fab. This is potentially a highly disruptive technology.

Because of the fine resolution required in creating the pattern (e.g., 20-micron-wide ITO conductors) and the relatively large number of electrode connections that must fit in a very narrow space at the edge of the touchscreen, most glass-based sensors are patterned using photolithography on a fabrication plant ("fab"). There are three basic sources of fabs: (1) converted from LCD color filter fabs, (2) converted from passive LCD fabs, and (3) purpose built. Existing p-cap fabs were expanded at a very rapid rate in 2011; the author estimates that the total capital expenditures ("capex") spent by the p-cap touch industry in 2011 was around $2b. The necessity of creating the sensor on a fab contributes substantially to the high cost of a p-cap touchscreen today. For example, a glass touchscreen module for a 10-in Android tablet in high volume currently costs the device OEM/ODM around $25 for the sensor, whereas the controller is typically under $5 (this does not include the cost of the cover glass and lamination).

There are at least five different materials competing to become the dominant ITO-replacement material, including copper metal mesh, silver nanowires, carbon nanotubes, conductive polymers, and ITO inks. In the author's opinion, the material with the most market traction so far is metal mesh. Two examples of companies working with metal mesh include Atmel and Unipixel. Atmel recently announced their XSense™ sensor film; it uses a metal mesh printed roll-to-roll on film.[9] Atmel's partner for the mesh and printing equipment is Conductive Inks Technology in the UK. Because the transparent conductor is metal, the material's sheet resistance is very low (less than 10 ohms/square and in some cases, as low as 0.6 ohms/square). This provides increased noise immunity and helps support both active and passive styli. Unipixel has been working for several years on its UniBoss copper metal mesh with a conductor size of 5 microns (invisible). The mesh can be printed roll-to-roll in a single pass at room temperature; Unipixel appears to be nearing production readiness.[10] In fact, scuttlebutt within the touch industry in June 2012 indicates that Unipixel is already providing (under NDA) small quantities of metal mesh for production of 32-in p-cap touchscreens.

Silver nanowires are a close second behind metal mesh. The leading supplier of this material is Cambrios; the optical and electrical properties (transmissivity and sheet resistance) of Cambrios' material are highly competitive with ITO. The material has been used by Synaptics in the first non-ITO p-cap touchscreen used in a smartphone (Samsung's CricKet™ brand, sold only in Asia).[11] This is much more important than it may seem; it is the beginning of direct competition for capital-intensive, high-cost p-cap sensor manufacturing.

3M is an example of a company working with both silver nanowires and metal mesh. 3M is planning to combine their well-known microreplication process with a solution-processable metal mesh or silver-nanowire material to create roll-to-roll printed p-cap sensors on film that can be laminated to glass. A joint venture between 3M and Quanta has been launched in Singapore to market 3M's p-cap sensors to the consumer electronics OEM/ODM manufacturing tablet and larger products (but not smartphones).[12]

The author believes that within 5 years, metal mesh and/or silver nanowires will be used in up to half of all tablet-sized and larger p-cap sensors because it will substantially reduce the cost of sensor production. This will put intense pressure on the owners of p-cap fabs, particularly those who specialize in larger touchscreens. If they cannot compete, many of those p-cap fabs will either become idle or be converted to some other use—similar to what happened to passive LCD fabs when TFT LCDs became dominant.

2.5 P-cap made with 10-micron wire instead of ITO

There are currently two forms of p-cap that are made with 10-micron wire instead of ITO. These are (1) self-capacitive, supporting one or two touches, and (2) mutual capacitive, supporting 10+ touches with palm rejection. Both of these forms are available on glass or plastic.

The self-capacitive form of wire-based p-cap has been on the market more than 10 years; it works by measuring a change in radio frequency (RF) signal frequency caused by the addition of human body capacity to an electrode (Binstead's IP) rather than directly measuring a change in the capacitance of the electrode. The best known supplier of this form of p-cap is Zytronic in the UK; their products have typically been glass based in 5-in to 15-in sizes and used in commercial applications such as Automatic Teller Machine (ATM) machines and point-of-sale terminals. In large-format applications, the best known supplier is Visual Planet (also in the UK); their products have typically been film based in 40-in to 100-in sizes and used in "through store-window" applications, where closed retailers engage potential customers outside of business hours by letting them interact with (for example) a product selection application through the store's windows. The significant visibility of the rather widely spaced wire pattern has always been somewhat of an impediment to this technology, although in applications where the viewing time is very short (such as in ATM machines), it is less of a problem.

The mutual-capacitive form of wire-based p-cap was introduced to the market in June 2012 by Zytronic.[13] It uses the more common technique of directly measuring the change in capacitance between electrodes rather than the RF-based technique used in the older self-capacitive products. The mutual-capacitive wire pattern is much denser than the self-capacitive version, consisting of 6×6 mm cells containing wires spaced about 1.5 mm apart. The wires in each cell cross (as expected in mutual capacitive) without problems because the wires are insulated. Because of its much higher density, the mutual-capacitive wire pattern is much harder to see (less visible) than the self-capacitive wire pattern. This lower visibility, along with the highly flexible automation that Zytronic has applied to the process of creating these touchscreens in any size up to 72 in (and larger later), portends a longer life than expected for the technology.

3 Analog resistive

The invention of analog resistive touchscreens is generally attributed to Elographics (now Elo TouchSystems) in 1971.[14] The original resistive technology was used in an opaque pen digitizer; it was not until 1977 that a transparent version (curved to fit the face of a CRT monitor) was developed. There is some possibility that Sierracin/Intrex's four-wire analog resistive touchscreen may actually predate Elo's transparent version because Sierracin/Intrex first started selling ITO-coated PET film in 1973.[15] In any case, at 35 years, resistive is the oldest touch technology currently in mass production.

An analog resistive touchscreen is simply a mechanical switch mechanism used to locate a touch. The construction of a typical resistive touchscreen is shown in Fig. 7. A glass substrate and a flexible film (usually PET) are both coated on one side with the transparent conductor ITO. With the two coated sides facing each other, the two conductive surfaces are separated by very small, transparent, insulating spacer dots. A voltage is applied across one or both of the sheets (depending on the type of resistive touchscreen). When a finger presses on the flexible film, the two conductive surfaces make electrical contact. The resistance of the ITO creates a voltage divider at the contact point; the ratio of the voltages is used to calculate the touch position.

3.1 Analog resistive variations

Resistive touch technology has three key variations: (1) the number of "wires," (2) the layer construction, and (3) the options. The number of wires refers to the number of connections to the sensor; the three common types are four-wire, five-wire, and eight-wire.

In a four-wire touchscreen (shown in Fig. 8), connections are made to bus bars on the left and right (X) edges of one conductive sheet, and bus bars on the top and bottom (Y) edges of the other. To determine the X position of the touch, the controller applies a voltage across the X connections and measures the voltage at one of the Y connections. The controller then reverses the process, applying voltage across

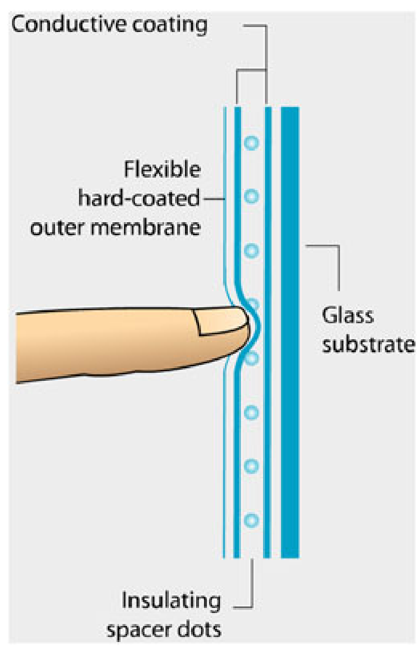


FIGURE 7 — An analog resistive touchscreen is simply a mechanical switch mechanism used to locate a touch. Two conductive layers are separated by tiny insulating spacer dots; when the two layers are pressed together, an electrical contact is made. The touch location is calculated from the ratio of voltages on the conductive layers. Source: Elo TouchSystems.

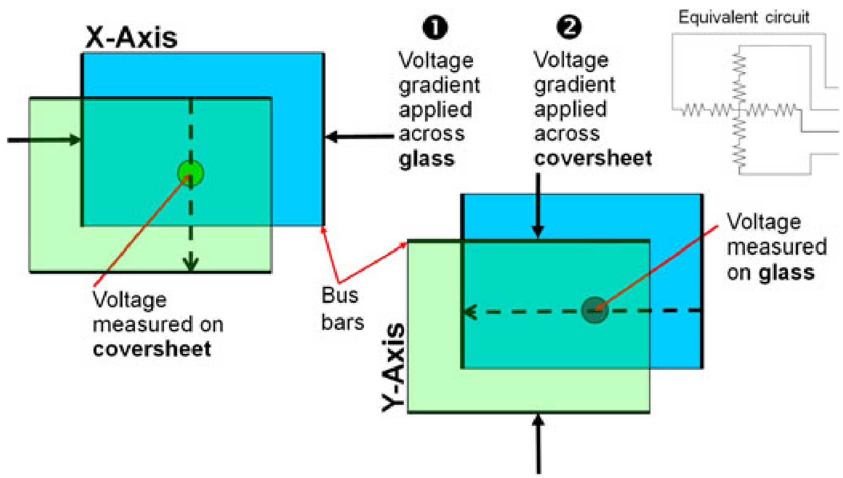


FIGURE 8 — In a four-wire touchscreen, a voltage gradient is applied between the two X-axis bus bars on the glass, and the resulting voltage is measured on the coversheet. Then, the voltage gradient is applied between the two Y-axis bus bars on the coversheet, and the resulting voltage is measured on the glass. Source: the author.

the Y connections and measuring the voltage at one of the X connections to determine the Y location.[16]

In a five-wire touchscreen (shown in Fig. 9), the X and Y voltages are applied to the four corners of the lower conductive sheet, and the upper sheet is used only as a contact point (wiper). To determine the X position, the controller applies a voltage to the two right-hand X-axis corners and grounds the two left-hand X-axis corners. The coversheet (the fifth wire) is used as a voltage probe to measure the X position. The controller then reverses the process, applying a voltage to the top two Y-axis contacts and grounding the bottom two Y-axis connections. Again, the coversheet is used as a voltage probe to measure the Y position. A five-wire touchscreen is always ready for a touch; when waiting for a touch, the four corners are driven with the same voltage, and the coversheet is grounded through a high resistance. When there is no touch on the screen, the voltage on the coversheet is zero. When the screen is touched, the controller detects the increased current flow to the coversheet and starts the measurement process as previously described.

The key difference between four-wire and five-wire touchscreens is service lifetime; four-wire is typically rated for 1M touches with a finger (or 100,000 characters with a stylus), whereas five-wire is typically rated for 30M touches with a finger. This difference is due to the way the upper conductive sheet is used; using it as only a contact point rather than a resistive voltage divider allows the condition of the conductive coating to deteriorate much further before ceasing to function.

An eight-wire touchscreen is a four-wire touchscreen with an extra wire connected to each bus bar to allow measuring the voltage directly at the sensor. The key advantage of this technique, generally called "four-terminal sensing," is that the separation of voltage and current eliminates the impedance contribution of the four wires carrying current from the controller to the sensor. This reduces drift in the touchscreen calibration.

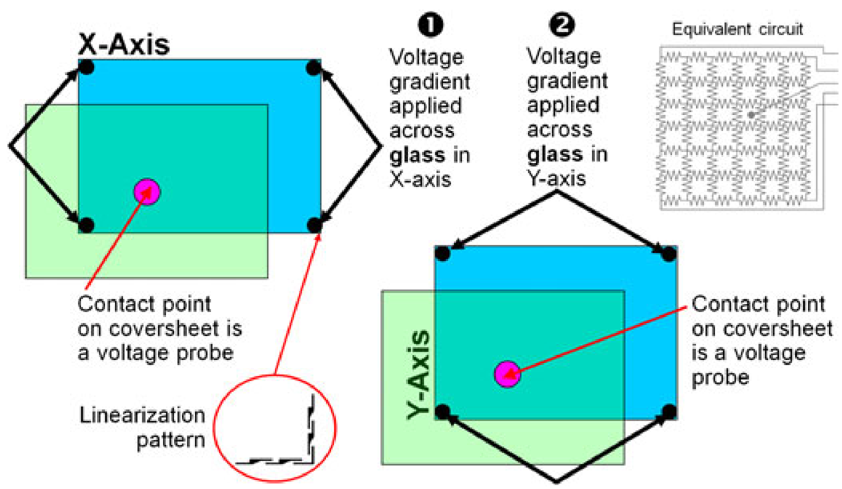


FIGURE 9 — In a five-wire touchscreen, a voltage gradient is applied along the X-axis of the glass, and the coversheet (wire #5) is used as a voltage probe. Then, the voltage is applied along the Y-axis of the glass, and again, the coversheet is used as a voltage probe. Source: the author.

In the past, there were also "six-wire" and "seven-wire" resistive touchscreens; in general, these were created by touchscreen manufacturers who were trying to design around Elo TouchSystems' patents on the five-wire design. The six-wire variation added an extra ground layer on the back of the glass substrate; however, it had no real effect on performance. The seven-wire variation added two extra sense wires (like the eight-wire design) to decrease drift because of environmental changes, but it did not work very well. These unusual products performed essentially the same as five-wire touchscreens.

Resistive touchscreens utilize six different layer constructions, as follows:

1. Film/film
2. Film/glass
3. Film/plastic
4. Film/film/plastic
5. Glass/film/glass
6. Glass/glass

The first term in the construction is the top layer (i.e., four of the constructions use PET film as the top layer); the last term in the construction is the substrate. The first two of the constructions account for 85% of the market, with the majority of the suppliers of those constructions located in Taiwan and China.[1] The first construction is used mostly in mobile devices, whereas the second construction is used in both mobile devices and commercial applications. The third construction is used mainly in products where glass breakage cannot be allowed (e.g., children's toys). The fourth construction is a film/film touchscreen attached to a rigid plastic substrate for improved durability; the fifth construction is known as "armored" because it eliminates the durability issues of the PET top layer; the sixth construction is used mainly in automotive applications because of its environmental robustness.

Resistive touchscreens are available with a large number of options, many more than for any other touch technology. Common options include the following:

- Hard coating—for durability
- Antireflection coating—to reduce diffuse reflections
- Antiglare coating—to change specular reflections into diffuse reflections
- Antifingerprint coating—to prevent fingerprint oils from adhering to the top surface
- Antipollution (or "anticorruption") coating—to prevent substances such as permanent-marking ink from adhering
- Antimicrobial coating—for medical applications
- Ruggedized substrate—for durability
- Surface armoring—laminating microglass on top of film/glass construction for durability
- High transmissivity/low reflectivity—for outdoor use

Analog resistive is a single-touch technology—i.e., it does not support real multi-touch. As noted near the beginning of this paper, consumer expectation set by more than one billion smartphones and tablets is that touchscreens must support multi-touch. In 2008, a resistive controller enhancement sometimes called "simulated gestures" was developed as a marketing workaround. There are several methods of implementing simulated gestures; one is to measure the current consumed by the sensor during operation. With a single touch, the current is normally constant and thus not monitored, but with two contact points, the two conductive sheets become resistors in parallel, which increases the current consumption. This allows analog resistive to support a few simple two-finger gestures such as zoom and rotate, but it cannot pass standard multi-touch tests such as the Microsoft Windows 7 Touch Logo. Simulated gestures are important in marketing touchscreens because they allow low-end analog resistive touchscreens to appear to be similar to the iPhone's p-cap touchscreen. In reality, the user experience with resistive simulated gestures is very different not only because of the limited gesture capability but also because resistive touchscreens require significantly more touch force than p-cap, which makes it difficult to consistently press hard enough while moving two fingers at the same time.

3.2 Analog resistive advantages, disadvantages, applications and future

Analog resistive has a number of advantages, which accounts for the fact that it was the dominant touch technology until 2010/2011. The advantages include the following:

- Works with finger, stylus, or any nonsharp object—i.e., "touch with anything"
- Lowest-cost touch technology—$1 or less per diagonal inch of screen dimension
- Widely available from around 100 suppliers—itis a commodity
- Easily sealable to IP65 or NEMA-4 environmental standards
- Resistant to screen contaminants
- Low power consumption

There are only four significant disadvantages, but they are all in direct conflict with the new *de facto* standard established by p-cap. They are (1) poor durability because the PET top surface is easily damaged, (2) poor optical quality because up to 20% of the display's emitted light can be lost to layer reflections, (3) relatively high touch force, and (4) as noted previously, the lack of multi-touch. These disadvantages are causing resistive to rapidly lose market share to p-cap in consumer electronics applications.

The situation is quite different in commercial applications, where resistive in 2011 still had more than a 50% market share in revenue and more than a 75% market share in units [1]. The major commercial applications for resistive include automotive, industrial/factory automation, retail/point-of-sales, kiosks for point-of-information and self-check-in, and office equipment such as copiers and printers. The reasons for the continuing strength of resistive are as follows:

- Resistive has been the standard for 35 years, so everyone is used to its disadvantages

- There is little demand for multi-touch in most commercial applications
- Commercial applications are mostly point-and-click, with almost no use of swipe gestures
- There is less demand for flush bezel in commercial applications, although this is starting to change
- There is significant demand for stylus use
- There has not been anything in the commercial touch world remotely like the "iPhone Seismic Event" that changed everything in the consumer touch world

Resistive touch technology has nowhere to go but down in both consumer electronics and commercial applications. Its primary advantages in consumer applications are its low cost and its stylus capability. P-cap will take over both of these—stylus in 2012 or 2013 and low cost (under $2/in) within 5 years. The author predicts that resistive's market share in units in consumer electronics applications will be well under 10% within 5 years.

In commercial applications, resistive will lose share mainly to p-cap. The rate at which that will happen depends on (1) how quickly the cost of p-cap falls, (2) how quickly suppliers sign up to meet the more specialized needs of commercial applications, and (3) how quickly demand increases in each application for p-cap's key capabilities (multi-touch, flush bezel, and very light touch). For example, the demand for flush bezel is likely to increase much faster in customer-facing applications such as healthcare and point-of-information than in point-of-sale or industrial/factory automation applications. Similarly, the demand for multi-touch is likely to increase much faster in casual and casino gaming (as entertainment establishments try to capture more of the Millennial generation) than in point-of-sale, where it is difficult to imagine any need for multi-touch (for example) on a McDonald's order terminal. The author predicts that resistive's market share in units in commercial applications will drop by one-third to one-half within 5 years.

3.3 Analog multi-touch resistive (AMR)

A form of analog resistive called "matrix resistive" or "digital resistive" in which the sheets of transparent conductor (ITO) are segmented into multiple individual areas has existed for many years. It was originally invented for use with opaque membrane-switch panels—for example, simple 4 × 3 number pads. It is called "digital" in these applications because the conductors are either touching (on) or not (off); there is no analog four-wire touchscreen concept involved. It is used today in some industrial applications where a machine operator is required to have both hands on the screen for safety reasons.

When the iPhone ignited the seemingly insatiable desire for multi-touch everywhere, matrix resistive was reborn as "analog multi-touch resistive" (AMR). In this technology, shown in Fig. 10, each conductive surface is patterned into strips so that each overlapping intersection of strips forms a square. Generically, this technology is usually known by the acronym AMR; however, some touchscreen suppliers have branded their own version of the technology. For example,

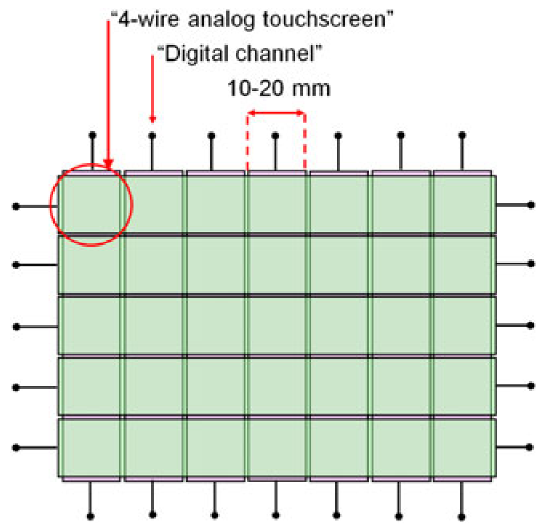


FIGURE 10 — In an analog multi-touch resistive touchscreen, the normally uniform conductive layers are patterned into strips so that each intersection of strips forms a square, typically 10–20 mm on each side. Each square acts like an independent four-wire analog touchscreen. Source: the author.

Touch International calls it "multi-touch analog resistive sensor." Another name sometimes used for this technology is "hybrid analog-digital resistive." This name is derived from the fact that each individual area or square of ITO is "digital" because contact in any square can be uniquely identified by location (e.g., the number "3" in a 10-key pad). However, the exact location of the contact "within" a square is determined by the same analog voltage divider method used in single-touch resistive, thus, the "hybrid" name.

In an AMR touchscreen intended for use in a desktop all-in-one computer (for example), the squares are typically 10–20 mm wide—about the width of one finger. This means that if the user holds two fingers closely together, the result may be recorded as one or two touches, depending on the location of the touch. In other words, although the technology was developed to compete with the multi-touch capability of p-cap at a lower cost, it does not actually work very well. This is one of a number of reasons that AMR has not achieved any traction in the consumer electronics market whatsoever. Other reasons include the following:

- It is not significantly lower cost than p-cap
- It is quite difficult to make properly, especially in larger sizes
- It has all the same fundamental limitations of resistive (relatively high touch force, low optical performance, and low durability)

The author believes that AMR touch technology will remain a niche curiosity with no significant market share in either consumer electronics or commercial applications.

3.4 Stantum's multi-touch resistive

JazzMutant, a French supplier of music controllers, was the first company to market a commercial product using a multi-touch interface (the Lemur™, in 2005).[17] When JazzMutant decided to market their multi-touch technology separately, they renamed the company as Stantum. Predating the iPhone by 2 years and AMR by 3 years, Stantum's technology (illustrated in Fig. 11) is a unique variation on matrix resistive called "Interpolated Voltage-Sensing Matrix" (iVSM™). The key differences between iVSM and AMR are as follows:

- The width of a typical iVSM square is 1.5 mm—much smaller than a finger, which produces a large performance improvement over AMR's multi-touch.
- Each square operates as a "digital switch" (on/off) rather than an analog four-wire touchscreen as in AMR; because of this, the technology is sometimes called "digital multi-touch resistive."
- The controller is optimized for both finger touch and stylus touch; for example, it incorporates "palm rejection" (the ability to ignore any touches other than the tip of the stylus), which is critically important for effective stylus use.
- The controller is designed for use in embedded devices, that is, it consumes very little power, it implements effective power management modes, it has a low memory and code footprint, and so forth.

The uniqueness of iVSM has allowed Stantum to develop a strong IP portfolio on the technology. This is in contrast with AMR, which as described earlier, has very limited significant IP associated with it, because it is based on the commonly known "matrix resistive" concept. Because of the strength of their IP, Stantum decided to use a licensing business model rather than become a touchscreen hardware supplier. Stantum initially licensed their controller to two ASIC manufacturers (ST Microelectronics and Sitronix, the latter of which has discontinued the product) and partnered with Gunze USA, a touchscreen manufacturer focused on commercial applications. Stantum has had moderate success in commercial and military applications, where the combination of finger and stylus is in more demand. Most recently, Stantum has partnered with Nissha Printing in developing a version of iVSM called "Fine Touch Z," which includes a layer of Peratech's transparent pressure-sensing material between the two substrates, greatly increasing the pressure-sensing capability of the touchscreen.[18]

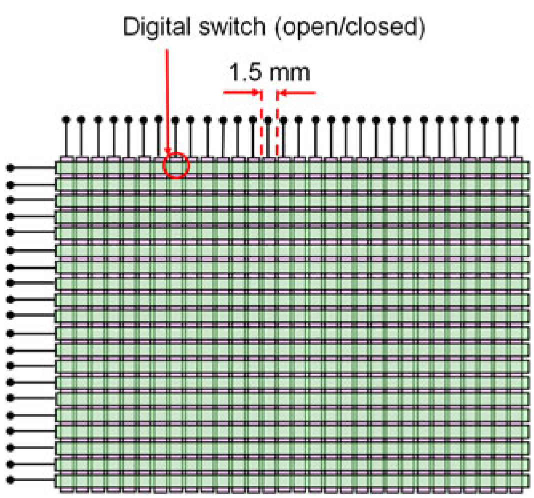


FIGURE 11 — Stantum's iVSM multi-touch resistive is similar to multi-touch resistive with three key differences: (1) the scale is very different, with typical square sizes of 1.5 mm, (2) each square is simply a digital switch, not a small four-wire touchscreen, and (3) the algorithms that process multiple touches are much more sophisticated and much faster than those in typical multi-touch resistive touchscreens. Source: the author.

Even though Stantum's implementation of multi-touch resistive is much better than AMR, it still suffers from the same three issues listed earlier that are limiting AMR. The author predicts that multi-touch resistive in any form will not have a significant impact on any touch market in the future.

4 Surface capacitive

Surface capacitive was invented and commercialized by MicroTouch Systems, a company founded in 1982 and acquired by 3M in 2001 to form part of 3M Touch Systems. As shown in Fig. 12, a surface-capacitive touchscreen consists of a uniform sheet of transparent conductor deposited on top of a sheet of glass. The standard conductive coating is antimony tin oxide deposited to produce a highly uniform sheet resistivity of 1200–2000 ohms per square. Lower-cost versions of the technology sometimes use ITO or tin oxide (TO) instead with lower sheet resistivity. The conductive coating is surrounded by and connected to linearization pattern electrodes made of printed silver frit that are in turn connected to the touchscreen flex tail (the purpose of the linearization electrodes is to correct the inherent nonlinearity [bow] associated with the properties of electrical currents flowing between corners of a rectangular conductive surface). The conductive coating and linearization electrodes are covered by a transparent dielectric hard-coat typically made of silicon dioxide; this layer often also includes antiglare functionality. The hard-coat may also include antistiction functionality that reduces the static friction between a finger and the surface; this makes dragging objects (e.g., cards in a video poker game) much easier.

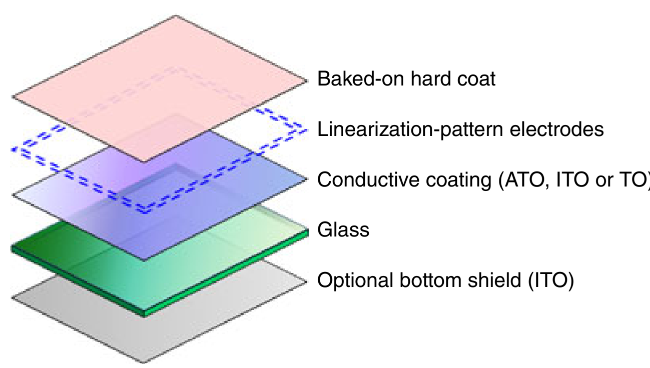


FIGURE 12 — A surface-capacitive touch sensor consists of a uniform transparent conductive coating on top of a sheet of glass. The conductive coating, surrounded by linearization pattern electrodes, is protected by a baked-on organic and silica hard-coat. ATO, antimony tin oxide; ITO, indium tin oxide; TO, tin oxide. Source: Touch International.

Also shown in Fig. 12 is an optional bottom shield made of ATO, ITO, or TO; its purpose is to shield the conductive layer from the Electromagnetic Interference (EMI) emitted by the display. The bottom shield increases the cost of the touchscreen and reduces the transmissivity, it is often seen as undesirable. Equivalent EMI reduction is often accomplished through software running on the touchscreen controller.

Surface capacitive uses a uniform electrostatic field established across the conductive coating by applying an Alternating Current (AC) signal to the four corners of the conductive coating. All four corners are driven with exactly the same voltage, phase, and frequency. When a user's finger contacts the top coating, a small amount of electrical energy is capacitively coupled from the conductive coating to the user, causing a small amount of current to flow through each corner connection. The controller identifies a touch by comparing a known "baseline" current in the no touch state with the change in current when a user touches the screen. The touch location is identified by measuring the amount of current supplied to each corner; the magnitudes of these currents are proportional to the proximity of the touch location to the corners. The controller electronics measures these currents, converts them to Direct Current (DC), filters them to remove noise, amplifies them, converts them to digital via an analog-to-digital converter, calculates the touch location, adds appropriate characterization information, and outputs the location coordinates to the host computer.[19]

The primary applications for surface capacitive are in regulated gaming (casinos), point-of-sales/retail terminals, and point-of-information/self-check-in kiosks. Regulated gaming involves a very long approval cycle for any hardware or driver changes; this will slow down any possible transition to p-cap. However, surface capacitive is not as durable as p-cap because the ITO layer is on the top surface of the glass, covered only by a protective coating. Anecdotal evidence points to scratches (presumably by diamond rings) as the number one cause of failure in casino applications of surface capacitive, which means that the greatly increased durability of p-cap is likely to be very appealing in casino applications. Another factor that will tend to drive p-cap into casino applications is the casinos' desire to attract the Millennium generation. According to a survey by Casio Player Publishing, the average age of a casino patron is 45. To attract younger customers, casino operators believe that games must be made more interactive and exciting; multi-touch and multitasking technologies can help accomplish this.

Standard surface-capacitive technology is inappropriate for mobile use because it requires a very stable reference ground to establish the baseline current for the "no touch" condition. CapPLUS, a variation of surface capacitive employing "reversing ramped field capacitive" (RRFC™) technology, very cleverly eliminates the restriction against mobile use.[20] The technology was invented by Touch Konnection Oasis (TouchKO), a small company founded in 1996 in Texas. TouchKO was acquired by Wacom in 2007, but little market traction has been achieved with the technology during the 5 years since the acquisition. As long as it remains a relatively expensive single-touch technology from a sole source, this is unlikely to change.

Surface capacitive is a single-touch technology. A "simulated gesture" capability similar to that in analog resistive was developed for surface capacitive by a 3M competitor around 2009, but it has had little effect because surface capacitive is used almost exclusively in commercial applications, where the demand for multi-touch has so far been much less than in consumer electronics applications. However, the author believes that the demand for multi-touch in some commercial applications is likely to change in the near future. Many users of commercial applications (e.g., casino game players and public-access kiosk users) are likely to have smartphones and/or tablets with p-cap touchscreens, so they have a built-in expectation of multi-touch. The providers of casino games and kiosk software are likely to respond to that expectation by enhancing their products with multi-touch functionality. This in turn will drive surface capacitive out of those applications.

Surface capacitive technology is quite mature; 3M has refined it to the point where there's not much more that can be improved. 3M has maintained a majority share of the market ever since the acquisition of MicroTouch Systems in 2001, but the total surface-capacitive market in 2011 was under $150m, so it is not a significant factor in the overall 2011 touchscreen market of $11b. Over the next 5 years, the market for surface capacitive will decline slightly in units, but because of steadily eroding average selling prices, the revenue will decline by around 25%. Correctly sensing the future of touch, 3M has shifted its focus from surface capacitive to p-cap, as evidenced by the tiny share of booth space that 3M currently allocates to surface capacitive at trade shows. As the market for surface-capacitive shrinks, Asian competitors are starting to exit the market, which will accelerate the rate of decline. The bottom line is that surface-capacitive touch technology is entering its end-of-life phase; the author predicts that within 5–10 years, the technology will be a historical curiosity.

5 Surface acoustic wave (SAW)

Surface acoustic wave (SAW) in its current form was invented in 1985 by Dr. Robert Adler, a famous inventor at Zenith[21] (Dr. Adler is best known for being the coinventor of the ultrasonic TV remote control, first sold in 1956).[22] Zenith sold SAW touchscreen technology in 1987 to Elo TouchSystems, which at the time was owned by Raychem and known as Elographics. After the sale, Robert Adler continued consulting for Elo, actively contributing to the commercialization of SAW technology into the 1990s.

As shown in Fig. 13, a SAW sensor is relatively simple, consisting of a piece of glass, four piezo transducers, and four reflector patterns made of fired-on glass frit. The piezo transducers are configured in pairs, one for the X-axis and one for the Y-axis. The X and Y transmitting transducers send

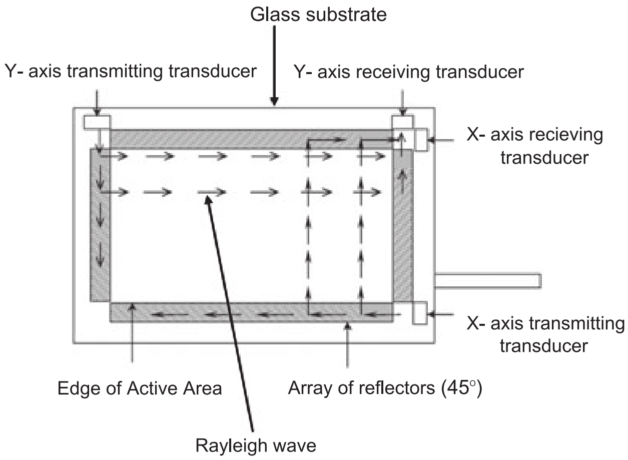


FIGURE 13 — A surface acoustic wave touch sensor consists of a glass substrate, two transmitting transducers (one per axis), two receiving transducers, and four 45° reflector patterns. Rayleigh waves travel from a transmitting transducer down a reflector, across the screen, and up the opposite reflector to a receiving transducer. Source: Elo TouchSystems.

bursts of ultrasonic (typically around 5 MHz) Raleigh waves across the surface of the glass, aimed down the X and Y transmitting reflectors. The reflectors consist of a series of ridges at a 45° angle; as the Rayleigh waves hit the ridges, they are reflected across the screen. A matching set of receiving reflectors on the opposite edges of the screen directs the waves towards the X and Y receiving transducers. The transit time of any given Rayleigh wave from transmitting transducer to receiving transducer depends on the length of the path; waves reflected by the beginning of the reflector take less time than waves reflected by the end of the reflector. In this way, physical location on the screen is mapped into the time domain. When a human finger or other soft (sound-absorbing) object touches the glass, it absorbs a portion of specific X and Y Rayleigh waves. As shown in Fig. 14, the touch location is determined by measuring where the reduction in wave amplitude occurs in the time domain for the X and Y waves. By measuring the amount of amplitude reduction, an indication of the touch pressure in the Z-axis can be obtained—although this is rarely carried out in practice.

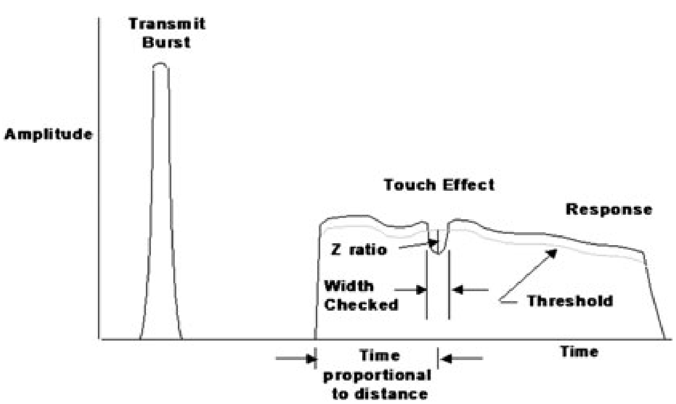


FIGURE 14 — In a surface acoustic wave touchscreen, a transmit burst of Rayleigh waves in the X-axis or Y-axis produces an amplitude response curve in the time domain; the location of a touch on an axis is determined by the time-domain location of an amplitude dip. Source: Elo TouchSystems.

As previously noted, resistive touch technology has a majority share of the revenue in the commercial-application touch market; SAW and surface capacitive compete for most of the remainder. SAW has a broader range of applications than surface capacitive because it has lower cost, better optical performance, higher durability, easier integration, and more suppliers. SAW's primary applications are public-access kiosks (point-of-information), point-of-sales, ATMs, and gaming machines.

SAW was originally just a single-touch technology, but the two largest suppliers, Elo TouchSystems and General Touch, have both developed two-touch versions. Elo's approach is to add a second set of reflectors with an angle other than 45° to provide an additional source of touch location data. The primary drawback of two-touch SAW is that SAW requires a significant amount of force to register a touch, between 20 and 80 g, depending on the implementation. Even for a single-touch application, this is much more force than p-cap requires (which is essentially zero). Maintaining sufficient pressure with two fingers while performing a gesture such as zoom or rotate is fairly difficult. Even worse, having to press hard to perform a swipe gesture just does not feel right. All-in-one consumer desktop computers from Lenovo and Samsung have been marketed with two-touch SAW, but there does not appear to be much consumer market penetration beyond that. Windows 8 will end any consideration of SAW in the consumer market because the Windows 8 touch specifications require a minimum of five touches.

Another problem with standard SAW is that it requires a bezel to cover the reflectors around the border of the glass. Both Elo TouchSystems and General Touch have developed a bezel-less single-touch version. Elo's approach is to move the transducers and reflectors to the underneath of the glass and round the edge of the glass so that the waves flow smoothly from the front surface to the back surface of the glass. Because there is little available space on the underneath of the glass because of the frame of the LCD, instead of using two sets of reflectors, Elo TouchSystems uses a single set and multiplexes them. The shaped edge and location of the transducers and reflectors make this configuration more difficult to integrate than p-cap in a bezel-less device.

The author believes that Elo TouchSystems' ultimate intent in creating two-touch and zero-bezel SAW is to slow down the inevitable penetration of p-cap into SAW's market share. It is difficult to predict whether this will be successful or not because commercial touchscreen sales are not just about technology—the relationship between the vendor and the customer is often as important as the technical specifications.

6 Infrared (IR)

The first widely recognized example of an infrared (IR) touchscreen appeared in 1972 in the Programmed Logic for Automated Teaching Operations, Model 4 (PLATO IV) educational system at the University of Illinois.[23] In this system, a

16-by-16 grid IR touchscreen was overlaid on an orange plasma bit-mapped display to provide finger-selectable functions. One of the first commercial implementations of an IR touchscreen was in 1983 in the HP-150, HP's first touch microcomputer (it had a 9 in Cathode Ray Tube (CRT) and ran the Control Program for Microcomputers (CP/M) operating system).[23] During the 1980s and 1990s, Carroll Touch was considered to be the leading supplier of IR touchscreens. AMP acquired Carroll Touch in 1984. In 1999, Tyco International acquired AMP and then later the same year acquired Raychem, who had acquired Elo TouchSystems (Elographics) in 1986. In this way, Carroll Touch became part of Elo TouchSystems in 1999.

As illustrated in Fig. 15, a traditional IR touchscreen has IR LEDs along two adjacent sides of the screen and IR photodetectors along the other two sides. Each IR LED is pulsed in sequence, emitting light that is received by the opposing photodetectors (the sequenced pulsing is why this technology is sometimes called "scanning IR"). A grid of IR light beams in the X and Y directions is therefore formed just above the surface of the screen. When a finger or any IR-opaque object breaks the beams, a controller calculates the location of the touch. A minor but significant enhancement to IR that was invented in the early 1990s by Elo TouchSystems was the concept of "one transmitter, multiple receivers." Instead of establishing a one-to-one correspondence between transmitting and receiving elements, each transmitting LED is seen by up to five receivers. This increases the robustness of the touch system because a receiver can become disabled without creating a dead spot in the touchscreen. A related enhancement was the concept of checking for stationary objects and ignoring them if nothing had changed in several minutes. This prevents contamination material (e.g., a blob of peanut butter) from creating a dead spot on the touchscreen; the use of multiple receivers allows the contamination to be "looked around," thus minimizing its effect. The term "traditional" is often used to indicate that the referred-to form of IR is fundamentally the same as it was in the 1990s. Several newer forms of IR have recently been developed; these will be discussed later in this section.

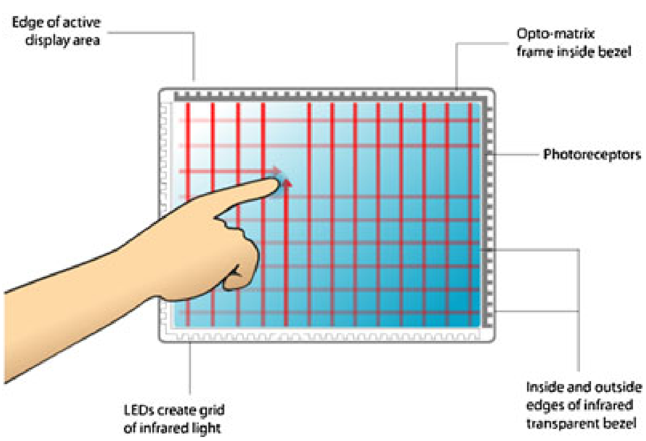


FIGURE 15 — A traditional infrared touch sensor consists of a frame with infrared light-emitting diodes (LEDs) on two adjacent sides and infrared photodetectors on the two opposite sides. The LEDs create a grid of infrared light; a touch is recognized when an infrared-opaque object blocks the light beams. Source: Elo TouchSystems.

Infrared has the smallest market share of any of the mainstream touch technologies discussed so far; total market size in 2011 was around $75 M. Almost all of this was in commercial applications, including ATMs, point-of-sale terminals, various kinds of kiosks, and large-format displays such as interactive digital signs and wayfinding stations. IR is one of the most robust touch technologies, capable of withstanding severe environments—for example, it can withstand direct sunlight and can be sealed against contaminants. For this reason, it is often used in outdoor touch applications. IR is also unique because it does not actually need any substrate at all—the IR light beams can be positioned directly above the display with no intervening glass. In that situation, the term "IR touch frame" is typically used instead of "IR touchscreen."

In most applications other than large-format, IR is used (1) because the device OEM has used it for a long time and believes that it is the best technology for his market (e.g., IBM in point-of-sales applications) or (2) because of its environmental capabilities. This means that IR is relatively unlikely to be replaced by p-cap. In indoor large-format applications, however, IR is facing significant competition from camera-based optical because of the lower cost of the latter, particularly for very large displays.

Infrared was originally a single-touch technology; when multi-touch became important, the major suppliers all started supporting some degree of two-touch. Because there are only two available axes of information (X and Y), two touches cannot be uniquely resolved without additional information (this is the same problem as ghost touches in self-capacitive). In the late 2000s, Elo TouchSystems developed a clever method of adding a third axis of information by using diagonal light beams (they called the additional dimension "U"). This allowed the resolution of two touches most of the time, except for the special case when the two touches were exactly in line with the diagonal beams. Unfortunately, Elo TouchSystems never put the technology into mass production because of its high cost.

The author believes that traditional IR will continue to exist as a unique technology, particularly in applications where environmental resistance is critical. Market share in small–medium sizes is likely to remain relatively constant during the next 5 years, whereas market share in large-format is likely to decline because of camera-based optical's growth.

6.1 "High-finger-count" multi-touch infrared

A common name has not been developed yet for this new form of IR that allows up to 48 simultaneous finger touches. The IR LEDs and photodetectors in this technology are more or less the same as in traditional IR; the difference is in how the controller manages them. Instead of simply looking for pairs of interrupted light beams, the controller in most current implementations of this new technology uses an "imaging" approach. The author is aware of three different architectures, each identified by their creator: (a) PQ Labs, (b) Image Display Systems (PulseIR), and (c) TimeLink. As illustrated in Fig. 16(a)–(c), one IR LED emitter flashes, and many or all of the IR photodetectors on the two opposite sides record their level of light intensity, producing a one-pixel-high "image" showing the shadows of all the objects between the LED and the photodetectors. Then, another IR LED flashes, and the process is repeated. By doing this extremely rapidly and then combining the image sequences, a relatively large number of shadow-creating objects can be tracked simultaneously. The hardware used in all three architectures is relatively similar; the difference in the user experience produced by these products is determined mostly by the quality of the algorithms used to interpret the "shadow-image" data, reject ghost points, handle occlusion, and track moving and nonmoving objects.

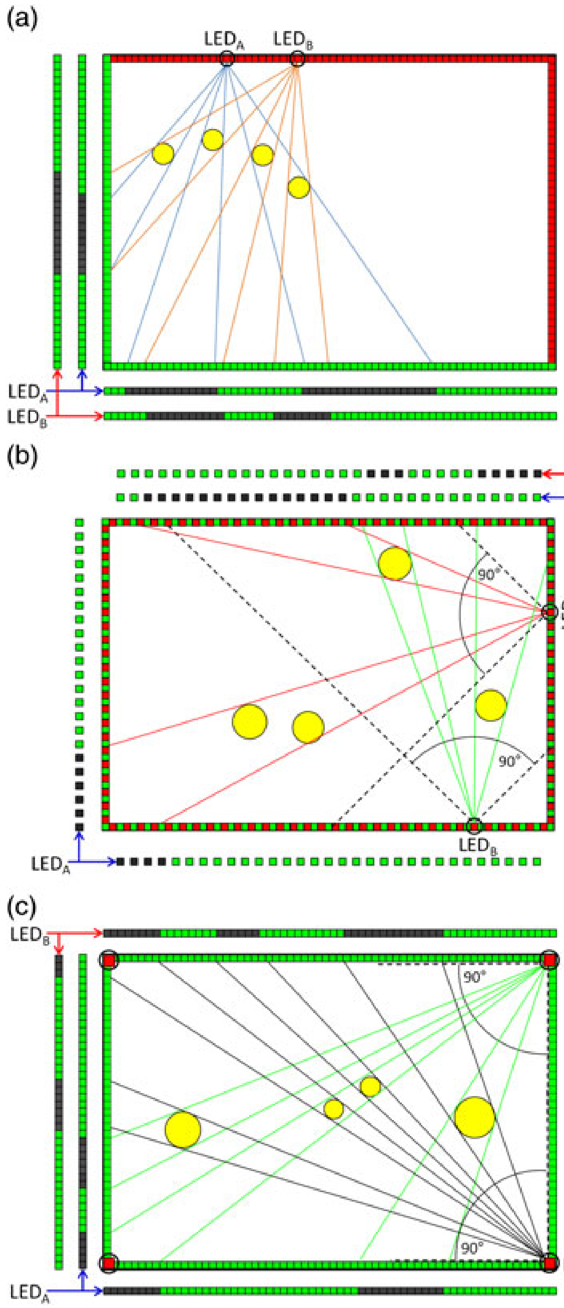


FIGURE 16 — "High-finger-count" multi-touch infrared touchscreens typically use an "imaging" approach. The author is aware of three different architectures, each identified by their creator: (a) PQ Labs, (b) Image Display Systems (PulseIR), and (c) TimeLink. The architectures are similar in that each infrared light-emitting diode (IR LED) emitter flashes, and many or all of the IR photodetectors on two or three opposite sides record their level of light intensity, producing a one-pixel-high "image" showing the shadows of all the objects between the LED and the photodetectors. Source: the author.

There are only a few suppliers of this technology so far; the best known ones are PQ Labs (the initiator of the category), Citron (DreamTouch™ brand), Image Display System (PulseIR™ brand), TimeLink, and ZaagTech.

The main limitations of this technology are the need for very high-speed sequencing and a large amount of continuous image processing. Because the maximum resolution of which this technology is capable is related to the spacing between the IR photodetectors, line drawing with this type of touchscreen can show evidence of "stair stepping." Also, as the touch objects get larger or closer to the IR LEDs, their shadows become larger, which in effect reduces the amount of data the images are capable of holding.

The primary problem with this technology is the lack of a clear application. In the author's opinion, this technology is driven by mainstream enthusiasm about multi-touch rather than any actual application need. Current commercial IR applications rarely need more than two touches, and nobody has defined "any" real applications for 20–40 touches. Another impediment is that the problem of identifying which touch belongs to which user does not yet have an elegant (practical) solution. Multiplayer games on large horizontal displays (gaming tables) are probably the best opportunity for high-finger-count multi-touch IR, but it is not clear that this technology is fast enough or has enough resolution for that application. Large displays used in multiperson gaming in casinos today (e.g., roulette) typically used wire-based p-cap because it is fast, the touchscreen surface can be made flush, it is unaffected by light-blocking objects on the surface, and it is readily available (commercial applications of ITO-based p-cap are still so new that it can be difficult to find a supplier, while Zytronic is happy to sell their wire-based p-cap).

High-finger-count multi-touch IR technology is not suitable for interactive whiteboard applications because of inadequate resolution, slow speed, and limited touch object size. Interactive whiteboard applications generally require a stylus and very rapid recognition of the stylus being lifted ("pen-up") by less than 1 mm. IR cannot do that, regardless of how many touches it supports. The author believes that this technology is not going anywhere in the next 5 years. When applications are developed that truly require 20–40 simultaneous touches, it may have a chance, if it is competitively priced (which is certainly not the case today).

6.2 Waveguide infrared (Digital Waveguide Touch by RPO)

Beginning around 2000, an Australian startup named RPO began developing optical waveguides targeted at the "last mile" telecommunications market. When that market collapsed in 2002 because of extreme overexpansion of fiber, RPO regrouped and looked for a new application. In 2004, they decided to use the optical waveguides they had developed in a variation of traditional IR touchscreens. They named their technology Digital Waveguide Touch (DWT™). As illustrated in Fig. 17, instead of using a large number of discrete IR LEDs as emitters, they used only two LEDs—one for X and one for Y. The light was evenly distributed across the touchscreen substrate in both directions by lenses and reflectors. Then instead of using a large number of discrete IR photodetectors, they used a very low-cost polymer waveguide to partition and channel the received light on two sides of the screen into a line-scan Complementary Metal-Oxide Semiconductor (CMOS) sensor containing 100+ pixels per side. The waveguide was produced on a fab by using photolithography, so it was capable of very fine resolution—the waveguide channels could be as small as 10 microns each. The result was a low-cost, high-performing IR touchscreen optimized for the 3-in to 15-in (mobile) size range.[24,25]

Where the technology fits best is on devices with reflective screens (e.g., e-readers that use E-ink's electrophoretic display). IR's ability to operate without any additional layers on top of the screen is an excellent match with a reflective screen's need to effectively use every photon of light that is available (RPO's glass substrate, a form of waveguide, can be placed underneath the e-reader display). However, like all touch technologies, Digital Vision Touch (DViT) has some fundamental limitations in this application, as follows:

- Multi-touch is limited to two touches; ghost touches are minimized in firmware but not completely eliminated.

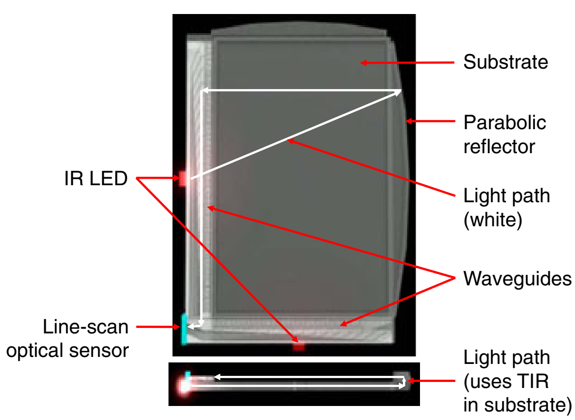


FIGURE 17 — In a waveguide infrared touch sensor, infrared light-emitting diodes (IR LEDs) inject light into two edges of a glass substrate. Parabolic reflectors spread the light across the top surface of the substrate; optical waveguides receive the light and direct it into a line-scan optical sensor. TIR, total internal reflection. Photo source: RPO; annotation by the author.

- A bezel is required to protect the waveguides and reflectors; total height is only about 1.5 mm—but it is still not zero.
- The technology is relatively sensitive to debris on the screen because the waveguide channels are only 200 microns above the surface.

RPO was counting on a partnership with a very large LCD/consumer–electronics manufacturer (one big customer). When the partnership suddenly derailed at the end of 2010, RPO was not sufficiently prepared with an alternative source of funds to support the manufacturing ramp required by the consumer electronics market. After a total of $55m investment over more than 10 years, RPO went into liquidation in the spring of 2011. The asset (IP) liquidation sale took place during February 2012. The purchaser was a nonpracticing entity, a type of firm commonly known as a "patent troll," so it seems very unlikely that this technology will be put to productive use again.

7 Camera-based optical

Although camera-based optical touch only came to prominence in 2009 with the launch of Windows 7, the technology has existed for more than 30 years. In 1979, Sperry Rand Corp. was the first to patent the concept of using two IR linear image sensors (they were Charge-Coupled Device(s) (CCDs) at the time) to locate the position of a touch on the top surface of a display. SMART Technologies in Canada and NextWindow in New Zealand both developed the first commercial CMOS-based optical touch systems independently in the early 2000s. SMART used the technology in a few of their products during the 2000s but did not start making significant use of it until 2010. Hewlett-Packard was the first to use optical touch in a desktop product, launching the TouchSmart™ consumer all-in-one computer in 2007 with NextWindow's touch technology. SMART filed a lawsuit against NextWindow for patent infringement in April of 2009 and then licensed the technology to Pixart in June of 2009. Pixart immediately began supplying optical sensors to Quanta for the launch of Windows 7 in October 2009; Quanta became NextWindow's primary competitor. SMART acquired NextWindow in April of 2010, thus ending the lawsuit and lessening the financial impact of Quanta as a competitor. Combining the optical touch IP of both companies made more sense than the possibility of one company invalidating one or more of the other's patents as a probable outcome of the lawsuit.

Camera-based optical is a form of light-blocking IR touch ("camera" here refers to an assembly that typically includes an image sensor, a lens, an IR filter, a housing, and a cable). In the most common form of camera-based optical touchscreen (illustrated in Fig. 18(a)), a peripheral backlight is provided via IR LEDs in the corners of the screen with a retroreflector around the periphery of the screen (a retroreflector is a material that returns light in the direction from which it came, regardless of the angle of incidence). As a result of the retroreflectors, light is radiated from the edges of the screen across the surface of

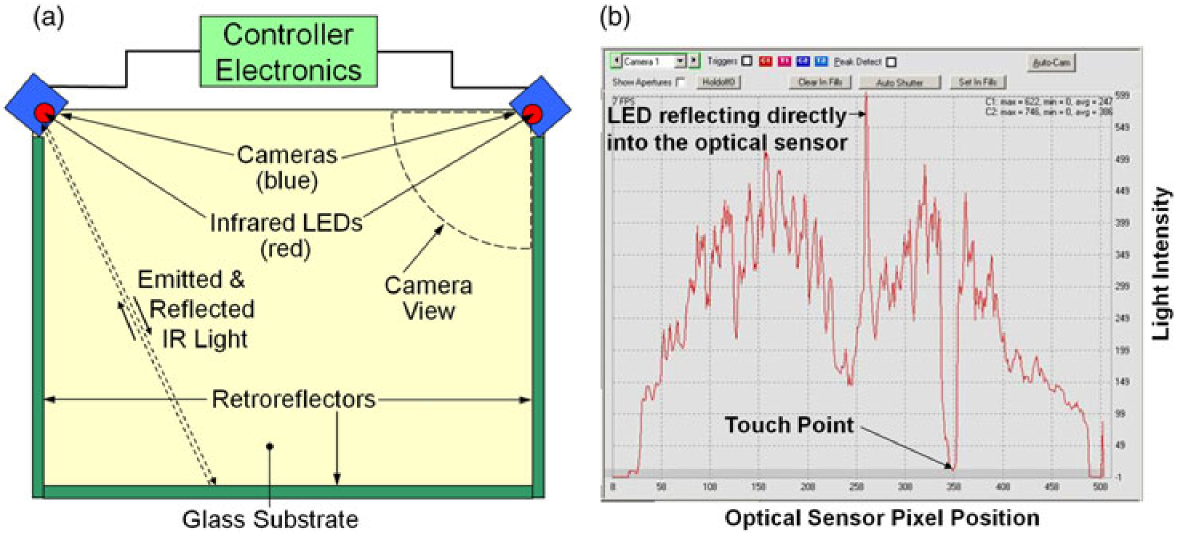


FIGURE 18 — Camera-based optical touch uses a backlight created by infrared light-emitting diodes (IR LEDs) in the corners of the screen and a peripheral retroreflector. Complementary metal–oxide semiconductor line-scan sensors (cameras) are placed in two or more corners of the screen; when an IR-opaque object touches the screen, the peripheral light is blocked and a shadow is seen by the cameras. Source: NextWindow.

the screen. CMOS line-scan or area imagers (cameras) are placed in two or more corners of the screen; when a finger touches the screen, the peripheral light is blocked and a shadow is seen by the cameras. Note that even if the camera uses an area imager rather than a one-pixel-high line-scan imager, it is not seeing a gray-scale image of the touching finger; it is simply seeing the presence or absence of light. A controller processes the data from the cameras and uses triangulation to determine the location of the touching finger.[26]

Figure 18(b) shows a graph of light intensity seen by one 512-pixel optical sensor. The sharp dip in the graph at pixel 358 is the result of a touch on the screen (i.e., a point where all of the peripheral backlight is blocked). The moderate dip around pixel 250 is the junction of the two edges of the screen (i.e., the bottom and right-hand edges as seen by a camera in the upper left corner); this is the most distant point from the camera. The sharp peak around pixel 270 is the one point where the retroreflector is sending light directly back into the camera.

The majority of camera-based optical touchscreens used in desktop products in 2011 had only two CMOS sensors, mainly for cost reasons. Using triangulation, two cameras are required to calculate the X and Y locations of a single touch point. If two simultaneous touch points can be seen by both cameras (i.e., each camera sees two distinct shadows), then there are four potential touch points—two real touch points and two “ghost” points (false touches positionally related to real touches). This is the same problem that exists with self-capacitive p-cap, traditional IR, and single-touch SAW—all touch systems where information can be obtained only from two axes. Distinguishing real points from ghost points in optical touch requires the application of sophisticated algorithms operating on multiple sets of points over time. Another situation in which advanced algorithms is important is when the position of the two simultaneous points is such that one of the cameras cannot distinguish between them (i.e., one point occludes the other). Much of an optical touchscreen’s controller processing time in a two-camera optical touch system is used running algorithms to eliminate ghost points and compensate for occlusion. In fact, the quality of the multi-touch experience in a two-camera optical touch system depends largely on the sophistication of the algorithms, not the quality of the hardware. For these reasons, many large-format (>30 in) optical touchscreens use four cameras to provide more data sources. Four cameras can provide two unambiguous touches except for one special case, where both touches are on one of the diagonals between the cameras such that both cameras see an occluded view.

Current applications for camera-based optical touch are in two main areas: (1) desktop all-in-one touch computers and touch monitors, and (2) large-format interactive information, digital signage, conference and training rooms, and large interactive LCDs replacing whiteboards in some educational applications. The desktop application area developed mainly because Microsoft’s Windows 7 Touch Logo specification was written around the capabilities of camera-based optical, which at the time was the lowest-cost technology capable of supporting two touches. The Windows 8 Touch Logo specification is written around p-cap, with a minimum requirement of five simultaneous touches. NextWindow has been able to meet the Windows 8 Touch Logo specification by using six cameras—one in each corner with two additional cameras trisecting the top edge of the screen.

The primary competition for camera-based optical in large-format is traditional IR; secondary competition comes from wire-based p-cap, SAW, dispersive signal technology (DST) from 3M, and acoustic pulse recognition (APR) from Elo TouchSystems (the latter three technologies are all limited to a maximum size of 52 or 55 in). Camera-based optical’s primary advantage over traditional IR is its scalability, which translates into lower cost for larger touchscreens. A traditional IR touchscreen of any size must have a printed circuit board completely surrounding the screen, whereas a camera-based optical touchscreen can use printed retroreflectors that can be attached to a plastic or metal bracket. The latter is much lower cost. A secondary advantage of camera-based optical over traditional IR is higher resolution and speed.

Because both camera-based optical and traditional IR depend on blocking IR light from reaching a sensor, they are both subject to the same fundamental limitations, as follows:

- Sensitivity to ambient IR light, such as sunlight (traditional IR currently incorporates a much more-developed solution to this problem)
- Sensitivity to debris on the screen (the effect of debris can be minimized but not completely eliminated through the use of clever algorithms)
- The need for an absolutely flat and rigid substrate (the closer the IR beams are to the surface, which is necessary to minimize "pretouch," the more a lack of planarity becomes a problem)
- Profile height (typically 3 mm for a desktop-sized screen and up to 10 mm for a large-format touchscreen)

Because of the high cost of p-cap in desktop sizes, the Windows 8 PC OEM/ODMs are likely to use p-cap only in high-end touch models; optical touch will probably be the technology of choice in mainstream models. This should keep optical touch growing steadily in the 15-in to 30-in range. In large-format applications, both optical touch and traditional IR have individual strengths, so it is likely that both will continue to exist in the large-format market for a number of years. Over time, camera-based optical will overtake traditional IR because the hardware is simpler and more capability can be added through software.

8 LCD in-cell

The term "in-cell" means that the touch sensor is located "between" the two sheets of glass that make up the LCD cell. Specifically, that means that the touch sensing elements are integrated into the TFT array, integrated into the color filter layer, or both. The concept is that touch should naturally be integrated into the LCD with no additional sheets of glass and no coatings so that it becomes a standard part of every display. The reality is that (1) for an acceptable user experience, essentially every LCD used in a touch application requires some form of protective covering because of the fragility of the color filter glass and the softness of the top polarizer (typically 2H–3H) and (2) it is turned out to be much more difficult and taken much longer to successfully integrate touch into an LCD than anticipated. The good news is that as of June 2012, in-cell touch appears to have finally reached realistic commercialization with at least two commercial products shipping (more information on this is provided later in the paper).

8.1 Light-sensing in-cell

There are three in-cell touch technologies: light sensing, capacitance sensing, and voltage sensing.[27] The focus of most current research is capacitance sensing, with light sensing a distant second. None of the LCD manufacturers are spending any significant effort on voltage sensing. In light-sensing in-cell touch, optical sensors are integrated into the TFT array. Depending on the design, they may sense visible light, IR light, or both. Prior to 2010, researchers were focused more on visible light because it is readily available from ambient lighting and the display backlight. However, handling the extremely wide range of lighting conditions from direct sunlight to total darkness, with the implied automatic transition from front lighting (sensing shadows) to back lighting (sensing reflections), turned out to be an insurmountable problem. In addition, many researchers seemed to ignore the obvious problem that visible light cannot get through a black area of the LCD, making black areas untouchable. For these reasons, most researchers currently are working with high-intensity IR emitters embedded in the backlight, as shown in Fig. 19.

High-intensity IR is necessary because the light must travel from the backlight through the LCD, be reflected off the touch object, and travel through the LCD again to the optical sensors in the backplane. Another reason that high-intensity IR is necessary is the relatively low sensitivity of amorphous silicon (aSi) IR photodetectors. To counteract this problem, in the SUR40 (described in the following text), Samsung used amorphous silicon germanium (aSiGe) sensors instead. This provides a 15X increase in sensor sensitivity, at the cost of (1) more complexity in materials and process and (2) a 15X increase in the touchscreen's sensitivity to "ambient" IR. In light-sensing in-cell, the number of touch sensors varies from one per display pixel (rare) to one per 16 display pixels. The primary reason the ratio is almost never one-to-one is that

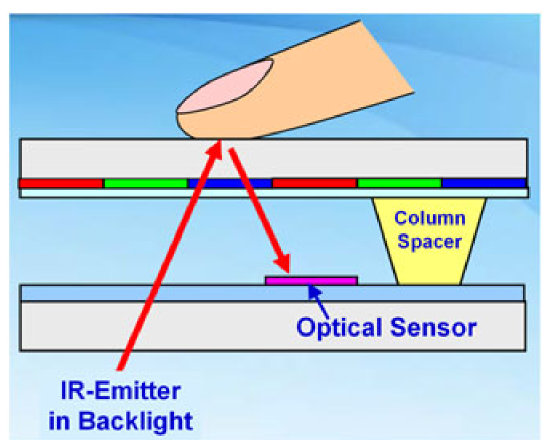


FIGURE 19 — Light-sensing in-cell touch integrates optical sensors into the thin film transistor layer. Current implementations use high-intensity infrared emitters integrated into the backlight as the light source. Emitted infrared (IR) light reflecting from a touching object is seen by the optical sensors and processed as a touch. Source: Samsung.

the IR photodetectors reduce the aperture ratio; using one photodectector per 16 pixels reduces the percentage aperture loss to a manageable single-digit number.

The author is unaware of any successful product that has been shipped "in volume" with light-sensing in-cell touch. The best known shipping product is the Samsung SUR40 touch display for Microsoft Surface 2.0, currently selling for $8400. The SUR40 is a 40-in full-HD (1920 × 1080), 4-in thick Samsung touch LCD with an embedded 64-bit Windows 7 PC running Microsoft Surface 2.0 software. The cover glass on the LCD is made of optically bonded Corning Gorilla Glass. When the SUR40 was announced at Consumer Electronics Show (CES) in January 2011, it was widely reported that its in-cell touch function used one light sensor per display pixel (two million sensors!). That would be by far the most sophisticated light-sensing in-cell touch that has been developed. Unfortunately, now that the product is actually shipping, Samsung representatives at trade shows say that it uses one light sensor per eight display pixels. Because the pixel density of a 40-in full-HD display is 55 dpi, the light sensor density is therefore only about 7 dpi. That is barely enough resolution to recognize object tags, much less "read" (scan) printed documents placed on the surface of the display.

With 259K light sensors, the SUR40's system-level touch technology is definitely vision-based (discussed later in this paper). In vision-based touch, the touchscreen provides an "image" of the entire surface and everything that is touching it. In the case of Surface 2.0, that is up to 50+ simultaneous touches at a frame rate of 60 Hz (too slow to meet the Windows 8 Touch Logo requirements). Each touch appears as a bright spot or blob of IR light in the image. Light-sensing in-cell touch is not always vision-based; if the display is small and the number of display pixels per touch sensor is very high, the touch system may only report the boundaries of the touch areas, similar to the output of p-cap.

The author has spent a small amount of time testing a SUR40, and so far, he has found the performance to be disappointing (there was too much lag between the touch and the displayed result). Anecdotal reports from colleagues who have actually purchased a SUR40 with Surface 2.0 tend to confirm this observation. Another factor that does not bode well for this particular implementation of light-sensing in-cell touch is its severe limitation on ambient lighting. A Samsung document entitled "Samsung SUR40 for Microsoft Surface Venue Readiness Guide" (dated December 06, 2011) includes a table listing the maximum amount of ambient light allowed to avoid performance degradation.[28] The limit varies depending on the type of light source, ranging from 600 lux for compact fluorescent lights to 50 lux for incandescent lights. The author regards this as a very serious limitation; can you imagine a home gaming table in an environment limited to only 50 lux?

Samsung has told the author that they have given Microsoft a 3-year to 4-year exclusive on the SUR40; the fact that Samsung is willing to do this implies that they do not believe that the technology has any near-term volume opportunities.

8.2 Capacitive-sensing in-cell

There are three forms of capacitive-sensing in-cell, (1) "pressed" capacitive, (2) self-capacitive, and (3) "true" mutual capacitive. In pressed capacitive (illustrated in Fig. 20), each sensing element consists of two electrodes: a conductive column spacer on the color filter side and a flat electrode on the TFT side. When the surface of the LCD is pressed (deflected), the pressure changes the dielectric constant of the liquid crystal material between the two electrodes, which changes the mutual capacitance between the two electrodes. Note that the change in distance between the two electrodes (a few microns) is not a significant source of the change in capacitance. Note also that like all other pixel-oriented in-cell technologies, the number of display pixels per touch sensor is almost never 1:1 but instead more typically in the range from 4:1 to 16:1. The capacitance between the two electrodes is measured using one of several methods, the most common one being a comparison with a reference capacitor incorporated into each sensing element.

Although the capacitance being measured is mutual (between two electrodes), the environment in which it is being measured is entirely different than a standard p-cap touchscreen. Not only are the configuration of electrodes and the method of measurement different, but also, the touch measurement timing cycle is dependent on (and highly integrated with) the timing cycle of the LCD. This means that a custom controller for each specific implementation of pressed capacitive from each LCD manufacturer is required.

The most fundamental problem with pressed capacitive is that because the color filter glass must be deflected to register a touch, the use of a cover glass is impractical—even though it is widely understood throughout the touchscreen industry that essentially "all" LCDs require some form of cover glass in real-world touch applications. Adding a cover glass to pressed capacitive (1) increases the amount of touch force required to deflect the glass (highly undesirable in light of the p-cap *de facto* standard) and (2) reduces the touchscreen resolution because for a given touch force, as the glass gets thicker the area of deflection becomes larger. Finally, there

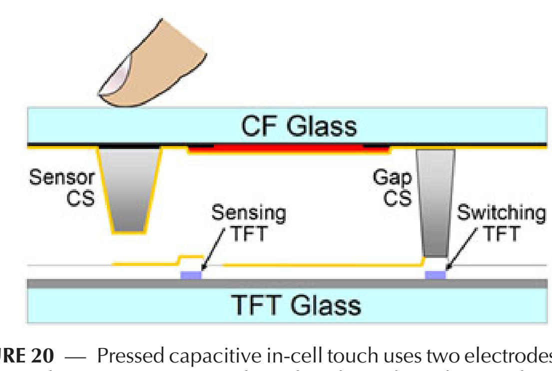


FIGURE 20 — Pressed capacitive in-cell touch uses two electrodes, a conductive column spacer (CS) on the color filter side and a flat electrode on the thin film transistor (TFT) side. When the color filter (CF) glass is pressed (deflected), the pressure changes the dielectric constant of the liquid crystal material, which changes the capacitance between the two electrodes. Source: LG Displays.

is some disagreement in the industry regarding whether continual deflection of an LCD's surface will cause reliability problems as the LCD ages.

In spite of these negatives, there is a line of Samsung point-and-shoot cameras shipping in volume that uses pressed capacitive in-cell sensing. This particular implementation of pressed capacitive was first described by Samsung in a SID 2007 paper.[29] The product line started with the Samsung ST10 point-and-shoot digital camera, first shipped in April 2009. Since then, Samsung has shipped about a half-dozen new models using the same touchscreen; one of newest is the ST700, which first shipped in July of 2011. The author believes that (1) the ST10 was actually the first commercial product that shipped with any form of in-cell touch and (2) the quality of the user experience with these in-cell touch-screens is far below that of any p-cap touchscreen. Because a cover glass cannot be used with pressed capacitive, the display shows discoloration because of liquid crystal pooling when touched and is easily damaged. The relatively high force required to activate pressed capacitive combined with the potential for damage is such that Samsung recommends using a supplied plastic stylus ("touch pen") rather than a finger (the use of a stylus concentrates more force in a small area). Figure 21 contains two illustrations and a list of cautions from the ST700 User Manual;[30] they speak volumes about the user experience. User reviews say even more; here are a few comments extracted from online reviews: "The touchscreen is too slow"; "The touchscreen is not on par with most of today's digital products"; "The touchscreen is a magnet for fingerprints and smears"; "The touchscreen is a little quirky, it only works sometimes"; "Poor touchscreen."

The second, less commonly researched form of in-cell capacitive sensing is self-capacitive, illustrated in Fig. 22. In this touch-sensing method, each sensor element has only one electrode on the TFT side. When a finger touches the surface of the LCD above the electrode, capacitive coupling between the user's body capacitance to ground and the sensing electrode causes a change in the voltage across a reference capacitor connected to the electrode. Detection and measurement of the voltage change are required to recognize a touch. Deflection of the LCD is not required in this touch-sensing method. However, the distance between the finger and the electrode on the TFT side is critical; the greater the distance becomes (i.e., because of the cover glass required in real-world touch applications), the lower the SNR of the touch-sensing system becomes. This effectively rules out the use of a cover glass, which makes self-capacitive in-cell touch sensing impractical.

The third form of in-cell capacitance sensing is so new that a common industry name does not exist for it yet; its current name is "true" mutual capacitive. The label "true" is used to distinguish it from other forms of in-cell capacitive touch that use two electrodes (e.g., pressed capacitive) but that do not function like mutual-capacitive p-cap. Most of the development of "true" mutual-capacitive in-cell touch appears to have

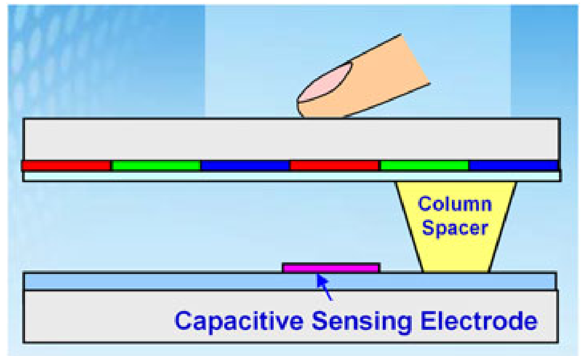
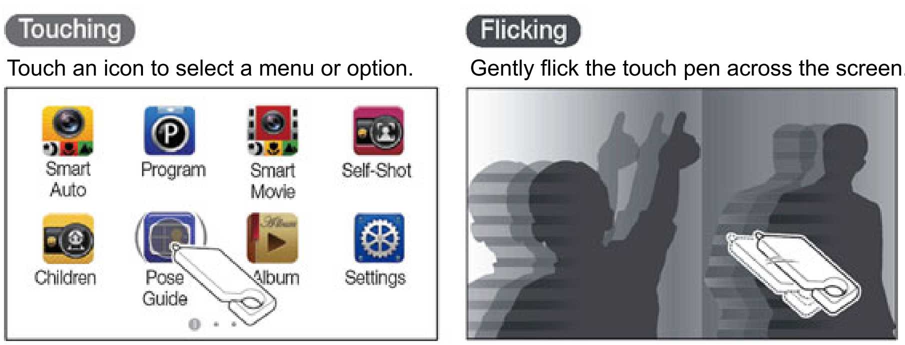


FIGURE 22 — Self-capacitive in-cell touch uses a single electrode on the thin film transistor side connected to a reference capacitor. When a finger touches the liquid crystal display, the voltage across the reference capacitor changes because of the capacitive coupling of the user's body capacitance to ground. Drawing source: Samsung and the author; information source: Toshiba Mobile Display.



- Do not use sharp objects, such as pens or pencils, to touch the screen. You can damage the screen.
- The touch screen may not recognize your inputs if you touch multiple items at the same time.
- The touch screen may not recognize your inputs if you touch the screen with your finger.
- When you touch or drag the screen, discolorations may occur. This is not a malfunction, but a characteristic of the touch screen. Touch or drag lightly to minimize the effect.
- The touch screen may not work properly if you use the camera in extremely humid environments.
- The touch screen may not work properly if you apply screen protection film or other accessories to the screen.

FIGURE 21 — An excerpt from the Samsung ST-700 Digital Still Camera User Manual. This camera uses an in-cell pressed capacitive sensing touchscreen; the cautions and warnings in the manual presage a user experience significantly inferior to that of p-cap. Source: Samsung.

been carried out by Synaptics working in partnership with the major LCD manufacturers.[31,32]

Figures 23 (for non-in-plane switching [IPS] LCDs) and 24 (for IPS LCDs) illustrate several possible configurations of “true” mutual-capacitive in-cell touch (remember that these and similar stack-up drawings are highly simplified and are not intended to represent actual physical configurations). In Fig. 23, the Y-electrodes are formed using standard on-cell techniques, whereas the X-electrodes are formed by segmenting the existing $\text{Voltage}_{\text{Common}}$ (VCOM) layer. In Fig. 24(a), the ITO shield layer that is normally used on top of the color filter glass in an IPS LCD is segmented to form the Y-electrodes, whereas the X-electrodes are created in the TFT array either by adding traces or by multiplexing (making multiple use of) existing traces. This latter possibility is not just a pipe dream; one of the major LCD manufacturers recently told the author that they have successfully prototyped “true” mutual-capacitive in-cell on an IPS LCD by using existing traces in the TFT array as X-electrodes. This means that this configuration can be accomplished with only one additional mask (the one required to segment the ITO shield layer), which is a significant cost point for an LCD manufacturer. Technically, both Figs. 23 and 24(a) are a hybrid of on-cell and in-cell constructions, although for marketing purposes, they are likely to be identified as just “in-cell.” In Fig. 24(b), both the X-electrode and Y-electrode are integrated into the TFT layer, resulting in a fully in-cell configuration. All three of these configurations require the integration of the touch controller and the LCD driver because of (1) the dual-use of existing structures such as the VCOM layer or existing TFT-array traces and/or (2) the need to achieve a sufficiently high SNR in the presence of LCD noise “and” external noise injected from sources such as AC adapters (“sufficiently high” currently appears to be defined as at least 50 dB or greater than 300:1; this is an order of magnitude higher than the typical SNR reported in research papers on all other forms of in-cell touch).

FIGURE 23 — A “true mutual-capacitance hybrid on-cell/in-cell” touch system in a Vertical Alignment Liquid Crystal Display (VA LCD) uses on-cell Y-electrodes with exactly the same function and location as standard on-cell (row 4), whereas the X-electrode is formed by segmenting the existing $\text{Voltage}_{\text{Common}}$ (VCOM) layer on the inside of the color filter glass (row 7). Because the VCOM layer becomes dual purpose, this architecture requires integration of the touch controller and LCD driver. TFT, thin film transistor. Source: the author.

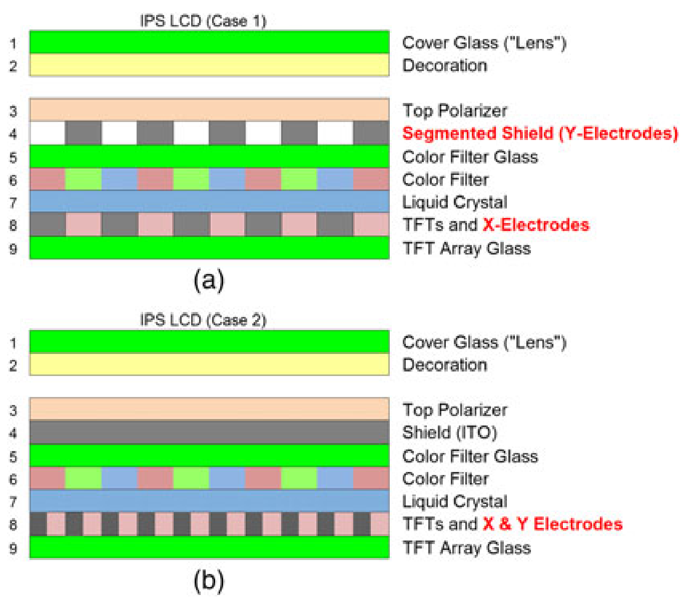


FIGURE 24 — A “true mutual-capacitance” touch system in an in-plane switching liquid crystal display (IPS LCD) can be architected in at least two ways. Case 1 (a) integrates the X (drive) electrodes into the thin film transistor (TFT) array (row 8) and segments the existing shield layer that is usually deposited on top of the color filter glass (row 4) to form Y (sensing) electrodes; this results in a hybrid on-cell/in-cell configuration. Case 2 (Figure 24(b)) integrates both the X-electrode and Y-electrode into the TFT array (row 8), resulting in a fully in-cell configuration. In both cases, achieving a sufficiently high signal-to-noise ratio in the presence of LCD noise requires integration of the touch controller and LCD driver. Source: the author.

The key factor that makes “true” mutual-capacitive in-cell touch different from all other types of in-cell touch that have ever been attempted is that “it has been successfully deployed in two high-volume commercial smartphones” (the Sony Xperia P and the HTC EVO Design 4G).[33] Achieving an “iPhone-quality” touch experience with in-cell technology and a cover glass (versus the unsatisfactory Samsung camera pressed capacitive touch experience described earlier) is an impressive achievement, but one must always remember that there is no “true” free lunch. As noted previously, “true” mutual-capacitive in-cell requires integrating the touch controller and the LCD driver. Because of the seemingly ever-increasing pixel density and the lack of size and resolution standardization in mobile phone LCDs, each new mobile phone series could require a different custom Integrated Circuit (IC) design. It remains to be seen if the benefits of touch controller and LCD driver integration (lower Bill of Materials (BOM) cost, easier flex design, more efficient supply chain, etc.) outweigh the detriments (increased customization, less IC reuse in new designs, etc.). The real battle between the LCD manufacturers (in-cell) and the touchscreen manufacturers (one-glass) is just beginning.

8.3 Voltage-sensing in-cell

In in-cell voltage sensing (also called “switch sensing” or “contact sensing,” illustrated in Fig. 25), each sensing element incorporates two microswitches in the form of conductive column spacers integrated into the color filter side and mating flat contacts integrated into the TFT side. When the surface of the LCD is pressed (deflected), one or more pairs of microswitches close, changing the signal voltages for the X and Y coordinates

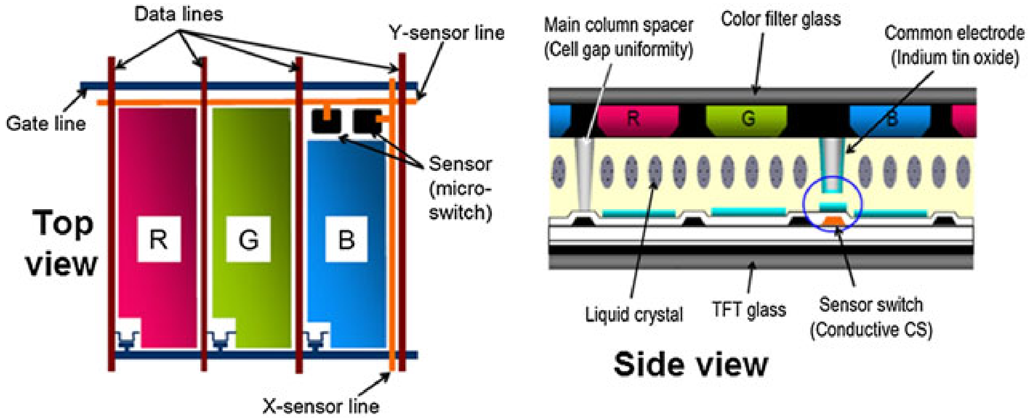


FIGURE 25 — Voltage sensing in-cell touch uses two microswitches in the form of conductive column spacers on the color filter side and corresponding flat contacts on the thin film transistor (TFT) side. When the color filter glass is pressed (deflected), the microswitches close, changing the signal voltages for the X and Y coordinates. Source: Samsung.

from high (open circuit) to low (closed circuit). This method of in-cell touch sensing is quite similar to pressed capacitive, so it shares many of the same disadvantages. These include the inability to use a cover glass, a totally custom controller, potential LCD reliability problems, and reduced aperture ratio (depending on the number of display pixels per touch sensor). The author is unaware of any commercial products shipping in volume that use in-cell voltage-sensing touch.

8.4 In-cell summary

In-cell touch has been under development for about 10 years; with the advent of "true" mutual-capacitive in-cell, it has finally reached realistic commercialization for the first time. Although a line of consumer point-and-shoot cameras using in-cell pressed capacitive has been shipping for several years (e.g., the Samsung ST700, previously described), the user experience with that product is unsatisfactory in both performance and usability when compared with p-cap. One of the main reasons for the poor user experience is pressed capacitive's inability to use a cover glass. One commercial-application product using in-cell light sensing is shipping in very small volume (the Samsung SUR40 with Microsoft Surface 2.0, previously described), but the user experience reported so far is less than satisfactory. The environmental lighting limitations of in-cell light sensing (as implemented in the SUR40) are likely to become a significant impediment to success. In-cell light sensing allows the use of a cover glass over the display, but it must be thin and optically bonded to the display to minimize the distance between the touching finger and the optical sensors. This creates a potential operations problem because LCD manufacturers want to produce high volumes of a limited number of display models, not a customized and bonded cover glass for each model of a product that an OEM sells. The author is unaware of any products being shipped that use either in-cell self-capacitive sensing or in-cell voltage sensing.

Now that commercialization of in-cell touch has finally been achieved, over the next few years, the market will determine whether the benefits outweigh the detriments. The author believes that although in-cell will definitely take some market share from one-glass and discrete p-cap solutions in the consumer electronics market, that share is unlikely to exceed 10%–15% during the next 5 years.

9 Bending wave

Bending waves are a form of mechanical energy created when an object impacts the surface of a rigid substrate. Bending waves differ from surface waves in that they travel through the full thickness of the substrate rather than just on the surface of the material; one advantage that results from this difference is superior scratch resistance. When an object such as a finger or stylus touches the substrate, bending waves are induced that radiate away from the touch location. As the waves travel outwards, they spread out over time because of the phenomena of dispersion, where the velocity of a bending wave propagating through solid material is dependent upon the wave's frequency. An impulse caused by a touch contact generates a number of bending waves within the substrate, all at different frequencies. Because of dispersion, these bending waves propagate out to the edges of the glass at different speeds rather than in a unified wave front. The result is that sensors at the edges or corners of the substrate receive a wave formation that does not resemble the original impulse at all; the wave formation is further modified by reflections from the internal surfaces of the substrate. The net result is a chaotic mass of waves all interfering with one another throughout the substrate. The key difference in the two existing touch technologies that utilize bending waves is how that chaotic mass of waves is processed.

9.1 Acoustic pulse recognition (APR by Elo TouchSystems)

In APR touchscreens, the substrate is "characterized" in advance by tapping the substrate in thousands of locations by using a robot. The bending wave "signature" of each location is sampled and stored in a lookup table in nonvolatile RAM that is associated with the particular substrate. In operation, bending waves produced by a touch are sensed by four piezoelectric transducers located asymmetrically on the perimeter of the substrate (see Fig. 26). The asymmetry helps ensure that the signatures are as complex as possible; a high level of complexity helps differentiate the signatures. A controller processes the output of the four transducers to produce the "signature" of the current touch and then compares it with the stored samples in the lookup table; interpolation between samples is used to calculate the correct touch location.[34]

The concept of APR was developed in the early 2000s by Tony Hardie-Bick, an individual inventor at SoundTouch Ltd., a small company in the UK. Elo TouchSystems acquired the assets of SoundTouch in 2004 or 2005. After some development for commercialization, the technology was announced in 2006. It was designed to be a replacement for analog resistive, before multi-touch became important.

A touch technology based on the same fundamental idea of sensing bending waves was developed simultaneously and independently by Sensitive Object in France (it was branded "ReverSys").[35] Sensitive Object's and Elo TouchSystems' IPs did not infringe each other, but they were closely interleaved, so the two companies executed a cross-license agreement in 2007 shortly after the launch of both products. The two companies continued to develop separately after the agreement was signed because the purpose of the agreement was to avoid a lawsuit over the existing IP, not to share IP going forward. One of Sensitive Object's key innovations was a method of quickly characterizing a substrate in just a few steps, versus Elo TouchSystems' method of tapping the substrate 1000+ times with a robot arm. Elo TouchSystems purchased Sensitive Object in January of 2010 for $62m.[36] The combination of the two companies' IP produced a very strong portfolio. However, it has taken Elo TouchSystems some time to fully digest the acquisition. The author expects Elo TouchSystems to launch some new products on the basis of the combined IP by the end of 2012.

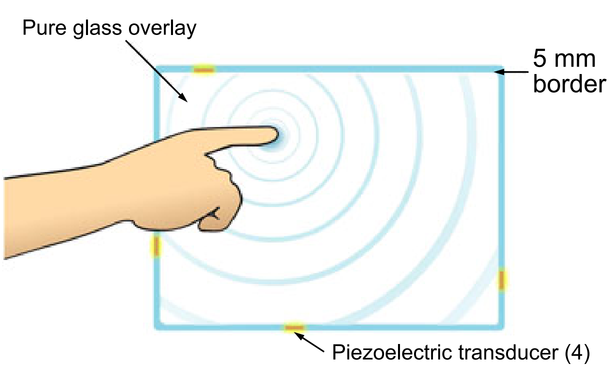


FIGURE 26 — An acoustic pulse recognition touch sensor consists of a piece of glass with four piezoelectric transducers on the back surface of the glass. When a finger or any object contacts the glass, bending waves are produced in the glass substrate and sampled by the transducers; a controller determines the touch location. Source: Elo TouchSystems.

APR/ReverSys has the following fundamental limitations:

- It is not deterministic. Touching the same exact location many times produces a "cloud" of points surrounding the target coordinates. This means that drawing with a stylus will not produce exactly the same result every time. This is quite different from analog resistive, where touching the same exact location always produces the same coordinates (unless you happen to be touching directly on top of a spacer dot, in which case, the coordinates could vary by the size of the spacer dot, typically less than 50 microns).
- It requires a "tap" to produce enough bending waves to be detected. If a shy or uncertain user "sneaks up" on an APR touchscreen and presses it without a distinct tap (even if the user presses very hard), the touch will not register.
- It does not have a "hold" function (equivalent to keeping a mouse button depressed). When the touching object stops moving, bending waves are no longer produced. This means that the commonly used sequence of drag-hold-drag on the Windows desktop does not work because the APR driver must issue an automatic mouse-up at the beginning of the hold period. Elo TouchSystems has invented a clever way around this limitation, but the concept has not been refined sufficiently to be released to production yet.
- The bending wave detection algorithms can be optimized to detect a series of rapid taps, such as occur in a point-of-sales application or optimized to detect the continuous bending waves that result from drags, such as occur when drawing—but not both at the same time. When an APR touchscreen is initialized, the application designer has the option (via a control panel applet) of selecting the desired optimization; selecting a compromise for "general-purpose applications" results in neither case working as well as it could.
- It is fundamentally a single-touch analog technology. Elo TouchSystems has developed a method of sensing two simultaneous touch points, but in a world dominated by p-cap, that is not enough. Like the touch and hold concept, APR two-touch has not been refined sufficiently to be released to production yet.
- The mounting (clamping) of an APR touchscreen is critical to good performance. If you consider the difference in sound produced by tapping a free-hanging sheet of glass versus a sheet that is clamped tightly on all four sides, it is obvious why this is so. This means that OEMs/ODMs and system integrators must be trained on how to properly integrate an APR touchscreen.

The author believes that with the dominance of p-cap and the substantial list of limitations earlier, APR as it is today is unlikely to become a mainstream touch technology. One niche that may be promising is that of touch for e-readers.

E-readers typically use electrophoretic displays (electronic paper displays [EPDs]), which are reflective. Adding any additional layers in front of a reflective display is undesirable. However, a thin-glass APR substrate can be included behind an EPD; because an EPD is typically flexible, touches would transfer directly to the APR sensor. Elo TouchSystems may also be able to exploit various other nontraditional application niches through the incorporation of ReverSys' ability to make any rigid object into a touch-sensing surface.

9.2 Dispersive signal technology (DST by 3M)

The key difference between Elo TouchSystems' APR and 3M's DST is that instead of comparing the bending waves produced by a touch with stored characterization samples, DST analyzes the bending waves in real time to calculate the touch location.[37] Figure 27 presents a graphic representation of the effects of bending waves on a glass substrate. The third graphic is representative of a wave pattern that APR would sample and compare; the fourth graphic represents the result of processing the pattern through DST's real-time algorithms. As noted in the beginning of this section, the transmission velocity of bending waves through the substrate changes with frequency, causing the signal to be dispersed or spread. Upon receiving the signal, DST's approach is to reintegrate the spread signal by applying processing that allows for the differences in delay versus frequency, then applying correlation processing between the four sensors before ultimately triangulating the original touch coordinates. In effect, it is a form of spread-spectrum technique that is inherently tolerant of signal reflections and interference.

NXT PLC in the UK licensed their DST core technology exclusively to 3M in 2003. NXT (which renamed itself as HiWave Technologies in 2010) is known as the creator of the first flat-panel loudspeaker. In this device, piezoelectric transducers mounted on the periphery of a rigid substrate are driven with an audio signal, causing the substrate to function as a speaker diaphragm. NXT had realized (and patented) the reverse idea that vibrations (bending waves) in the substrate could be sensed by the transducers and used to locate the source of the waves (the touch location). 3M and NXT did a substantial amount of joint development to commercialize DST technology, with 3M preannouncing their first DST product in 2004 and actually launching the product in 2006. The initial launch was not successful; 3M withdrew the first product from the market for more than a year, finally relaunching it in 2007. Because 3M's bread-and-butter product was (and still is) surface-capacitive touchscreens in sizes from 5.7 to 32 in, 3M targeted DST at large-format displays between 32 and 55 in to avoid cannibalizing any of their surface-capacitive business.

Applications of DST are similar to those for camera-based optical and traditional IR; interactive information and digital signage are the primary focus. DST has most of the same limitations as APR, as follows:

- It requires a "tap" to produce enough bending waves to be detected
- It does not have a "hold" function
- It is fundamentally a single-touch technology (although 3M has told the author that they are developing a two-touch capability)
- The touchscreen mounting (clamping) is critical to good performance

A 3M representative at a trade show in mid-2011 told the author that 3M has stopped all development on DST except for the completion of the two-touch capability. Without further development, the technology will eventually become uncompetitive. The author expects that although 3M will continue selling DST into existing applications in the near term, within 5–10 years, the technology will disappear from the market.

10 Force sensing

Force sensing has always been seen as the "holy grail" of touch sensing because the simplest possible method of detecting a touch should be to just measure the pressure (force) of the touch in multiple locations on the substrate and then triangulate to find the origin. If only it were that simple!

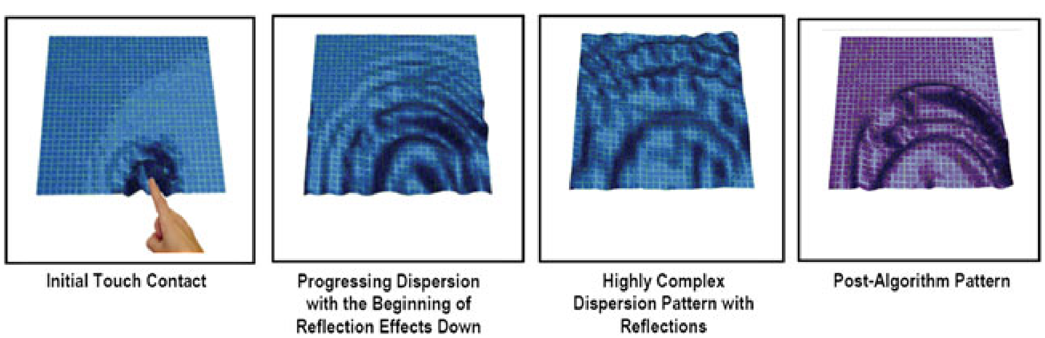


FIGURE 27 — This figure is a graphic representation of the effect of bending waves on a glass substrate. The third graphic is typical of a pattern that acoustic pulse recognition would sample and compare offline; the fourth graphic is the result of processing the pattern through dispersive signal technology's real-time algorithms. Source: 3M Touch Systems.

The earliest known commercial product based on force sensing was IBM's "TouchSelect" touch overlays for 12-in to 19-in CRT monitors in 1991. This technology used strain gauges to mount the touchscreen. It was unsuccessful, lasting no more than about 3 years on the market. The next commercial incarnation of force-sensing touch in the USA was launched in 2007 by QSI, a Utah-based manufacturer of human–machine interface products and mobile data terminals. The technology, branded as InfiniTouch™, employed a clever beam-mounting method for the strain gauges that eliminated any horizontal component of the touching force.[38] To avoid impacting their existing business, QSI spun off the force-sensing technology in 2008 into a subsidiary named Vissumo.[39] The subsidiary was insufficiently capitalized to undertake the nontrivial task of selling a new touch technology into a crowded market, so they ran out of money and shut down in 2009 (QSI was acquired by Beijer Electronics in 2010 and is now known under that name).

In a separate attempt at commercializing force-sensing touch, MyOrigo in Finland in 2000 developed a force-sensing touchscreen for an advanced user interface on a proposed smartphone. MyOrigo was sold to its management in 2004 and restarted as F-Origin. F-Origin went bankrupt in Finland in 2005, and the assets were purchased by a US investor who reformed F-Origin in the US in 2006. F-Origin further developed its force-sensing technology (branded as zTouch™) during 2007–2008 but could not obtain any traction in the consumer electronics market because of the prevalence of p-cap. They restructured in 2009 with an investment from TPK (the world's largest supplier of p-cap) and began marketing zTouch in 2010. F-Origin is currently focused on commercial applications where the durability and environmental resistance of force-sensing touch technology are particularly valuable.[40]

Force-sensing touch works by supporting the display (or cover glass) on force sensors, typically either strain gauges or piezoelectric transducers. To obtain accurate measurements of the force applied to the touch surface, the display and/or cover glass' movement must be constrained so that it only moves in the Z-direction. There are several ways of accomplishing this; Fig. 28 illustrates the suspension spring-arm method currently employed by F-Origin.

Like any touch technology, force sensing has some unique advantages and disadvantages that derive from the physics of the technology. The key advantages of force sensing include the following:

- No coatings or films, just a rigid substrate (better optics and durability than resistive)
- Touch-with-anything capability (even better than resistive)
- High durability and extended environmental capability
- The ability to use pressure as another variable in decoding the intent of a touch
- The capability of employing a 3D (nonplanar) substrate with embedded objects

The key disadvantages include the following:

- Very difficult to achieve multi-touch (the number of sensors required increases rapidly)
- Minimum touch force (it is not zero like p-cap)
- Difficult to achieve flush (zero-bezel) design

The author predicted earlier in this paper that multi-touch will become significant in commercial applications. Given that prediction, the author believes that force-sensing technology is likely to disappear in the next 5 years.

11 Planar scatter detection (PSD)

Planar scatter detection is a unique form of optical touch invented at Flatfrog, a startup founded in early 2007 in Sweden that shipped its first product in May 2012. The core of their touch technology could be termed "optical waveguide analysis." The "waveguide" is the touch substrate, which can be any dimensionally stable transparent material. It does not have to be rigid or flat, which is a relatively unusual characteristic for an optical touch system. It also does not have a minimum thickness. The basic functionality of Flatfrog's system is shown in Fig. 29. In a planar scatter detection (PSD) touch sensor, light is injected into the edges of an optical substrate by multiple IR LEDs and remains confined inside the substrate by total internal reflection (TIR). A touch scatters a portion of the light because of frustrated TIR (FTIR); multiple IR photodetectors interleaved with the LEDs on the edges of the substrate detect both the scattered light and the remaining (reduced-intensity) TIR light. Complex algorithms determine the location of all objects on the surface by analyzing the light intensities.

One of the aspects that make PSD different from standard FTIR is that the light resulting from FTIR is analyzed within the substrate; it does not have to escape like in vision-based

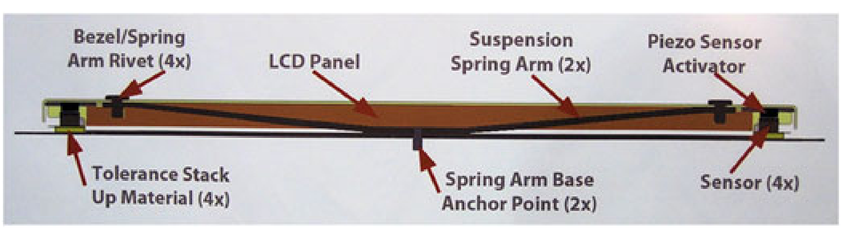


FIGURE 28 — Force-sensing touchscreens work by supporting the display and/or cover glass on force sensors. To obtain accurate measurements of the force applied in the touch, the assembly's movement must be constrained so that it only moves in the Z-direction. There are several ways of accomplishing this; the figure shows the suspension spring-arm method currently employed by F-Origin. LCD, light-emitting diodes. Source: F-Origin.

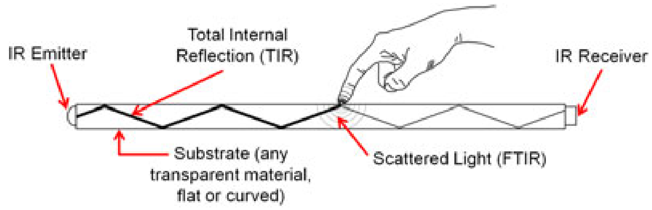


FIGURE 29 — In a planar scatter detection touch sensor, light is injected into the edges of a substrate by multiple infrared (IR) light-emitting diodes. A touch scatters a portion of the light because of frustrated total internal reflection (FTIR); multiple IR photodetectors detect both the scattered light and the remaining TIR light at the edges of the substrate. Complex algorithms analyze all the light intensities and determine the location of all touches on the surface. Source: Flatfrog.

touch. Another is that a touch only consumes a small amount of a given light ray, so that multiple touches can be located in a straight line with enough light left over to still be sensed at the edge. The number of IR emitters and receivers is roughly similar to a traditional IR touchscreen; about 160 pairs are required for a 32-in touchscreen. Because the circumference of a 32-in full-HD display is about 87 in, 200 pairs translate into one component roughly every 7 mm. Like traditional IR, PSD therefore requires a circuit board (or a waveguide attached to a circuit board) on all four edges of the substrate. Unlike traditional IR, a PSD touchscreen has a totally flush bezel because nothing projects above the surface of the display. Regarding scalability, Flatfrog cofounder Ola Wassvik said in an interview in the May 2009 issue of Veritas et Visus' "Touch Panel" newsletter that the key touch components for a 70-in system (191 perimeter inches) cost about 50% more than those for a 40-in system (109 perimeter inches) versus the 75% increase in perimeter.[41] This is in the same ballpark as traditional IR but certainly higher than camera-based optical.

A few of PSD's more interesting characteristics include the following:

- Scalable from 3 in to over 100 in (although Flatfrog is focusing on the 32-in to 55-in space first)
- Supports 40+ touches and meets the Windows 8 Touch Logo specifications (although they only apply to touchscreens up to 32 in)
- Works with finger, any type of glove (including woolen), stylus, and soft objects such as pencil erasers
- Supports both passive and active (light-emitting) styli; minimum tip diameter is only 0.25 mm
- Passive objects on the screen can be ignored, along with dirt and scratches
- Capable of extremely high refresh rates (over 1000 Hz) and very high resolution (400 dpi)

The author had an opportunity to spend a half-hour with a 32-in system at the end of 2011. The performance was quite impressive. PSD may offer some serious competition for traditional IR and camera-based optical in large-format and potentially even for p-cap starting from laptop-size and up. It is also significant that in addition to Intel Capital's recent $20m investment, one of Flatfrog's earlier investors is Promethean, the number two player in the interactive-whiteboard market after SMART Technologies. Given the characteristics as described, PSD should be able to seriously outperform both traditional IR and camera-based optical in the interactive-whiteboard application. However, as previously noted, PSD's cost does not scale as well as camera-based optical, so the performance advantage becomes less significant as the size of the whiteboard increases.

12 Vision-based

Vision-based touch here refers to the use of "machine vision" to detect and process touch in contact with a surface. Machine vision also implies heavy use of image analysis software to determine touch locations and other information about what is contacting the touch surface. Using 3D cameras to sense the motion of a user in space (e.g., as Kinect does) is also a use of "machine vision," but in this paper, it is excluded from discussion because it does not involve contact with a display.

There are currently three methods of producing vision-based touch: (1) projection, (2) multiple wide-angle cameras behind an LCD, and (3) light-sensing in-cell. The projection method used in vision-based touch is usually rear projection, with a camera located next to the projector (as shown in Fig. 30). FTIR is often used to generate light resulting from touches on the projection surface. Microsoft Surface 1.0, launched in 2007 (and many of the similar "touch tables" that followed in the next 4 years), are the best examples of rear-projection vision-based touch. The primary advantage of this method is that a system can be assembled at very low cost; the primary disadvantage is the physical size of a rear-projection system, plus the relatively low image quality that results from rear projection.[42]

An example of using multiple wide-angle cameras behind an LCD to produce vision-based touch can be found in the MultiTaction™ products from MultiTouch in Finland. In this case, the cameras are integrated into the backlight. The primary advantage of this method is the relative thinness of the display compared with projection (8 in for MultiTaction). The primary disadvantage is the cost and complexity of the

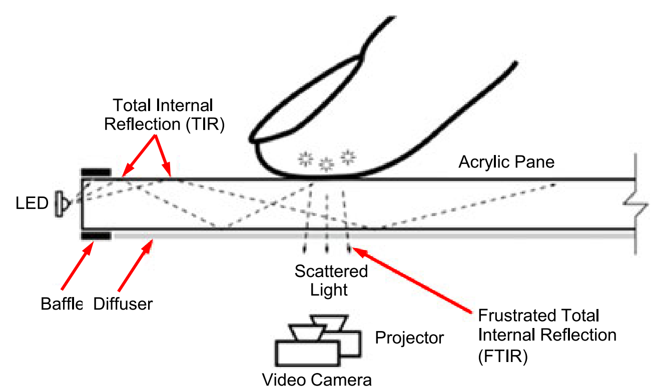


FIGURE 30 — The most common method of producing vision-based touch utilizes rear projection with a camera located next to the projector. Frustrated total internal reflection (FTIR) is most commonly used to generate light resulting from touches on the projection surface. LED, light-emitting diode. Source: Perceptive Pixel (Jeff Han).

solution. The author suggests that this method may be just a temporary way-stop on the path to fully capable light-sensing in-cell touch—although with the performance and environmental limitations of the Samsung SUR40, that is not so clear now.

The technology of light-sensing in-cell has already been discussed in the LCD in-cell touch portion of this paper. As mentioned previously, the Samsung SUR40 with Microsoft Surface 2.0 is the best current example of this technology. The advantage of light-sensing in-cell is that touch is fully integrated into the display. This actually allows the touch system to "see" near-field touch activities—that is, it can detect hover. However, the value of hover in applications other than standard Windows desktop-mouseover is unclear. The value of "proximity" (hover without location information) is clearer; an example can be found in automotive touchscreens where the screen remains dim (less of a distraction) until your finger approaches it. The key disadvantages of in-cell light sensing (as implemented in the SUR40) appear to be performance lag and environmental lighting limitations.

Applications for vision-based touch currently fall into two categories: (1) a common platform for touch research in many universities due to the high multi-touch capability and low cost of self-fabrication and (2) a new platform for traditional commercial applications, especially product-focused touch tables in retail stores.

The author believes that although vision-based touch is still in its infancy, it is here to stay as a niche technology. The primary reason is that it is not directly competing with other touch technologies. The "vision" aspect of the technology allows it to do things that other technologies cannot. One simple example is object recognition through the use of graphic tokens attached to objects. This enables an application where (for example) a digital camera or smartphone is placed on the touch surface and application software automatically downloads the photos from the device via Bluetooth and displays them for editing or arranging on the display—without the need for the user to give any commands.

13 Electromagnetic resonance (EMR) pen digitizer

An electromagnetic resonance (EMR) pen digitizer is a stylus-only touch technology. The stylus contains a small amount of electronics, so it is not passive like a stylus for analog resistive. Although it is stylus-only, some consumer electronics OEM/ODMs (particularly those who manufacture e-readers) refer to EMR pen digitizer technology as just "touch"—thus its inclusion in this paper.

EMR works by absorbing and releasing RF energy. As illustrated in Fig. 31, an antenna (consisting of a film or PC board with copper traces in loops) is placed "under" the display. In Wacom's version of this technology, the antenna is placed in transmit mode for a short period (e.g., 20 μs) to supply RF energy to the stylus. The stylus contains a resonant circuit (inductor–capacitor pair) that stores the energy. The antenna then switches to receive mode for another short period and captures the stored energy as it is released from the stylus. A controller analyzes the location of the released energy by measuring the signal level at each antenna loop and calculates the pen location.[43]

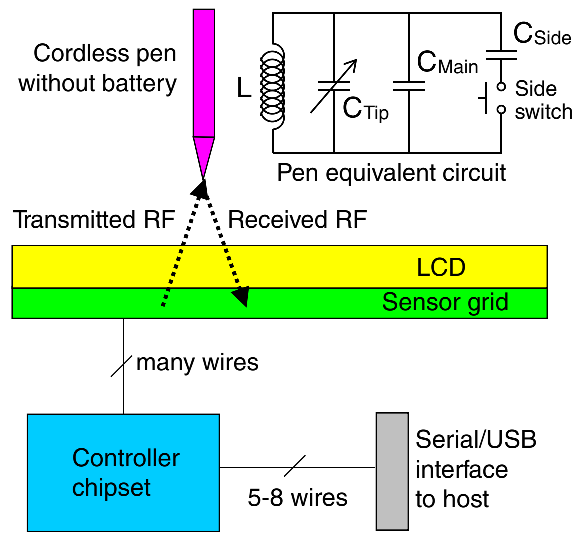


FIGURE 31 — In an electromagnetic resonance pen digitizer, the sensor is located behind the display. The sensor acts as both a transmitter (sending energy to the pen that contains a resonant circuit) and as a receiver (receiving the stored energy from the pen). RF, radio frequency; LCD, light-emitting diode; USB, universal serial bus. Source: Wacom and the author.

The batteryless and cordless EMR pen digitizer was invented by Wacom in Japan in 1984. Several competitors copied the technology in the 1990s, but because of the strength of Wacom's IP, they all used a battery in the pen (generally seen as undesirable). Now that Wacom's core patent has expired, competitors such as Waltop are beginning to create batteryless pens. However, it is not as easy as it seems, and Wacom has had more than 20 years to perfect the technology.

The primary application for pen digitizers has always been desktop graphics tablets and tablet monitors used by artists and children. The first use of the technology in mobile devices was the Microsoft Tablet PC that was launched in 2002 and is still sold today mainly into commercial applications. With the advent of e-readers, the pen digitizer moved into a second mobile application. An EMR pen digitizer is particularly well suited for devices with reflective screens because the sensor is located behind the display, leaving the reflective display completely unobstructed.

The primary advantages of EMR over the standard resistive and capacitive methods of providing a stylus are as follows:

- The sensor is behind the screen, so there is no overlay
- Mouseover ("hover") is inherent in the design, so the pen works just like a real mouse
- Very high resolution (typically 1000+ dpi)
- Pressure sensing is inherent in the design (useful for artists)
- Palm rejection is inherent in the design (essential for practical stylus use)

The primary disadvantages are as follows:

- The pen contains electronics, so if it is lost, the system's stylus functionality is lost with it
- Integrating the sensor between an LCD and its driver board is not always possible
- The technology is sensitive to magnetic material and fields (shielding is required in most applications)
- Pen-only (no finger-touch; adding it requires combining technologies—see the following text)

The author believes that EMR pen digitizers in mobile devices will remain in the market for at least the next 5 years. Although the technology's disadvantages are significant, the advantages over the resistive and capacitive methods of providing a stylus are significant enough to keep EMR alive as a niche technology.

14 Combinations of technologies

It should be clear from the information presented in this paper that "there is no perfect touch technology." No single technology meets all requirements of all applications. Combinations of technologies are one approach to creating a better touchscreen. Examples can be found in Tablet PCs, e-readers, and point-of-sale terminals. An example of each follows.

The latest Microsoft Tablet PCs often combine a resistive or p-cap finger-capable touchscreen with an EMR pen digitizer. In the case of p-cap, a single controller can be used to drive both touchscreens, which enables automatic mode switching between pen and finger.

In May 2011, Hanvon announced a new method of combining technologies to accomplish the same goal of pen-and-finger operation. Hanvon combines their EMR pen digitizer with an array of pressure-sensing piezo-capacitors in the same plane as the EMR sensor (illustrated in Fig. 32). The piezo-capacitors, which are the same component that is used in the tip of the pen for pressure sensing, enable sensing finger pressure "through" an e-reader's EPD.

IBM is one of the major providers of point-of-sales terminals. IBM prefers to use traditional IR in their point-of-sales products. However, to minimize the problem of "pretouch" (where the finger breaks the IR light beams and triggers a touch without actually touching the surface of the display), IBM includes a pressure-sensing piezoelectric transducer in the touchscreen mounting scheme so that touch coordinates are produced only when the user is guaranteed to be touching the screen. In this application, the transducer detects the "presence" of a touch, whereas the IR touchscreen detects the "location" of the touch.

The author believes that combinations of touch technologies are very likely to continue to exist during the next 5 years, although combinations of major technologies are usually limited by the cost of the combination. Combinations of a major and minor technologies are more likely to occur, for example, p-cap combined with a single IR camera to enable the detection of near-field gestures in the space above the touchscreen, beyond the range of hover detection.

FIGURE 32 — Hanvon's dual-mode (pen and finger) digitizer combines their electromagnetic resonance digitizer with an array of pressure-sensing piezo-capacitors in the same plane as the electromagnetic resonance sensor (labeled "Electromagnetic Resonance Technology (ERT) unit"). The piezo-capacitors enable sensing finger pressure through the electronic paper display (EPD) typically used in an e-reader. Source: Hanvon.

15 Conclusions

This paper has described 13 categories of touch technologies with 38 different variations, as follows:

1. Projected capacitive (self-capacitive, mutual capacitive, on-cell, one-glass solution, ITO replacements, and wire based)
2. Analog resistive (four-wire, five-wire, eight-wire, AMR, and Stantum's iVSM)
3. Surface capacitive (standard and Wacom's CapPLUS)
4. Surface acoustic wave (standard, two-touch, and flush bezel)
5. Infrared (traditional, high-finger-count, waveguide, and mobile)
6. Camera-based optical (two-camera and more than two cameras)
7. LCD in-cell (light sensing, three types of capacitive sensing, and voltage sensing)
8. Bending wave (Elo TouchSystems' APR and 3M's DST)
9. Force sensing (standard)
10. Planar scatter detection (standard)
11. Vision-based (projection, multiple wide-angle cameras, and in-cell light sensing)
12. Electromagnetic resonance pen digitizer (standard)
13. Combinations of technologies (three examples)

Although just the first two categories earlier with their total of 11 variations account for more than 95% of all touchscreens shipped, "all" of the remaining 11 categories with their 27 variations currently have applications and buyers. The message that this clearly communicates is "there is no perfect touch technology."

Appendix

TABLE 1 — Figure topics.

Figure #	Figure topic
1	Touch market penetration by technology, 2008–2017
2	Projected capacitive (p-cap) self-capacitive and mutual capacitive
3	Projected capacitive (p-cap) controller
4	Standard p-cap mutual-capacitive layers
5	On-cell p-cap mutual-capacitive layers
6	One-glass-solution p-cap mutual-capacitive layers
7	Analog resistive
8	Analog resistive four-wire
9	Analog resistive five-wire
10	Analog multi-touch resistive (AMR)
11	Multi-touch resistive by Stantum (iVSM)
12	Surface capacitive
13	Surface acoustic wave (SAW)
14	SAW waveform
15	Traditional infrared (IR)
16	"High-finger-count" multi-touch infrared
17	Waveguide infrared (Digital Waveguide Touch) by RPO
18	Camera-based optical
19	LCD in-cell light sensing
20	LCD in-cell pressed capacitive
21	Samsung digital camera with LCD in-cell pressed capacitive
22	LCD in-cell self-capacitive
23	LCD in-cell "true" mutual capacitive (non-IPS LCDs)
24	LCD in-cell "true" mutual capacitive (IPS LCDs)
25	LCD in-cell voltage sensing
26	Bending wave, acoustic pulse recognition (APR) by Elo TouchSystems
27	Bending wave, dispersive signal technology (DST) by 3M Touch Systems
28	Force sensing
29	Planar scatter detection (PSD) by FlatFrog
30	Vision-based, rear projection
31	Electromagnetic resonance (EMR) pen digitizer
32	Electromagnetic resonance combined with force sensing

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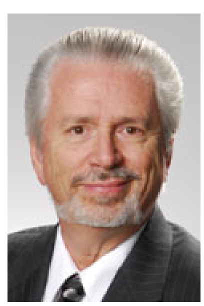

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