Tactile Sensing in Human-Computer Interfaces: The Inclusion of Pressure Sensitivity as a Third Dimension of User Input

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Abstract

This paper presents a review of tactile technologies for human-computer interactivity via touch interfaces, where touch force is measured as a third dimension of user input along with touch location. Until recently, tactile technologies for computing applications have detected only the location of a touch (or several touches simultaneously) with no additional information about the force or pressure the user imparts to the interface. Such additional input may open up new applications in force-enhanced gestures, for example the touch force may dictate the linewidth used in drawing software, or the speed of a scroll gesture may be increased with increasing applied force. Here we review the underlying physical principles behind several force sensitive touch technologies. The latest innovations by leading technology developers, only available in the patent literature, are also described and where public data exists the force-resistance behaviours of several key technologies are compared in terms of their sensitivity and range of response. The advantages and disadvantages of each technology are discussed, along with the current and possible future applications in consumer electronics. It is shown that the concept of pressure–sensitivity as an additional user input mechanism is fast gaining traction, with many implementations already found in commercial products. Furthermore, a study of the patent trends shows that this functionality may soon become commonplace in the new generation of consumer electronic devices.

Keywords: Tactile sensing, Human-computer interactions, Touchscreen technology

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1. Introduction

Tactile sensing has become increasingly important in human-computer interactions (HCI), introducing novel and intuitive ways for the user to interact with a computer interface, such as in machinery control panels, point-of-information (POI) and point-of-sales (POS) kiosks, and device interfaces in consumer electronics. Touch may be detected on an integrated trackpad (such as in a laptop) or on a transparent touchscreen overlaid onto the display (for example in smartphones and tablets), thus eliminating the need for a separate touch interface as the user can directly interact with the icons shown on the underlying display.

Currently most touch interfaces can detect only the location of the touch, i.e. the device knows if and where it is being touched, but with no information about the force of the touch. However recent advances have begun to incorporate force or pressure sensitivity as a third dimension of user control. The pressure sensitive component may be incorporated directly into the touch location sensor. Alternatively, the pressure sensing component may take the form of force sensors external to the location sensing interface. This includes force sensors which are placed underneath the corners of the interface or force sensors found in an external device such as a pressure-sensitive stylus. The addition of pressure-sensitivity opens up new methods of interactivity, including pressure based text entry, menu selection and handwriting/signature recognition [1, 2, 3], and force enhanced gestures for scrolling, zooming and image manipulation [4, 5].

Force or pressure–sensitive tactile sensors can already be found in applications such as robotics and electronic skin [6, 7], and in biomedical applications such as bite force measurement in dentistry and human gait analysis [8, 9]. Here, tactile sensing may be defined as the "detection and measurement of contact parameters in a predetermined contact area and subsequent pre-processing of the signals at the taxel level, i.e., before sending tactile data to higher levels for perceptual interpretation" [10]. These applications have been the topic of many review articles which describe the latest research and innovation [11, 12, 13, 14].

Whilst there exist several reviews on the underlying technologies for location sensing in touch interfaces [15, 16, 17, 18, 19, 20] and advances in multi-touch and 3D gesturing [21, 22], to date there is no review in the literature which discusses the inclusion of pressure sensitivity into touch interfaces. The aim of this review paper is to draw together the various methods of adding pressure sensitivity to touch interfaces in HCI applications via specialised tactile sensors. First, we present a short introduction to the various methods of pressure sensing used for tactile applications, along with the advantages and disadvantages of each. Then the applications of these sensors in HCI touch interfaces are discussed in detail. The technologies have been broadly split according to application, including keyboards, laptop trackpads, and transparent touchscreens. For the latter, a distinction is made between resistive and capacitive technologies. Together, these account for 80% of the total revenue and 95% of all touchscreen units shipped in 2011 [15] and most pressure–sensing solutions are focussed here. However, the inclusion of pressure–sensing in other touchscreen technologies is also briefly discussed. A distinction is also made between pressure-sensing solutions which are incorporated directly into the touch module of the device (e.g. continuous thin films or 2D matrix arrays of sensors incorporated into the touchscreen structure) and a small number of discrete sensors placed outside of the touch module (e.g. four force sensors placed underneath the display).

2. Pressure Sensing Mechanisms

Sensor	Modulated Physical Parameter	Operating Principle	Manufacture Details	Advantages	Disadvantages
Strain Gauge	Resistance	Applied pressure causes change in length and cross–sectional area of conductive coil	Can be micro–machined and embedded into a polymer to create a thick film sensor array with mechanical flexibility	Well established design and manufacture processes Easily integrated into existing circuitry High spatial resolution achievable for micro–machined strain gauges	Response scales with surface area – can be large in the lateral dimension Insensitive to lateral force Sensitive to temperature fluctuation and humidity Less sensitive than piezoresistive sensors Non-linearity and hysteresis of response
Piezoresistive	Resistance	Applied pressure changes inter–atomic spacing such that electrons are promoted or demoted from conduction band	Can be micro–machined and embedded into polymer to create a sensor with mechanical flexibility	Well established design and manufacture processes High sensitivity, especially to low applied pressure Smaller lateral dimension than strain gauge High spatial resolution achievable for micro–machined piezoresistors	Piezoresistive material can be brittle and fragile Relatively costly materials When embedded into polymer there can be a loss in sensitivity
Conducting Polymer Composite	Resistance	Applied pressure deforms the composite resulting in more conduction pathways between filler particles	Can be printed by screen–printing or similar	Simple fabrication techniques mean low cost for large area fabrication Mechanically flexible and robust structure Low power consumption due to high resistance of off–state	Conduction is isotropic – can lead to low spatial resolution Hysteresis effects due to mechanical properties of polymer causes poor repeatability of response Typically have a low dynamic range
Intrinsically Conductive Polymer	Resistance	Applied pressure deforms the polymer causing current flow between adjacent polymer chains	Can be printed by screen–printing or roll–to–roll	Mechanically flexible and robust structure Low-cost large-area fabrication	Typically low sensitivity Conduction is isotropic - can lead to low spatial resolution
Piezoelectric	Voltage	Applied pressure causes redistribution of internal charge and produces a voltage	Can be printed by screen–printing or roll–to–roll	High sensitivity Mechanically flexible and robust structure	Cannot detect a dynamic force Requires amplifier to boost output signal Cross–talk between piezo– and pyroelectric effects Cross–talk between sensor elements in array
Capacitive	Capacitance	Applied pressure decreases the electrode separation and increases the mutual capacitance between the electrodes	Complex fabrication techniques, e.g. photolithography and thin–film deposition to produce complex 3D structure	High sensitivity Not affected by temperature variations Small sensor size leads to high spatial resolution	Sensitive to electromagnetic interference leading to poor signal to noise ratio Requires relatively complex circuitry with high power consumption Cross-talk between sensor elements in an array
Inductive	Magnetic inductance leading to a change in voltage	Applied pressure causes displacement of a magnetic core through a primary coil, inducing a voltage which is measured by secondary coil	Typically bulky, mechanical structure not suited for thick or thin film deposition techniques	High sensitivity and dynamic range High repeatability of response with little or no hysteresis	Bulky structure such that arrayed sensors would provide low spatial resolution Possible frictional losses between magnetic core and coil
Optical	Light intensity	Applied pressure deforms optical fibre and decreases the light intensity measured at CCD detector	Sensors may be produced by embedding optical fibres in a polymer	No cross-talk between sensors Insensitive to external electromagnetic noise Can be flexible and durable when embedded into polymer	Hysteresis effects due to mechanical properties of polymer leading to poor repeatability of response Signal can be attenuated by initial misalignment of the sensor leading to false–touch effects.

Table 1:
Comparison of pressure–sensitive tactile technologies

The most commonly used tactile or touch pressure sensors are based on resistive, capacitive, piezoelectric, inductive and optical sensing. Each of these techniques has advantages and disadvantages which are summarised in Table 1. Further information on tactile sensors can be found elsewhere in the literature, for example Yousef *et al* give an excellent review of tactile sensor arrays for robotics applications, detailing the spatial resolutions of each sensor array discussed [13].

2.1. Resistive Pressure Sensors

2.1.1. Strain Gauges and Piezoresistors

A piezoresistor exhibits a change in electrical resistance with applied stress. This type of response is seen in semiconducting materials including germanium and silicon (polycrystalline or amorphous). When a stress is applied to a semiconductor resistor with initial resistance R, the change in resistance ΔR is given by

$$\Delta R = R(\pi_l \rho_l + \pi_t \rho_t) \tag{1}$$

where π is the piezoresistive coefficient and ρ is the applied stress along the longitudinal and transverse directions, denoted by the subscripts l and t respectively. The piezoresistive coefficient is related to the change in the inter-atomic spacing when a stress is applied to the material, making it easier or harder for electrons to be promoted into the conduction band.

Piezoresistivity may also be observed in metals, although the piezoresistive coefficient is often much smaller than that of semiconductor materials. Here, the effect is mostly due to the change in geometry of a conductor under applied stress which affects the current flow through the material. Strain gauges use this effect to detect applied pressure. They have long winding conductive coils so that when the sensor is deformed through an applied pressure the cross section of the coil decreases and the conduction length increases, thus decreasing the resistance through the coil. Strain gauges typically have a higher sensitivity than piezoresistors. However piezoresistors are capable of giving a higher output per unit area and are typically smaller in the lateral dimension.

Both piezoresistors and strain gauges can be embedded into an elastomeric polymer which provides mechanical flexibility. However the response of the sensor can then become prone to creep and hysteresis effects, especially for piezoresistive sensors.

2.1.2. Conducting Polymer Composites

Conductive polymer composites comprise electrically conductive filler particles dispersed into an insulating polymer matrix. The conductivity of the composite is

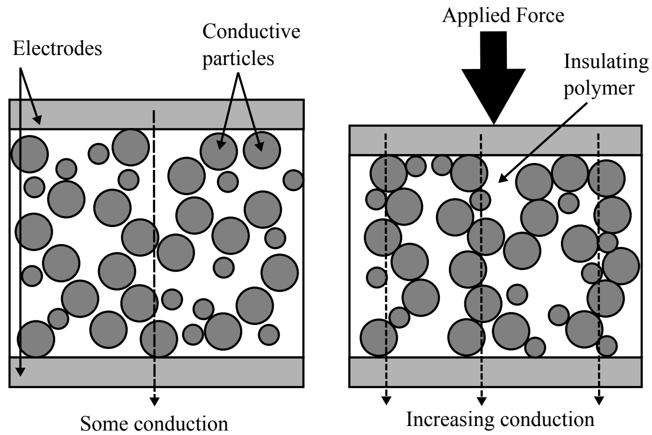


Figure 1: A network of conducting filler particles is dispersed in an insulating polymer matrix at a loading close to the percolation threshold and deposited between two electrodes. Compression of the composite increases the number of conductive pathways throughout the composite.

strongly dependent on the filler volume fraction and the nature of conduction between individual particles. At a low loading the particles are well dispersed and there are very few conductive pathways through the composite, leading to high resistance. At the critical particle loading (the percolation threshold) the conductivity increases as a greater number of conductive pathways are formed. This is described by percolation theory or effective medium models. At loadings close to the percolation threshold the resistance becomes very sensitive to deformation. A pressure sensor may be realised by fabricating a conducting polymer composite such that in its natural undeformed state the filler content is close to the percolation threshold. Then when the composite is deformed the spacing between filler particles decreases producing a large increase in the conductivity of the composite. This mechanism is represented in Fig.1. The sensors are naturally flexible and are usually robust with a simple and well-established manufacture process. However, the response may be prone to hysteresis effects and typically has a low sensing range. Some conductive polymer composites have been fabricated to exhibit a large dynamic range in response to pressure. In this case there is a high loading of conductive particles which have a rough surface texture which is completely wetted by the polymer. Conduction is via a pressure-induced quantum tunnelling conduction mechanism [23, 24, 25].

2.1.3. Conductive Polymers

For intrinsically conductive polymers, the flow of electrons is through the conjugated backbone of the polymer which has either p-type or n-type doping. Compression of the polymer allows charge to transfer between adjacent polymer chains. Examples of intrinsically conductive polymers include polyaniline, polypyrrole and polyacetylene. Their use as a flexible pressure sensor has been well researched, for example see [26, 27] and in many cases they can be deposited using a screen-printing or roll-to-roll printing process [28]. Whilst their mechanical flexibility makes them robust sensors, in their basic form they are inelastic and typically exhibit a low sensitivity to applied pressure.

2.2. Capacitive Pressure Sensors

The capacitance change between a fixed electrode and a deformable electrode, separated by an air gap or other dielectric medium, may be used to detect an applied force. The capacitance between two plates of area A separated by distance d by a medium with permittivity ε_r is given by

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d}. \tag{2}$$

Hence, a change in the spacing between electrodes, for example caused by a force applied to the upper electrode, can result in a measurable change in capacitance. It is also possible to use a spacer layer whose dielectric properties change with applied force. Capacitive sensors show high sensitivity even at low applied forces and they are insensitive to temperature variations. Sensor arrays can be printed onto flexible thin films, for example, Pritchard *et al* demonstrate an array of capacitive sensors with 150 nm thick gold electrodes and a 1.5 μm thick Parylene C dielectric layer [29]. Substrate dependent, the sensors can be very thin and the sensor arrays are capable of giving a high spatial resolution. However complex circuits are often required to address and read-out from each capacitive sensor in the array and there is a problem of cross-talk between nearby sensors. The sensors also have a high sensitivity to external electromagnetic interference.

2.3. Piezoelectric Pressure Sensors

Piezoelectric materials undergo a change in the surface charge density with the application of stress, due to either the formation or realignment of induced dipoles within the material. When the piezoelectric material is placed between two electrodes, a voltage can be measured where the amplitude is directly proportional to the stress applied and to the piezoelectric coefficient. Pyroelectric materials generate a voltage due to changing temperature. When thermal energy is absorbed

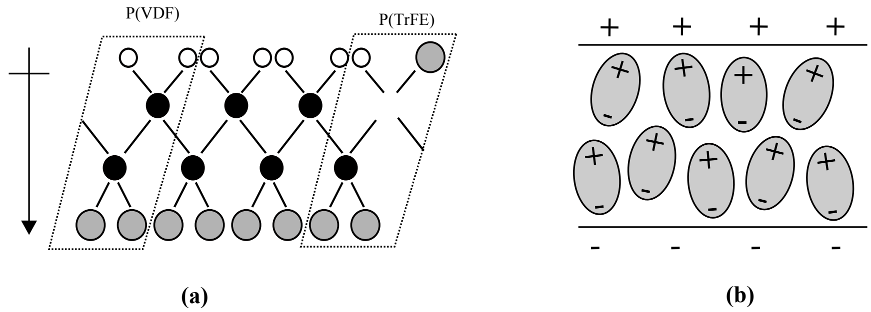


Figure 2: (a) Molecular arrangement inside a P(VDF-TrFE) nanocrystal, where black circles represent carbon atoms, grey circles represent fluorine atoms and white circles represent hydrogen atoms. The distribution of electrical charge produces a permanent dipole moment. (b) Thin polymer film containing nanocrystals of P(VDF-TrFE). Electrical poling results in the alignment of the nanocrystal dipoles along the direction of the applied electric field. Compression of the film will cause a change in dipole orientation, inducing an electrical signal.

the material expands or contracts, again changing the surface charge density. The ferroelectric polymer polyvinylidene fluoride (PVDF) exhibits both a large piezoelectric and pyroelectric responses and can be printed to form a transducer or pressure sensor device [30, 31, 32].The copolymer P(VDF-TrFE) (polyvinylidene fluoride–tri–fluoroethylene) is often used as it has a greater crystallinity after annealing. The structure of P(VDF-TrFE) is shown in Fig.2(a). The alignment of hydrogen and fluorine atoms give the structure a permanent electric dipole moment. Fig.2(b) shows a thin film composed of P(VDF-TrFE) nanocrystals, where the dipoles have been aligned through the application of an electric field double that of the coercive field strength (a process called poling). Upon compression of the film by an applied force, the orientation of the dipoles is altered and an electrical signal is induced.

Once touched, the induced voltage discharges over a short time-scale through the internal resistance of the PVDF layer, and this is a large problem for the detection of static forces. This technology is therefore unsuitable for the detection of a constant force. There can also be a problem of cross-talk between adjacent sensors in an array. However the voltage output can be large even for small deformations due to the high sensitivity of the piezoelectric material, and the sensor elements do not require a power supply. They can be printed, or otherwise deposited, onto flexible substrates making them well suited for flexible applications.

2.4. Inductance Pressure Sensors

A primary conductive coil induces a magnetic field which is then sensed in a secondary sensing coil. This principle is used in the linear variable differential transformer (LVDT), where displacement of a magnetic core through the primary coil changes the induced voltage measured in the sensing coil. This voltage is directly proportional to the length of core magnetically coupled to the sensing coil. The LVDT is primarily used as a displacement sensor. Displacing the magnetic core changes the coupling length between core and coil and produces a measurable change in the amplitude and phase of the voltage in the sensing coils. The displacement of the magnetic core can also be linked to the force applied to it so that this type of sensor is also suitable for force or pressure measurement. The sensitivity and dynamic range of these sensors are typically very high, however they can be quite bulky so that a sensor array may give a low spatial resolution. However, they show virtually no hysteresis effects and have a high repeatability.

2.5. Optical Sensors

A basic optical pressure sensor consists of an LED light source and a CCD detector separated by a length of optical fibre. When a force is applied to sensor, the optical fibres bend and the light received at the CCD is attenuated. It is possible to embed a mesh of optical fibres into an elastomer to produce a flexible pressure sensitive sensor [33]. Optical sensors are insensitive to electromagnetic noise and suffer no cross-talk effects between adjacent sensors. They can be robust and flexible when embedded into a polymer matrix. However initial bending or misalignment of the sensor may produce unwanted signal attenuation and false–touch effects.

3. Sensor Requirements and Considerations for Applications in HCI Touch Interfaces

A force sensor may be defined as giving a constant reading as a function of applied force irrespective of the contact area. A pressure sensor will give, with a constant applied force, a reading which is inversely proportional to the area of applied force. Most sensors described in this review are a combination of both, where the sensor output depends on both the applied force and the contact area. However, the term ‘force sensitive’ is often used in the literature and especially in the patents when describing these devices. The devices are not always true force sensors and are not designed to measure exact levels of applied force. Rather, the device is designed to detect varying *levels* of applied force. The software can then execute a specific response depending on the force level detected, such as a light touch or a hard press.

For the purpose of HCI touch interfaces a light touch may be of the order of 0.1 N and a hard press up to 10 N. This force may be detected indirectly through:

- An increase in contact area between electrodes, associated with applying a force to a specific area of the device (purely a surface effect)
- Deformation of one electrode relative to the other causing either
  - Compression of a piezoresistive layer deposited between the electrodes, and therefore producing a change in resistance through the sensor
  - Straining of a piezoelectric layer deposited between the electrodes, and measuring a change in voltage across the sensor
  - A change in capacitance between the two electrodes resulting from the change in spacing between them
- A combination of the above.

Of course, in real-world applications force is applied via a human fingertip or a stylus over a finite area. For the former, the area over which the force applies depends upon the force itself – as a human fingertip is compliant by nature and the harder the press the larger the touch area. It is often assumed this contact area remains constant, and testing of the touch interfaces usually involves a probe of fixed dimension. The area over which the force applied is important, especially for touchscreens which rely on deformation of the upper electrode. For the same value of force, a larger area upon which the force acts will result in a smaller maximum deflection than if the force is applied over a smaller area. Hence only a measure of the pressure will allow direct comparison between technologies for which the dimensions of the testing probe are different. However, in many cases (especially for those in the patent literature) this level of detail is not provided. Often in the patents the applied force is quoted in units of mass. Here we have approximated 10 g as equal to 0.1 N force for purposes of simplification. Throughout this review, the term pressure–sensitive is used to describe touch interfaces capable of detecting applied levels of force over a fixed contact area as described above. Where the dimensions of the test probe are identical, the response is quoted in units of force. For comparison of different technologies for which the available data is collected using probes of different dimensions, whenever possible the response is quoted in terms of pressure. If there is no data on contact area, the force is used instead with the caveat that direct comparison is difficult.

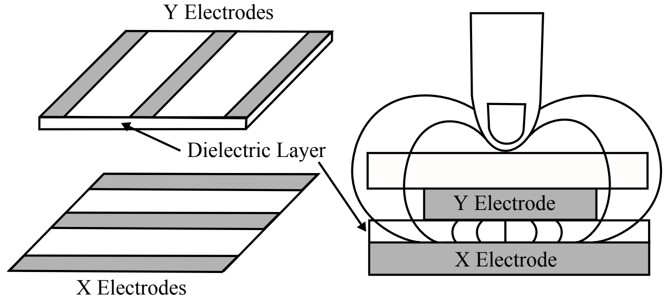


Figure 3: Projected mutual capacitive touchscreen. The approach of a conductive object such as a finger detracts from the charge stored between two fixed electrodes, resulting in a change in capacitance. For a matrix array of electrodes, each electrode intersection is capable of measuring a change in capacitance and hence a touch event.

The specific requirements for each sensor are strongly dependant on the intended application and how the input pressure is intended to be used. For example, in a keyboard the input pressure may be measured underneath each key and may define whether the output is an upper or lower case letter. Here, a distinction need only be made between a light touch and a hard press. For touchscreens overlaid on top of a display (either LCD or OLED), or for a trackpad of a laptop or similar, it may be advantageous to differentiate many different levels of pressure. Here, such detailed pressure information may be beneficial, for example for controlling brush stroke size in drawing software.

4. Applications of Pressure Sensors in HCI Touch Interfaces

4.1. Capacitive Touchscreens

4.1.1. Projected Capacitive Touchscreens

Projected capacitive (P-Cap) touchscreens work by measuring a change in capacitance associated with the increasing proximity of a finger to the touch interface. (Note that this is an entirely different principle to capacitive pressure sensors as described in Section 2.2 which detect pressure by the change in separation of two conductive electrodes). In self-capacitive systems, the capacitance of the human body acts to increase the self-capacitance of a single electrode. For mutual capacitive systems, the approaching finger detracts from the charge stored between a pair of electrodes and reduces the capacitance between the electrodes, as shown in Fig.3.

The transparent electrodes, usually Indium doped Tin Oxide (ITO), are printed in a matrix pattern such as rectilinear rows and columns or interlocking diamonds. Each electrode intersection is scanned individually, allowing every touch to be registered.

Capacitive touchscreens (specifically P-Cap) are currently the market leader for consumer electronics applications. With the release of the Apple iPhone in 2007, capacitive technology became mainstream and is now the standard for touchscreens in consumer electronics. Surface capacitive touchscreens are also available but are less common. Further information on all types of capacitive touchscreens can be found in the literature [15, 16, 17]. P-Cap touchscreens can only detect input from a human finger or conductive stylus and are highly sensitive to electronic noise. Performance is hindered by surface moisture or other screen contaminants. Because each electrode intersection is scanned using a high sampling rate the power consumption is high compared to resistive touch screens. However, they currently have higher spatial resolution than resistive touchscreens, require a very low activation force and are more durable due to their rigid design. These benefits have led to the dominance of P-Cap in touch interfaces for smartphones, tablets and trackpads.

Previous attempts to measure applied pressure in P-Cap touchscreens associated the size of the contact area with the force applied, as a harder press will result in a greater contact area between finger and screen due to the compliant nature of the human fingertip. A larger contact area means that more electrode intersections are triggered and by integration of the capacitance values recorded at each intersection the contact area can be calculated and the applied pressure can be estimated. This approach has been demonstrated in [34, 35]. A difference in contact area may also be used to differentiate between adult and child input and to adjust the device functionality accordingly [36]. However, one potential issue is that this approach requires additional calibration to compensate for variation in user finger sizes and has limited accuracy. For example, without user calibration the method cannot distinguish between a hard press from a small finger and a light touch from a large finger. It is difficult to detect anything beyond a moderately hard press, beyond which the touch area does not increase significantly.

4.1.2. In-Cell 'Pressed' Capacitive Touchscreens

In-cell touch refers to the internalisation of the touch sensors inside an LCD pixel array. As such, this technology is currently only found in the established LCD display industry and is not currently available for the newer OLED displays. Typically the sensor is integrated into the thin film transistor (TFT) array, the colour filter layer, or both. This should eliminate the need for further cover sheets or coatings on top of the LCD display. The benefit is that both the touch interface and the display are

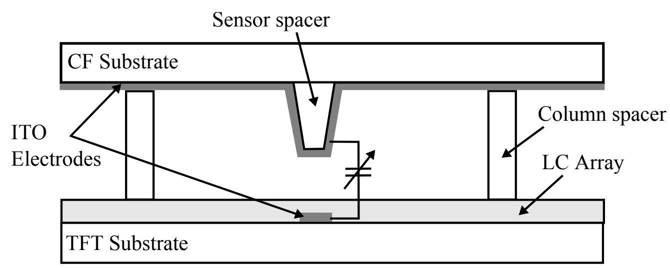


Figure 4: Pressed capacitive in-cell touch interface. The touch electrodes are incorporated into the LCD display and are deposited on the thin film transistor (TFT) substrate and the colour filter (CF) substrate. When the top surface of the LCD is pressed the colour filter substrate deforms, reducing the distance between the two electrodes and causing an increase in the mutual capacitance.

made as one manufacture process.

There are three main in-cell touch technologies; capacitive, voltage and light sensing, full details of which can be found elsewhere [37]. To the author's knowledge pressure–sensitivity has not yet been incorporated into in–cell voltage or light sensing technologies.

In-cell capacitive sensing has had the most success in terms of total research and commercial products, and can be further categorised as pressed, self, or mutual capacitive depending on the operating principles. The principles for the self and mutual capacitive are the same as for the P-Cap technology described earlier. However in the case of in-cell technology the touch electrodes are incorporated into the display module instead of being manufactured entirely separately from the display, allowing for thinner, lighter devices. Mutual in-cell P-Cap touchscreens, developed by LG Display for Apple, Inc. can be found in the iPhone 5 and iPhone 6 models. However, just like for P-Cap technology, internalising the detection of applied pressure is not currently possible.

'Pressed' capacitive in-cell touch sensing elements consist of two electrodes: a sensor spacer is incorporated onto the colour filter glass, and a flat electrode is deposited onto the TFT layer, underneath the liquid crystal array of the LCD. Often there is a further column spacer to prevent full contact between the two electrodes, as demonstrated in Fig.4. This uses the sensing principle described in Section 2.2. When a force is applied to the upper surface of the LCD, the colour filter glass deforms, causing the spacing between the electrodes to decrease and/or the dielectric constant of the liquid crystal material to change. Then, by Equation 2, a change

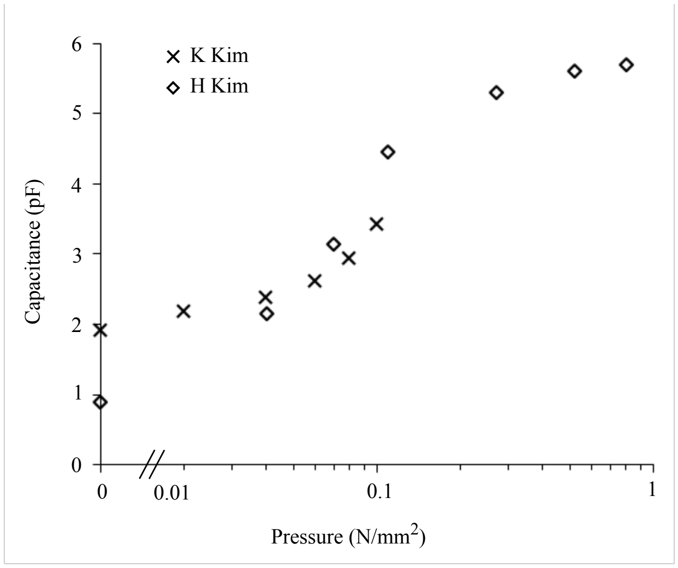


Figure 5: Capacitance output as a function of applied pressure, using data taken from [38, 40].

in the mutual capacitance between the two electrodes may be measured. In this way both touch location and touch force can be measured. Note that although the mutual capacitance is measured, this is very different to the mutual P-Cap technology described earlier. The electrode configuration is different, and in this case the mutual capacitance is changed by a physical force rather than the approach of a conductive object which 'steals' charge from the electrodes, as is the case for P-Cap. The touch resolution depends on the number of display pixels per touch sensor (and therefore the total number of touch sensors present in the entire display). This is typically in the range of 4:1 (high touch resolution) to 16:1 (lower touch resolution).

Because of the relation between the deformation (electrode separation) and the capacitance, this technology seems a promising candidate for the detection of pressure. Research has been conducted which investigates the change in capacitance with applied force. H. Kim *et al* designed and fabricated a 20x20 array of pressed capacitive touch sensors [38, 39]. Indium Zinc Oxide (IZO) electrodes were deposited onto flexible polycarbonate films. On the lower electrode an insulating layer of the polymer SU-8 was deposited at a thickness of 5 μm. The two electrodes were separated using spacer columns of SU-8, creating a void space 8 μm in height between the two electrodes. The insulator and spacer layer was formed from the polymer SU-8. The total thickness of the sensor array was 253 μm and an average optical transmittance of 86 % in the visible light range (380–770 nm) was measured. A force gauge with a contact area of 1 mm × 1 mm was used to apply force up to 0.8 N. The data, taken from [38], is replicated in Fig.5 which shows the measured capacitance as a function of the applied pressure on the touchscreen. It can be seen that the capacitance increases linearly from an initial value of 0.9 pF at zero pressure to around 4.5 pF at an applied pressure of 0.1 Nmm^{-2}. After this the capacitance value saturates. Numerical simulation confirmed that a force of 70 mN applied over 1 mm^2 was required to deflect the top electrode by 8 μm. At this maximum deflection the electrodes are in contact and there will be no further increase in the capacitance. Whilst this result demonstrates the principle of pressure sensing via pressed capacitive touch sensors, this particular sensor is only capable of differentiating applied force up to around 0.1 N and cannot differentiate anything beyond a light touch (0.1 N). Therefore, the pressure sensing capabilities are very limited.

K. Kim *et al* designed a similar sensor array using single wall carbon nanotube (SWCNT) electrodes separated by a compressive silicone gel [40]. The cross-array of electrodes were formed by scribing and patterning of SWCNT coated PET substrates. The electrode separation (silicone thickness) was approximately 500 μm. The optical transmittance was 81 % measured at a wavelength of 550 nm. The touchscreen was tested at forces from 0 to 5 N using a probe with diameter of 8 mm. The pressure-capacitance response, using data replicated from [40], is shown in Fig.5. It can be seen that the capacitance increases from and initial value of 1.92 pF at zero applied pressure to 3.42 pF at a pressure of 3.5 Nmm^{-2}. It is clear that the magnitude of the electrode separation plays an important role in determining the range of forces the touchscreen is sensitive to. When contact area is taken into account (as the same force, applied over a larger area will result in a smaller vertical displacement than for a force applied over a smaller area) a greater saturation force may be achieved using a greater electrode separation. However in practice a large electrode separation is disadvantageous, as it adds significantly to the overall thickness of the touchscreen. For devices such as smartphones and tablets, slimness is often prioritised.

One potential problem with the pressed-capacitive approach is that the electrode spacing, and therefore capacitance change, tends to be very small and the signal to noise ratio (SNR) is low. This is especially true for low applied forces. Noise is introduced by capacitive coupling between the force sensing and the display circuitry and is also inherent within the LCD. Often, more complicated circuitry is required to boost the signal and reduce the noise in the system. A research group affiliated to Sharp Laboratories have developed one method of overcoming the problem of poor SNR [41]. A high sensitivity active pixel sensor (APS) circuit is used along with in-pixel signal amplification. The circuitry of the force sensors and LCD are kept separate by using a series of bumps on the upper deformable electrode. The conductive coating on these bumps is electrically separate from the pixel electrodes. On the bottom electrode, a guard ring is etched around the sensor capacitor structure to electrically isolate the liquid crystal material in the force sensing region from the display pixel region. This reduces the electrical noise and allows in-pixel amplification of the sensor signal. Whilst there is no information regarding the thickness of the sensor build, the output voltage (calculated from the change in capacitance) is found to increase for applied forces between 0 and 2.5 N. The sensitivity of the response can be further modified by variations in the APS circuitry. C. Kim *et al* have also designed a similar device using active matrix circuitry [42]. In this case, the electrode gap is just 0.5 μm. However, only forces up to 0.2 N have been investigated using a 0.8 mm test probe diameter. The complex circuitry can often lead to a high power demand in these devices. Huang *et al* have counteracted this by using an algorithm which rectifies the non-linear relationship between applied force and output capacitance [43]. The touchscreen prototype by Chen *et al* can measure both normal and shear forces using an offset electrode pattern [44].

Despite the advances in read-out circuitry and enhanced SNR, a fundamental problem of pressed in-cell capacitive sensors for touchscreen technologies is the poor durability. Because the device is reliant on deformation of the color filter glass layer, there can be no protective cover glass on the top surface of the device. A cover glass layer is vital in high-end applications such as smartphones and tablets, to protect the LCD display from damage. Cover glass is just not compatible with pressed in-cell technology, as a greater activation force would be required to produce any response, making the device insensitive to light touches. Because of the greater stiffness of a thick cover glass layer, the area of deflection becomes larger for a given force resulting in greater error in the measured touch location. Furthermore, applying pressure to an LCD display can cause image artefacts which can last even after the finger is removed from the screen.

Several key technology companies, including Synaptics and Apple Inc., have patent applications which describe the incorporation of a pressed capacitive layer into a touchscreen [45, 46, 47]. In this format there are usually three sets of electrodes, where the lower two define a p-cap location sensor and the third is printed onto a deformable substrate which lies at the top of the electrode stack. The capacitance change between these electrodes and the uppermost in the p-cap sensor array can be used to quantify the applied force. However, to the author's knowledge this type of touchscreen can at present only be found in the Samsung ST550 and TL220 cameras. Here, the user is advised not to use sharp objects on the screen, and is further warned about the potential of discolouration of the LCD screen if the screen

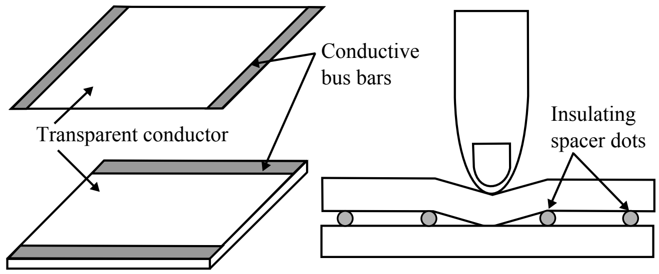


Figure 6: Four-wire resistive touchscreen. Two transparent electrodes are separated by an array of spacer dots. Touch by any object causes the upper electrode to deform and contact the lower electrode. The resistance of the electrode material acts as a voltage divider, where the ratio of the measured voltages give the location of the touch. In this format, only a single touch can be detected at any one time.

is pressed too hard [48]. The pressure sensitivity of this kind of touchscreen is not utilised at all in the camera.

4.2. Resistive Touchscreens

Resistive touch sensing was first commercialised by Elographics, Inc. in 1971, with a transparent touchscreen produced in 1977. A four-wire resistive touchscreen is shown in Fig.6. Two substrates, one of which must be sufficiently flexible, are coated with a transparent conductor such as ITO to form the electrodes. These are separated by an air gap created by small spacer dots (for example insulating glass beads) which prevent initial contact. When the user presses onto the flexible substrate, the two electrodes make electrical contact and a voltage is measured. The resistance of the ITO acts as a voltage divider, so that the ratio of voltages measured can be used to determine the position of the touch. In the four-wire format only a single touch may be detected at any one time. However, in 2005 JazzMutant (renamed Stantum in 2007) developed multi-touch resistive touchscreens using their patented Interpolated Voltage Sensing Matrix (iVSM) [49]. Here, the top and bottom electrodes are deposited in rows and columns, with each intersection forming a square with sides of 1.5 mm. Each square acts as a digital switch, with a current flowing when top and bottom electrodes make contact.

The input for a resistive touchscreen can be applied by a finger or any other (non-sharp) object, whether conductive or insulating. They have a lower power consumption than capacitive–style touchscreens as current only flows in the active on-state, and they are also cheaper per unit area. However, the main disadvantages are that only a single touch can be detected (in the 4-wire configuration) and the durability is poor, as ITO printed onto a flexible substrate is known to crack and flake when flexed [50]. A high activation force is also required that depends on the mechanical flexibility of the upper electrode and the depth of the air gap. Current applications for resistive touchscreens are usually in the commercial and industrial markets, for example retail point-of-sales and point-of-information kiosks, automotive and industrial touch controls.

For transparent touchscreens, it is possible to print a pressure–sensitive layer directly onto one of the transparent electrodes, for example using a screen-printing process. With a deformable upper electrode an applied pressure will act to modify the resistance of this layer. For a matrix array of electrodes, the resistance at each intersection is modified by the pressure–sensitive layer. The intersection with the lowest resistance corresponds to the touch location, and the resistance value indicates the level of applied pressure. For such a layer, several technical requirements must be met. For use in a touchscreen overlaying a display, there must be appropriate light transmission through the layer. The response must be uniform across the layer and be repeatable for a large number of presses. The resistance of the layer must show adequate variation over a range of forces from a light touch (0.1 N to a hard press (10 N), in order to create a number of pressure levels that can be differentiated by the read-out electronics. The layer should also be responsive at very light touches in order to minimize the activation force. Here we review several pressure sensitive layers that can be incorporated into a resistive touchscreen. They all comprise a transparent conductive polymer composite as described in section 2.1.2 deposited between two (transparent) electrodes, but the structure of the composite material is different in each case.

Motorola Solutions, Inc. ('Motorola') have developed a transparent pressure sensitive conducting polymer composite for use in touchscreen applications which is currently patent pending [51]. Conductive nanoparticles less than 100 nm in size, e.g. In-doped SnO_2 (ITO), SnO_2 or ZnO, are dispersed in a translucent insulating polymer such as a phenoxy resin, polyether, acrylic or silicone. The composite can be deposited onto a transparent electrode by spin coating, dip coating or screen printing and is then cured to produce a layer 1-10 μm thick. A prototype multi-touch enabled touchscreen using this pressure sensitive layer has been demonstrated [52]. The particle loading is 20-30 % by volume, and the layer is printed at a thickness of 1 μm and sandwiched between perpendicular arrays of transparent conductive electrodes. Optical transmission through the pressure sensing layer is at least 94 % of transmission through glass. A contact pressure cannot be established as no information is given on the area of the force-testing probe.

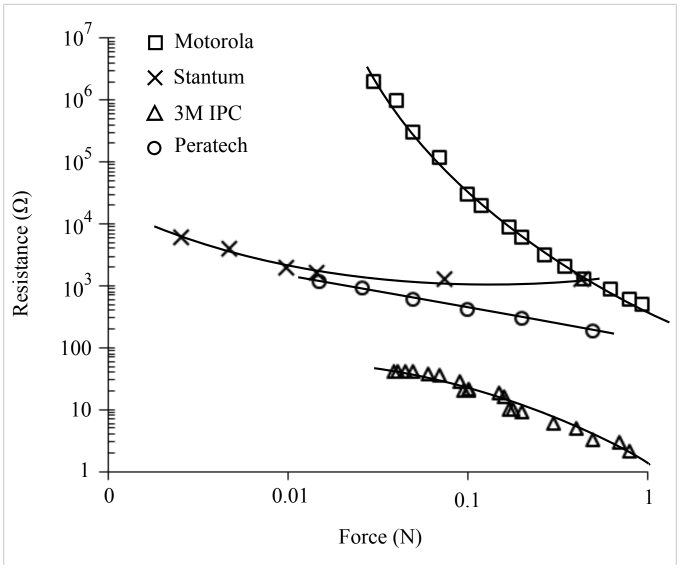


Figure 7: A comparison of the force-resistance response for various touchscreen technologies, reproduced from data provided by Motorola Solutions, Inc. [52], Stantum [56], 3M Innovative Property Company [57] and Peratech Holdco Ltd [62]. The resistance through the touchscreen is measured as a function of applied mass. Lines are drawn for each data set as a guide to the eye.

Instead, a typical force-resistance response is shown in Fig.7, reproduced from data provided in [52]. It can be seen that the resistance decreases exponentially with applied force, dropping from 20 MΩ at zero load to less than 5 kΩ for a 1 kg load. However, a significant activation force of 0.04 N (40 g) is required before resistance begins to decrease and so very light touches cannot be detected. Motorola have a number of other patent applications, including the incorporation of the pressure sensitive layer into a device and using the layer to validate touch inputs and eliminate false touch readings [53, 35].

It is possible to further control the conduction pathways by the alignment of magnetic filler particles using an external magnetic field. This effect has been studied previously for polymer composites containing nickel particles and carbon nanotubes [54, 55]. By applying an external magnetic field, the particles are aligned into columns which can span one dimension of the composite. In a pressure sensitive layer, the particles may be arranged into columns spanning the top and bottom electrodes, as shown in Fig.8. A lower particle loading is required to produce the necessary conduction pathways between the electrodes. Stantum have developed such

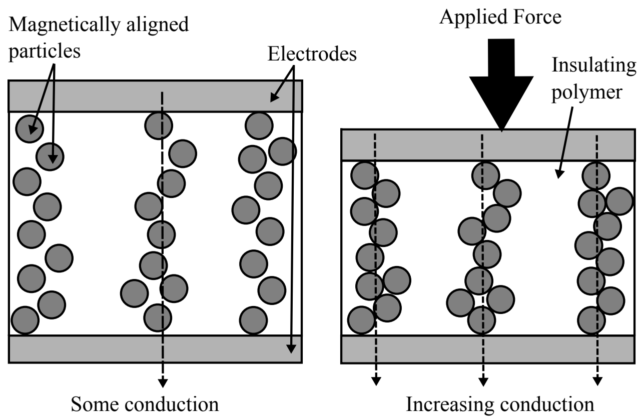


Figure 8: Conducting magnetic particles are dispersed in an insulating polymer and aligned into columns by applying an external magnetic field. The columns act as conductive pathways between top and bottom electrodes. By compressing the layer, the distance between neighbouring particles decreases, and charge transfer through direct percolation or quantum tunnelling increases, reducing the resistance through the sensor. This principle is used in a force sensing layer developed by Stantum [56].

a layer using this principle, which is currently patent pending [56]. Nickel particles are dispersed in an insulating polymer, for example silicone or polyurethane, at a loading of 0.3-10 % by volume. The nickel particles have a diameter of 2-5 μm and have a spiky surface topography, where the surface protrusions can be greater than 1 μm in length. The composite is deposited as a film 50-100 μm thick, and an external magnetic field of strength 3-10 mT is used to align the magnetic particles into columns spanning the thickness of the printed film. By adjusting the magnetic field strength the cross-sectional diameter of the columns can be altered, but is usually in the range of 20-25 μm. By applying a pulsed or sinusoidal magnetic field the cross section can be reduced to 10 μm. The strength of the magnetic field also controls the distribution of columns across the film.

When the layer is deformed the separation between the particles in each column decreases and more conduction pathways are formed, as shown in Fig.8. The resistance of each pathway may also decrease. It is known that a close proximity between nickel particles as described above can result in field-assisted quantum tunnelling [23, 24]. A force-resistance response for loads up to 500 g is shown in Fig.7, reproduced from data given in [56]. Again, no details on the contact area of the probe are given so contact pressures cannot be calculated. At zero applied force, the resistance is of the order 100 kΩ. A load of 100 g decreases the resistance to 10 kΩ, beyond which the resistance decreases marginally for loads up to 500 g. This insensitivity to larger applied forces may limit its applicability. Because fewer particles are required to produce the well-defined conductive pathways, greater optical clarity of the layer can be achieved. However, in practice the large film thickness of 50-100 μm will have a detrimental effect on the optical transmission. Details on this have not yet been reported.

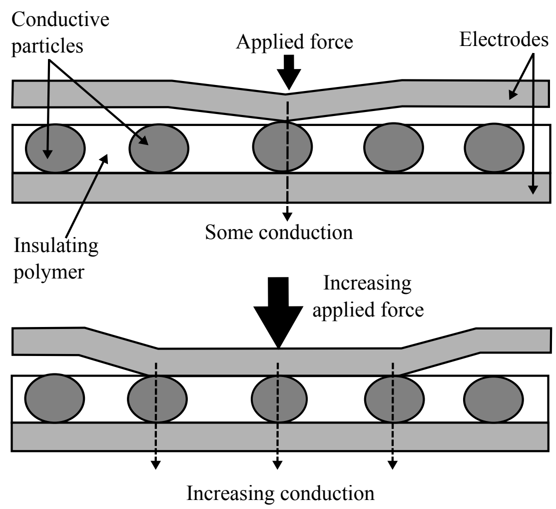


Figure 9: Conducting particles are dispersed in an insulating polymer film such that the particle size is of a similar dimension to the thickness of the printed film. With increasing deformation of the upper electrode an increasing number of particles are contacted. This principle is used in transparent force sensor developed by 3M Innovative Property Company [57, 58] and Peratech Holdco Ltd [62], although in the latter the particles themselves also show a decrease in resistance with increasing applied pressure.

In contrast to the methods described above, it is also possible to create a pressure sensing layer by dispersing a very low number of particles in the insulating polymer, provided that the particles are of a size comparable to the thickness of the printed layer. Rather than the conduction occurring through a convoluted pathway of small particles, of which there must be a high enough concentration so as to reach the percolation threshold, instead a low concentration of larger particles provides a series of conduction paths where the particles directly connect the top and bottom electrodes, as shown in Fig.9. This approach has been demonstrated by 3M Innovative Property Company (3M IPC), who have patented such a layer for use in force sensitive membranes and touchscreens [57, 58]. The layer, which can be deposited using blade coating (and likely screen-printing for large scale manufacture) is typically 1-10 μm thick and comprises conductive particles, for example ITO or silver-coated glass beads, dispersed in an elastomeric polymer. The particle size is of a similar dimension to the printed layer, such that the top surface of the particle may protrude above the film surface. Spacer dots may be dispersed onto the film surface to prevent initial contact between the film and upper electrode. Upon application of force to the touchscreen, the top electrode deforms and is brought into contact with one or more conducting particles, allowing current to flow. With increasing deformation, the top electrode contacts an increasing number of particles, thus decreasing the resistance between the electrodes. This is purely a surface effect as the resistance depends on the contact area of the touch and the layer is not intrinsically piezoresistive. It has been reported that the resistance R decreases with increasing applied force F according to

$$R = \frac{A}{F^n}, \tag{3}$$

where A and n are constants. The value of n indicates the sensitivity of the sensor where a larger value produces a greater decrease in resistance for a given increase in applied force. For a silicone rubber film of thickness 25 μm containing ITO-coated glass fibres the n value was reported to be 1.02 and the force-resistance response for this particular sensor is shown in Fig.7 which is reproduced from data provided in [57]. No details of the contact area of the force-testing probe are provided. It can be seen that the resistance decreases from 10 kΩ under a load of 40 g to around 20 Ω at 800 g. There is no data provided for loads higher and lower than this so first touch sensitivity cannot be assessed. The optical transmission through a 60 μm film containing silver coated glass beads with diameter 43 μm dispersed at a concentration of 140 particles per mm^2 was reported to be 91 % over the visible wavelengths 400-700 nm.

One potential issue in this type of pressure sensitive layer is the susceptibility of the upper electrode to damage from prolonged and repeated contact with protruding particles. Many transparent conducting electrodes suffer from poor durability under flexing. This is widely reported for ITO on flexible substrates and is one of the driving forces for developing a replacement for ITO [50]. Abrasion with hard particulates will further decrease the durability and lifetime of the sensor. One solution would be to use other transparent conducting electrodes such as graphene, metal nanowires, or carbon nanotube dispersions, all of which show enhanced durability over ITO [59, 60, 61]. Alternatively, as described in the patent [57], it is possible to fill the air gap between particles and top electrode with an insulating filler material which acts as a buffer material between electrode and particle.

A similar pressure sensitive composite layer has been developed by Peratech Ltd, since renamed Peratech Holdco Ltd ('Peratech) [62]. However in this case the particulates are agglomerates of many smaller conductive particles, e.g. spherical or acicular antimony-doped tin dioxide (ATO) particles with diameter 200 nm (and a length of 0.2-2 μm for the acicular particles). These are dispersed in an insulating polymer such as acrylic and/or polyvinyl resin, at a loading of 0.1-0.5 % by mass. The agglomerates have typical dimensions of 5-15 μm and are either formed as the constituent particles are mixed into the insulating polymer, or they can be pre-formed before adding to the polymer. A further patent details one possible composition of such pre-formed granules [63].

With increasing applied pressure, more agglomerates are brought into contact with the top electrode thus reducing the resistance through the layer, similar to the 3M IPC composite layer. However, the patent also infers that the agglomerates themselves are inherently pressure sensitive, such that a compressed agglomerate will exhibit a lower electrical resistance than when at rest. By compressing the agglomerates, the inter-particle voids are reduced and more of the constituent particles are brought into contact. Quantum tunnelling of electrons may occur from one particle to the next if the potential barrier caused by the insulating polymer binder is sufficiently narrow. The sensitivity is thus governed by surface and bulk effects, due to an increasing number of agglomerates contacting the upper electrode with increasing applied pressure, and the resistance of individual agglomerates decreasing due to compression.

The force resistance response of a layer comprising 0.2 % ATO agglomerates dispersed in an insulating varnish was determined using a probe tip of 8 mm diameter to apply a force of 0.15–5 N. The response of the touchscreen is shown in Fig.7, reproduced from data provided in [62]. The resistance changes from 15 kΩ to 2 kΩ when the load is increased up to 500 g. The optical transmission through this layer is 98 % when compared to transmission through the ITO/glass electrode.

This layer, marketed as QTC™ Clear, is used in FineTouch Z - a pressure sensitive transparent touch panel produced by a partnership between Stantum and Nissha Printing Co. Ltd [64]. FineTouch Z uses Stantum's iVSM technology and is capable of detecting 256 levels of pressure [65], with possible applications including palm rejection (when operating the touchscreen with a passive stylus), dynamic capture of handwriting, and fine control when using the device for drawing applications.

Fig.7 compares the variation in resistance response with applied force for each pressure–sensitive resistive touchscreen discussed. Direct comparison between each touchscreen is difficult as exact details regarding the build, for example the depth of the air-gap and the mechanical flexibility of the upper substrate, are not divulged. Also, the contact area of the probe used for the force-resistance measurements in each case is not always given, so the applied pressure cannot be calculated. However, some conclusions may still be drawn. The greatest range in resistance is seen for the touchscreen developed by Motorola, where the resistance drops over four orders of magnitude for loads between 40 g to 1 kg. However, a minimum load of 40 g is required to produce an initial response. Because of the nature of the pressure sensing layer, a large force may initially be required to provide the necessary deformation to the polymer in order to increase the number of conduction pathways. For the Stantum touchscreen, a decrease in resistance is observed above 3 g, but above 100 g there is no further significant decrease in resistance. Because there is initially a close proximity between neighbouring nickel particles in the column, a small activation force may be required to create the initial contact between the upper electrode and nearest particle, after which current can flow down the column without requiring further deformation of the layer. The touchscreens demonstrated by Peratech and 3M show a decrease in resistance over the full range of applied loads without the ultra-sensitive response of the Motorola touchscreen or the lack of sensitivity at high loads shown by Stantum. The resistance values for the 3M touchscreen are consistently lower than those demonstrated by Peratech, and the resistance drops below 100 Ω for loads greater than 200 g. High current flow leading to high power usage may be detrimental in some applications. In order to use the resistive layer as a voltage divider in a touchscreen assembly as described earlier, the resistance should not fall below that of the connectors and read-out circuitry. In this case, the Peratech pressure sensing layer is advantageous. For both the 3M IPC and Peratech results there is no resistance value reported for zero applied load. However, this can be adjusted by control over the air-gap and mechanical flexibility of the upper electrode.

4.3. Other Touchscreen Technologies

4.3.1. Surface and Bending Wave

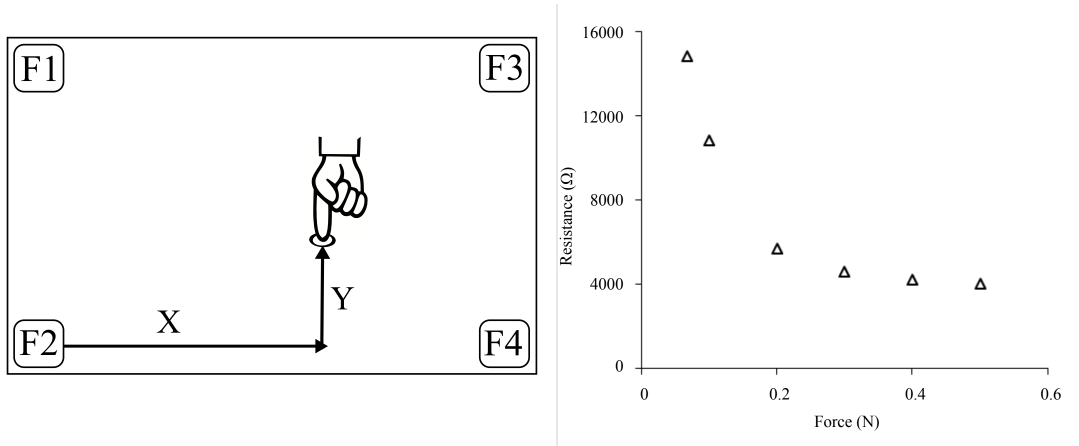
When an object impacts onto a rigid material, such as a finger contacting a touchscreen, both surface and bending waves propagate through the material. Whilst surface acoustic waves propagate on the substrate surface only, bending waves travel though the full thickness of the substrate, radiating outwards from the location of the touch. During a touch event, a number of surface and bending waves of different frequencies are produced which propagate through the touch interface at different speeds. Bending waves may also undergo reflections at the interface between internal surfaces of the substrate. Sensors at the edge of the substrate receive this complex signal, which is then used to determine the location of the touch.

Both Acoustic Pulse Recognition (APR) patented by Elo Touchsystems [66] and Dispersive Signal Technology patented by 3M [67] use bending waves in order to extract the touch signal. Both of these technologies use four piezoelectric transducers located asymmetrically on the substrate perimeter which convert the measured pressure from the acoustic wave to a voltage. However, the signal processing algorithms can currently only differentiate between touch input from various points on the touchscreen surface and cannot differentiate between different touch forces and so currently this technology is not pressure–sensitive.

Conversely, in Surface Acoustic Wave (SAW) touchscreens, the piezoelectric transducers send bursts of ultrasonic Raleigh waves across the touch surface in response to a supplied voltage. Reflectors at the edges of the touchscreen reflect the acoustic wave back across the screen and into the relieving piezoelectric sensors, which convert the pressure input back to a voltage. The transit time of the wave depends on its path length so that each physical location can be mapped into the time domain. When a human finger, or indeed any other sound–absorbing object touches the screen some of the Raleigh waves are absorbed. By measuring where the reduction in the wave amplitude occurs the touch location can be determined. The amount of reduction in the signal amplitude can in principle be used to determine the touch pressure. The IntelliTouch touchscreen produced by Elo Touch Solutions uses this principle and it is stated that pressure–sensing is possible. However no information is given about the levels of pressure that can be detected, beyond that a minimum of 85 g activation force is required [68]. To the authors knowledge, there are no devices currently available on the market that utilise the pressure–sensing capabilities of SAW touchscreens.

4.3.2. Optical Sensing Touchscreens

An infrared (IR) touchscreen typically consists of two IR LEDs along two adjacent sides of the touch surface and two receiving IR photodetectors on the other sides (i.e. a transmitter and receiver for both X and Y coordinates). The transmitters are pulsed sequentially, so that when the surface is touched, the IR beam is broken and the touch location can be calculated. Pressure information cannot be calculated as the touch force does not impact in any way on the IR photodetector. In camera-based optical touchscreens, IR LEDs provide a peripheral backlight across the touch surface with cameras placed in two or more corners of the screen which can detect the presence or absence of light. When a finger touches the screen the peripheral light is blocked and the cameras observe a shadow. Again, pressure information cannot



(a) (b)

Figure 10: (a) Four discrete force sensors placed underneath a touch interface or display may be used to determine both the location and force of a single touch. (b) Data for the resistance response of a touch display demonstrated by F-Origin, where resistance decreases with increasing applied force.

be recorded by this technology. To the authors knowledge, there are no pressure–sensing touchscreens available which utilise the optical pressure–sensing mechanism described in Section 2.

4.4. Pressure Sensors External to the Touchscreen

The previous sections described the incorporation of pressure sensors directly into the touchscreen assembly where the pressure sensing components are intrinsically part of the touchscreen assembly. There is an alternative method of adding pressure sensitivity, where pressure is assessed outside of the touch module. The pressure sensors may be found underneath the display, or even overlaid on top of the touchscreen in a transparent array. Pressure sensitive styli may also be used which send pressure information directly to the device controller or to specialised applications which can utilise these pressure levels.

4.4.1. Force Sensors underneath the Touch Interface

It is possible to incorporate discrete force or pressure sensors underneath the display unit. In fact, some touchscreens utilise this concept to measure both the location and the force of the touch, rather than detecting touch indirectly through a change in resistance or capacitance between two electrodes. These touchscreens comprise four discrete force sensors underneath the four corners of the interface as shown in Fig.10(a). The sensors used may be any of those described in section 2 such as strain gauges, piezoelectric transducers, capacitance sensors, inductance sensors or even force sensitive resistors, where each has its own benefits and drawbacks [69]. These are summarised in Table 1. In the touchscreen industry, this type of touch interface is usually referred to as 'force-based' to distinguish it from other technologies such as resistive or capacitive.

Analysis of the force or pressure recorded at each corner allows determination of the touch location. Whilst only three forces are necessary to triangulate the touch location, when pressed the touch surface will always undergo a small degree of deflection (as no surface may be classed as truly rigid) and the addition of a fourth sensor allows the effect of the deflection on the sensors to be accounted for. In addition, four sensors can easily be integrated into the common rectangular design of most touch panels.

Simplistically, the touch coordinates X and Y can be calculated by moment equations:

$$X = \frac{F3 + F4}{F1 + F2 + F3 + F4}, \quad Y = \frac{F1 + F2}{F1 + F2 + F3 + F4} \tag{4}$$

The touch force Z is simply equal and opposite in magnitude to the sum of the forces measured at each sensor.

$$Z = -(F1 + F2 + F3 + F4) \tag{5}$$

This concept first showed commercial success in 1991 when IBM developed their TouchSelect overlays for CRT (cathode ray tube) monitors, where the CRT screen was mounted on strain gauge force sensors [70, 71]. However, the product only lasted 3 years on the market and overall was unsuccessful. For force to be measured accurately, the movement of the screen or cover glass must be constrained to the downward (z) direction only, eliminating any lateral or off-axis forces. Because a touch event is not static and constant, the algorithm must account for any dynamic force profile measured at the force sensors. If these effects are not taken into consideration, the accuracy of the device in determining touch location is severely limited.

Several attempts have been made to overcome these issues. QSI Corporation developed their force sensing touch technology InfiniTouch™ using a beam mounting method, whereby the beams absorb most of the lateral forces. An accuracy of 1% across the X and Y dimensions is reported [72]. Furthermore, if the touch surface is constructed from a rigid material, and under normal operation is subject to stresses well below the limits of the material, then the effect of pre-stressing and over-constraint of the beams is negligible. The company F-Origin, Inc. have patented a different design which removes the issue of lateral forces. Their force sensing touch panel zTouch™ uses a suspension spring arm method, where the screen is supported by a looped filament or string, thus removing frictional forces [73, 74]. Furthermore, computing power has increased significantly since the 1990s, and digital signal processing integrated chips can be readily and cheaply obtained which are more than capable of processing the dynamic force waveforms from each of the four sensors. An example force–resistance response demonstrated by F-Origin zTouch™ is shown in Fig.10(b).

The major drawback with this technology is that usually these devices are only capable of detecting a single touch event. If the screen is touched in more than one location, the centroid of the applied forces will be calculated. In order for the device to become multi-touch, multiple force-sensing areas are required. For a grid of $n \times n$ force sensing areas, assuming there is a sensor at each corner of the discrete force sensing areas, a total of $(n+1)^2$ sensors are required. For a high resolution force response where a large n is required, the number of sensors necessary becomes very large and the complexity of the system escalates. The exception to this is Force-Touch™ developed by NextInput, Inc. who use an array of micro-electromechanical (MEM) force sensors underneath the touch interface to detect touch location and touch force to sub-millimeter and sub-millinewton resolution [75]. Furthermore, the addition of force sensors may add to the overall device thickness and weight.

The majority of applications for this technology make use of its other benefits rather than the addition of force sensitivity. These include the detection of touch from any object, conductive or insulating and the rugged and durable nature of the technology which is resistant to surface contamination. The touchscreen is usually cheap to manufacture as the cost is not dependent on the area of the touchscreen – large displays are feasible. Finally, the touch interface itself may be patterned, for example with drilled holes, textured areas or embossed Braille characters. These benefits make force based touchscreens ideal for outdoor applications, or other applications that need to withstand rough handling, input from gloved hands, contaminants such as dust and liquids, and extreme temperatures. Example applications include ATMs, information kiosks and industrial control panels. Of course, in any of these applications the force sensitivity may be used as an additional controllable input. However, due to the issues highlighted above, it is unlikely that this technology in its current state would ever replace the industry standard projected–capacitive touchscreens which are at present found in most smartphones and tablets.

In order to achieve pressure sensitivity along with the multi-touch capability of a capacitive touchscreen, a hybrid approach may be used. The touch location is calculated using a P-Cap touchscreen or similar (which has multi-touch capabilities), and the force of the touch is determined using the discrete force sensors. These so-called hybrid touchscreens provide a beneficial solution for applications such as smartphones and tablets where multi-touch is now a standard and necessary feature.

The hybrid approach can already be found in projected–capacitive laptop trackpads, as described in Section 4.5.3. Furthermore, Apple, Inc. also hold a patent detailing the inclusion of force sensors into trackpads and touchscreens [76, 77]. A recent press release states that the newly developed Apple Watch will have a pressure sensitive transparent touch interface which is capable of differentiating between a light tap and a hard press, where the hard press is used to shortcut to a specific demand [78]. The force sensors used can be strain gauges, capacitive membranes, silicone diaphragm or any other suitable force sensor. In [77], the FSR is described as one possible force sensor.

4.4.2. Pressure Sensitive Stylus

A stylus may be described as passive or active. A passive stylus comprises any conductive object, for example a metal rod, conductive plastic or conductive rubber–tipped pen, which can be used to replace finger–touch on a touchscreen. Passive styli are low cost, easily replaced and can be made to any size required. However, they provide no more resolution or functionality than the human finger. Active styli are typically enhanced with additional functionalities such as pressure and tilt measurement and require a power source in order to operate, which can either be drawn from the device or provided by an internal battery supply.

Electromagnetic resonance (EMR) styli draw their power from the device they are coupled with. The device has an additional sensing or 'digitiser' layer underneath the display in addition to the capacitive touchscreen overlaid on top of the display. The magnetic field generated by this layer induces a current in the stylus when it is within range of the device. The stylus uses this current to relay information on the use of the stylus (e.g. location, tilt, pressure) back to the touchscreen controller. An example of this type of stylus is the Samsung S-Pen (manufactured by Wacom Co. Ltd.) for the Galaxy Note 4 which can differentiate 2048 levels of pressure. The device allows for both capacitive input through finger–touch and stylus input through the digitiser layer. Whilst the stylus allows high–resolution pressure input, the addition of the digitiser layer adds to the thickness and weight of the device. An increased distance between the surface and the digitiser layer can lead to parallax issues, where the line is not drawn directly under the pen, as seen by the user.

Without a digitiser layer, the stylus requires an internal battery. N-Trig developed the DuoSense active stylus, which uses the same controllers as the capacitive touchscreen, i.e. it does not require an additional digitiser layer and instead uses an internal battery. The DuoSense can detect 256 levels of pressure. The Wacom Bamboo fineline is advertised for use with the Apple iPad and gives 1048 pressure levels. However, both of these styli are only supported by specific applications.

The pressure sensitivity is realised by the incorporation of a pressure sensor within the stylus, usually connected to the stylus nib such that retraction of the nib triggers the pressure sensor. Wacom. Co. Ltd. hold a patent detailing the use of an inductive style pressure sensor within a stylus, whereby the sensor is not constrained to detect axial forces only. This means that the stylus shows high pressure sensitivity at low pressures, even when the stylus is held in a non–vertical writing position. Wacom also hold a patent which utilises a conductive polymer composite as a pressure sensor, where the composite consists of spherical carbon particles of diameter 1–20 μm and hollow elastic microspheres of diameter 10–150 μm dispersed in an insulating silicone–based polymer. They state that this particular conducting polymer composite shows high repeatability with a low amount of hysteresis [79].

The pressure sensor used may also be optical, whereby movement of the stylus nib causes partial coverage of an LED light source or similar. The attenuation of the light signal is picked up by a photodetector and can be measured as a function of applied force on the nib [80, 81]. Otherwise, the pressure sensor may be capacitance based, whereby depression of the stylus nib causes one conductive plate to move relative to another such that the areas in direct opposition to one another are altered, thus changing the capacitance measured between the plates [82, 83]. BlackBerry Ltd. describe a pressure–sensitive stylus where pressure is detected through a change in air pressure inside an internal cavity within the stylus, when compared to external air pressure [84].

The advantage of these styli include their high pressure sensitivity, as these devices can typically differentiate between 256 and 2048 levels of pressure. Because only a single sensor is required, and the housing is large (the size of a typical pen) there is less constraint on the physical dimensions of the sensor.

However, the major disadvantage is that the stylus use and performance depends not only on the pressure–sensing capabilities of the pen, but also the display, chip, controller and driver support. For example, currently Apple products have no in–built pressure sensing capabilities in the touch screen. A pressure–sensing stylus would only work on specifically designed applications which can utilise this pressure sensitivity – and they may not utilise all pressure levels inherent in the pen. New devices such as the Samsung Galaxy Note series have an in–built digitiser layer which supports stylus input, and a range of applications in which the pressure–sensing

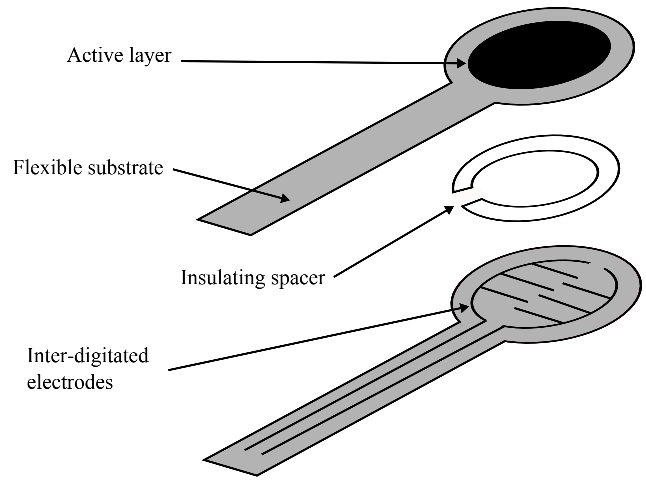


Figure 11: Force sensitive resistor. The active layer, consisting of small particles dispersed in a polymer binder, is screen-printed directly onto a flexible substrate and separated from inter-digitated electrodes by a spacer. Upon application of pressure, the active layer is pushed into contact with the electrodes.

capabilities can be utilised. However, the stylus provided will works solely for this device, and is expensive to replace if lost.

4.5. Keyboards and Trackpads

4.5.1. Force Sensitive Resistors

The force sensitive resistor (FSR) was first patented in 1977 by Franklin Eventoff [85]. An active resistive layer is screen printed onto a flexible substrate, and separated from a set of inter-digitated electrodes by a spacer layer such as a ring of insulating material which maintains air flow into and out of the cavity, as shown in Fig.11. In another format, the active layer is printed directly onto one electrode and separated from the second by the spacer. When the top layer is pressed the electrode(s) deforms into the spacer layer and comes into contact with the active layer. With increasing force a larger area of the active layer is in contact with the electrodes, decreasing the electrical resistance through the sensor.

The active layer in its most basic form is a screen-printable conductive polymer composite as described in Section 2.1.2, where the conductive particles are embedded into a printable base polymer. When printed, the active layer has micro or nano-scale surface protrusions, depending upon the size of the constituent particles. The resistance is highly dependent on the contact area, which itself is dependent on the

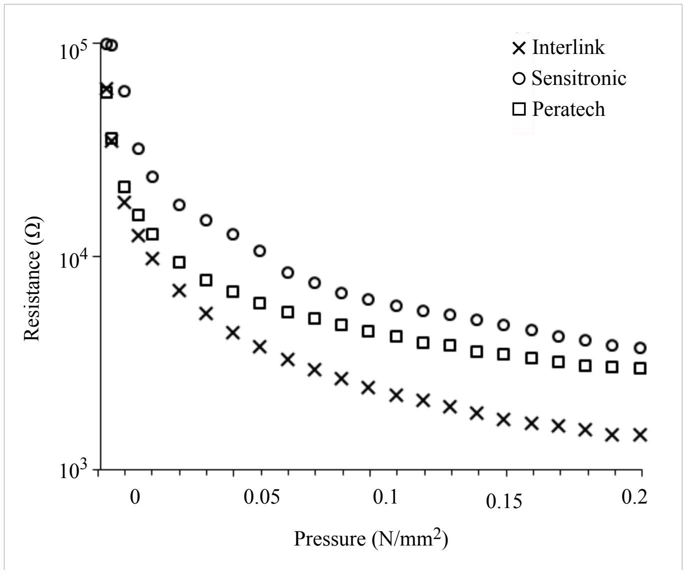


Figure 12: Force-resistance response of FSR sensors manufactured by Interlink Electronics, Sensitronics LLC and Peratech Holdco Ltd. In each case forces up to 10 N were applied using a load cell with a rubber probe with an 8 mm diameter. For each sensor, the resistance decreases over three orders of magnitude with increasing applied force.

force applied to the upper electrode.

For example, Interlink Electronics have patented an ink containing SnO particles of size 0.5-10 μm which create micro-protrusions at the surface of the ink, thereby increasing the number of electrical contact points between electrode and ink with increasing force [86]. The sensitivity of the response can be further controlled by the number and spacing (pitch) of the inter-digitated fingers, where a finer pitch will increase the dynamic range of the FSR.

In other commercial FSRs, the active layer itself is piezoresistive. Tekscan, Inc. describe an active layer which consists of a network of carbon black particles 1-1000 nm in size, dispersed in a polymer binder [87]. As shown in Fig.1, with increasing force a greater number of the particles within the active layer are brought into direct contact or close enough for quantum tunnelling of electrons to occur, thus decreasing the electrical resistance of the layer. Similarly, Peratech Holdco Ltd license a quantum-tunneling ink which contains both spherical insulating particles and acicular semiconducting particles [88]. Evidence suggests that charge transfer occurs via direct conduction and more significantly quantum tunnelling between the acicular particles [89]. The change in resistance can be attributed to both the change in contact area and the change in conductivity of the active layer. Fig.12 compares the force-resistance responses of three commercial FSR sensors - a 0.5 inch FSR™ 402 manufactured by Interlink Electronics (£5.42 per unit [90]), a 0.5 inch FSR101 ShuntMode™ manufactured by Sensitronics LLC (unit price $6 USD [91]) and a QTC™ sensor manufactured by Peratech Holdco Ltd (no pricing available). In each case, the active layer is printed onto inter-digitated electrodes as shown in Fig.11 and the sensor was loaded with forces up to 10 N using a load cell with a rubber probe of diameter 8 mm. It can be seen that for each sensor the resistance varies over three orders of magnitude when forces up to 10 N are applied, where the resistance decrease has a power law dependence on the applied force, with the exponent varying in the range -0.6 to -0.9. For the Peratech and Sensitronics sensors the response shows signs of saturation at higher forces. However the Interlink sensor shows a decrease in resistance even up to 10 N applied force. The activation force (the minimum force required to produce a decrease in resistance) is of the order of 0.15 N. This range of response makes FSR technology suitable for detecting many levels of applied force, from a light touch (0.1 N) to a hard press (10 N).

A further benefit of FSR technology is that it can be manufactured using low–cost large–area printing methods and as a component is easy to integrate into a device. The sensors are lightweight and thin, typically no more than 1 mm total thickness [92]. The sensor performance in terms of its sensitivity, activation and saturation forces (the force at which the resistance has levelled to a minimum value) can be controlled by the mechanical design of the sensor. The saturation force is a function of the area of applied force and the spacing of the inter-digitated fingers. FSR sensors tend to be insensitive to high frequency vibrations and acoustic noise pick-up. This can be useful in some applications in avoiding cross-talk between sensors. However, the reproducibility of the response can often be poor. For example, the FSR® 400 Series manufactured by Interlink Electronics quotes a batch to batch variation of resistance response of 6 %. Variation across a single sensor is quoted as 2 %. This stems from the inherent batch to batch variations common in printed technologies and also hysteresis effects caused by the mechanical relaxation of the host polymer. Whilst this variation means that the sensor is not suited to precise measurement of force, it is appropriate for use in tactile sensors where only approximate levels of applied force are required. The recovery speed of the sensor is limited by its mechanical rise time (i.e. the time taken for the deformed active layer to return to its original position) which is typically quite slow at 1–2 ms. Finally, the FSR can show a drift in resistance for a constant applied load. Whilst this drift is reversible, for applications where measurement of a static force is required, the drift must be taken into consideration.

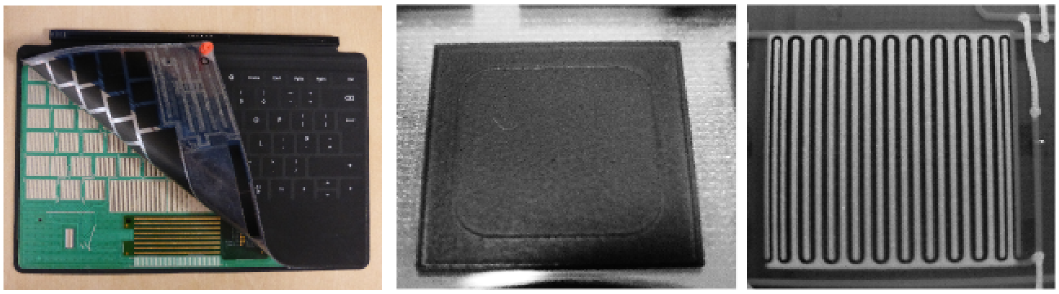
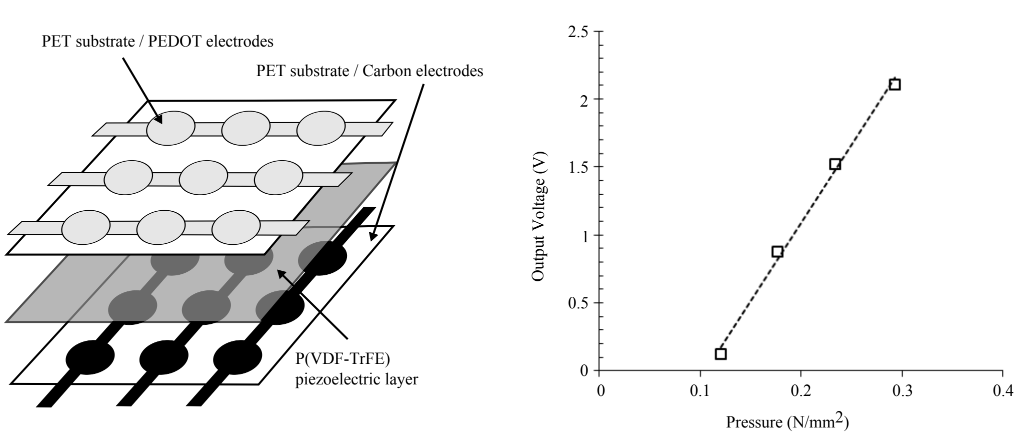


Figure 13: (a) Dismantled view of Microsoft Surface Touch Cover, a pressure sensitive keyboard containing FSR sensor technology. (b) An insulating spacer ring is printed directly onto the active layer of each FSR sensor. (c) Inter-digitated electrodes are printed directly onto the bottom substrate.

Primary applications for FSR sensors include biomedical, e.g. pressure mapping whilst walking [93], robotics [94] and musical synthesizers [95]. Various articles compare FSR technologies and describe their applications in these fields [92, 96, 97, 98]. FSRs can currently be found in some computer keyboards and laptop trackpads [**?**]. FSR sensors are used in the VersaPad® trackpad produced by Interlink Electronics. This consists of two FSR sensors sandwiched together and separated by spacer dots, and is offered as a rugged alternative to traditional projected–capacitive trackpads that can be used in high humidity environments or with gloved hands. The UnMousePad is a multi-touch location and pressure sensing trackpad using FSR technology, developed by TouchCo, Inc. in 2009 [99]. The Microsoft Touch Cover is a pressure sensitive keyboard for integration with Microsoft Surface tablets. Underneath each letter key is an FSR sensor measuring 15 x 15 mm and a set of inter-digitated electrodes, as shown in Fig.13. Microsoft Corp. hold a relevant patent detailing this system [100]. The pressure sensitivity is used to dismiss light touches as accidental and for rejecting unintended touch from the palm of the hand (palm rejection). Other possible uses detailed in the patent include using force to change the size, colour or case of text input and also for gaming applications. Because there are no moving parts, the keyboard is thinner and lighter (2.75 mm and 185 g) with a greater product lifetime compared to mechanical keyboards. The 'quantum tunnelling' ink licensed by Peratech Holdco Ltd is used in the 909 TouchPro drill produced by GlobalPowerBrands Int. Pty Ltd. Here the pressure sensitivity is used to control the speed of the drill rotation.



(a) **(b)**

Figure 14: (a) The structure of PyzoFlex® foil, consisting of the piezoresistive layer sandwiched between two electrode arrays, either carbon-based or PEDOT. Compression of the film induces a measurable voltage. (b) The PyzoFlex® foil produces a highly linear pressure–voltage response (data reproduced from [101]).

4.5.2. Piezoelectric Foil

PyzoFlex® foil, developed by Media Interaction Lab, is a pressure sensitive printable film. A piezoelectric ink containing randomly orientated nano-crystals of the copolymer P(VDF-TrFE) is printed at a thickness of 5 μm onto an electrode, which can be a screen-printable carbon-based ink or a transparent conducting polymer such as poly(3,4-ethylenedioxythiophene) (PEDOT), as shown in Fig.14(a). After printing the dipoles are aligned by poling. The top and bottom electrodes are connected perpendicularly so that a voltage signal can be read out from each electrode-PVDF-electrode intersection. Under applied pressure, or a change in temperature caused by a hovering finger, a voltage change can be detected due to redistribution of the dipoles, as demonstrated previously in Fig.2. Prototypes of the PyzoFlex® foil have been demonstrated, where pressures as low as 0.12 N/mm^2 produced a voltage of the order of 0.1 V [101, 102]. The piezoelectric coefficient is between 20–30 pC/N. The pressure-voltage response of the PyzoFlex® material, is shown in Fig.14(b), reproduced from data provided in [101], where forces were applied using a test probe 4.5 mm in diameter. It can be seen that for applied pressures in the range 0.12–0.29 N/mm^2 (corresponding to applied forces from 1.9–4.7 N) the voltage output is highly linear. No data is provided for pressures above 0.29 N/mm^2 so the saturation force cannot be determined.

However, there are still many issues with this sensor. Perhaps the main disadvantage is that the sensor cannot detect a dynamic force unless additional complex signal processing algorithms are used. This is because during application of a static force the induced voltage discharges through the internal resistance of the PVDF layer. The sensor can only truly detect a dynamic applied force.

Because the touch signal is small, both amplification of the signal and reduction of background noise via a noise filter is required. Signal noise is introduced from infrared light found in ambient lighting, and from cross-sensitivity between the piezo- and pyroelectric responses. Furthermore, the detection of multiple adjacent touches on the PyzoFlex® foil is currently problematic due to cross-talk between adjacent sensors. However, this technology shows potential in that the highly linear response facilitates mapping of the pressure levels, and the technology is suited to flexible applications. It is also possible to create a transparent sensor array by replacing the carbon electrodes with a transparent alternative such as PEDOT or a nanoparticle-based ink. Media Interaction Lab state that PyzoFlex® foil has applications in flexible displays using OLED display technology, although in principle it may be used in conjunction with any touch interface.

4.5.3. Projected–Capacitive Trackpads

The majority of laptop computers replace the mouse with an integrated trackpad. The trackpad consists of a location–sensing surface and perhaps one or two discrete buttons which provide a click function. For some trackpads, the entire trackpad is hinged such that pressing down in an area opposite to the hinge location (usually the bottom of the trackpad) provides the click mechanism.

The principles of projected–capacitive location sensing have previously been described in Section 4.1.1 where this technology is described for transparent touchscreen applications. The principles are essentially the same, except that of course a trackpad does not require a transparent touch surface, or transparent connecting electrodes.

Pressure–sensitivity may be incorporated into these trackpads by means of placing discrete force sensors external to the touch surface, for example underneath the touch surface. Location sensing is still achieved by projected–capacitive sensors. The details of this method have been described fully in Section 4.4.1. This approach has already achieved commercial success in laptop trackpads. ForcePad™ V.4 produced by Synaptics, Inc [103] can be used to define force–sensitive multi-touch gestures [104, 105]. Four force sensors underneath the corners of the trackpad allow the detection of up to 1000 g from up to five fingers simultaneously with 15 g resolution, and is converted into 64 discrete force levels. The hinge mechanism of the traditional trackpad (which allows for click input) is no longer required as the user can click anywhere on the trackpad by applying a force above a predetermined threshold. In this case, the lack of moving mechanical parts could enhance the product lifetime.

At the time of writing, Apple have released another update which states that their newly developed force–sensing technology, called Force Touch, will be present in the new generation of MacBook trackpads. Here, four force sensors are incorporated underneath the trackpad, such that the trackpad can register many levels of pressure which can be used for force–enhanced gestures such as zooming or scrolling.

Another method of including pressure–sensitivity is the inclusion of optical–based pressure sensors within the trackpad structure. The Synaptics ForcePad™V.3 detects applied pressure uses an image–sensing array in the trackpad. This relates the size of the contact area to the pressure–applied by the fingertip. If a hard press is detected (larger contact area between fingertip and touch interface) the click function is activated.

Application	Examples	Location Sensing Mechanism	Pressure Sensing Mechanism	Sensor Details	Pressure Sensing Capabilities	Advantages	Disadvantages
Keyboard	Microsoft Surface Touch Cover 2	Resistive – conducting polymer composite (FSR)	Resistive – conducting polymer composite (FSR)	One sensor measuring 15 mm x 15 mm underneath each key	Need only distinguish light touch and hard press for palm-rejection functionality	Keyboard is thinner and lighter than for traditional mechanical keys (2.75 mm and 185 g) Pressure sensitivity removes need for mechanically moving parts	Currently there is no haptic feedback when pressing each key
Laptop Trackpad	Interlink VersaPad™	Resistive – conducting polymer composite (FSR)	Resistive – conducting polymer composite (FSR)	One large continuous FSR sensor 41 x 57 mm underneath trackpad surface	Capable of detecting 256 levels of pressure although this feature is not utilised in the VersaPad™	Trackpad can detect input from any object Thin and lightweight compared to capacitive–style trackpads (¡15 g) Can be used in extreme environments such as high humidity	A minimum activation force is required to register a touch event Multi-touch functionality is not supported
	PyzoFlex® prototype only	Piezoelectric (PVDF-TrFE copolymer)	Piezoelectric (PVDF-TrFE copolymer)	Printed array of 16 x 8 piezoelectric sensors covering an area of 210 x 130 mm^2 Each sensor has 10 mm radius and thickness of 50 µm plus 175 µm substrate thickness [101, 102]	Capable of detecting applied pressure from 0.1–0.3 N/mm^2 (2–5 N)	Highly linear pressure sensing response May have applications for touchscreens if transparent electrodes are used Sensors can be fabricated using a low–cost print process Suitable for flexible applications	Can only detect a dynamic force unless complex signal processing algorithms are used Sensitive to electromagnetic noise and cross–talk between sensors Currently only low spatial resolution but this can be improved by increasing the spatial density of sensors
	Synaptics ForcePad™ v.3	Projected capacitive	Algorithm relating contact area with applied force	No physical sensors, algorithm only	Detection of force above pre-determined threshold to activate click function	Pressure sensitivity removes need for mechanically moving parts Trackpad is thinner and lighter than competitors (as thin as 1 mm)	Cannot distinguish multiple pressure levels Algorithm requires calibration prior to use Lack of haptic feedback associated with click
	Synaptics ForcePad™ v.4	Projected capacitive	Individual force sensors underneath four corners of trackpad surface	Sensor type is undisclosed but is likely to be strain gauge, piezoelectric, capacitive or similar	64 levels of pressure, up to 7 N force, from 5 fingers simultaneously	Pressure sensitivity removes need for mechanically moving parts Trackpad is thinner and lighter than competitors (3 mm) 64 pressure levels allow pressure sensitive gestures	Lack of haptic feedback associated with click
Force or pressure sensors underneath the touch interface	QSI Corp. InfiniTouch™ F–Origin Inc. zTouch™ NextInput, Inc. ForceTouch™	Force/pressure sensors external to touch interface	Force/pressure sensors external to touch interface	Piezo–resistive sensors underneath four corners of interface		Detection of touch from any object Rugged and durable touch interface is not sensitive to screen contaminants Cost is independent of area of touch interface Touch interface can be patterned or 3D	Only a single touch can be detected Friction or bending effects must be fully accounted for in order to achieve accurate location sensing
				Array of MEM force sensors underneath the display interface allows for multi–touch location and pressure sensing	Pressure sensing with sub–mN resolution		
Capacitive Touchscreen	Research only (although this technology is used in Samsung ST550 and TL220 camera touchscreens for location sensing only)	In-Cell pressed capacitive array	Capacitive pressure sensor	Sensor array 5 x 5 mm unit size at thickness 750 µm (excluding lower ITO electrodes) [40]	Detection of up to about 0.1 N applied force	Good transparency (¿ 86%) Suitable for flexible applications	Low signal to noise ratio Unsuitable for high–end applications such as smartphones and tablets due to issues with capacitive coupling with other device components
				20 x 20 sensor array with 2 x 2 mm sensor size at thickness 253 µm [38, 39]	Detection of up to 5 N applied force		
	Apple Watch Blackberry SurePress™	Projected capacitive	Individual force sensors underneath four corners of touchscreen/display modules	Sensor type is undisclosed but likely to be strain gauge, piezoelectric, capacitive or similar	Apple Watch will be able to differentiate between a light touch and a hard press	Easy addition of pressure sensing to any location sensing device Sensors are entirely separate to touchscreen hence need not be transparent Multi-touch location sensing is supported	Sensors may add to overall thickness of device Lateral forces on the sensors need to be eliminated to ensure accurate pressure readings Complex algorithm may be required to extract force from dynamic force profiles measured at each sensor
	Active Stylus e.g. Samsung S–Pen for Galaxy Note 4 (2048 pressure levels) N-Trig Active Pen (248 pressure levels) Wacom Bamboo Stylus fineline (1024 levels) Wacom Intuos Creative Stylus 2 (2048 levels)	Projected capacitive OR additional digitiser layer underneath display specifically designed for stylus input	Active stylus pen with in–built pressure sensor	Sensor type can be resistive (conductive polymer composite), capacitive, inductive or optical	Highly sensitive with many pressure levels, frequently used for artistic and drawing software	High pressure resolution (up to 2048 levels) Single sensor required Few constraints on sensor size and weight	Pressure sensing capability also dependent on device (controller, chip) and applications (software and drivers) Digitiser layer used in some devices adds to device thickness and weight Some styli may require charging or replacement batteries Expensive to replace if lost or broken
Resistive Touchscreen	Research or prototype only	Resistive	Resistive – conducting polymer composite	Percolative network of nanoparticles spanning 1–10 µm transparent layer. 12 x 16 sensors across 3.5 inch touchscreen [51]	Detection of 0.04 – 1 N force is reported	Current flow only when touchscreen is pressed – low power consumption Supports multi-touch input and input from any object Insensitive to electromagnetic noise	Additional layer may impact on optical transmission through touchscreen Particles may abrade with ITO electrodes leading to shorter product lifetime Resistive layer is prone to hysteresis effects
				Magnetically aligned particles spanning 50–100 µm transparent layer. Currently patent only [56]	Detection of up to 0.5 N force is reported		
				Single layer of particles in 1–10 µm transparent layer [57]	Detection of up to 0.8 N force is reported		

Table 2:

Comparison of pressure–sensitive tactile technologies for applications in human–computer interaction

5. Comparison of Pressure Sensing Touch Technologies and Future Trends

As a summary, Table 2 compares each technological application discussed in this paper in terms of its sensing mechanism, how the pressure–sensitivity is utilised, and the advantages and disadvantages of the technology in this particular application. whether the technology has already achieved commercial success and the relevant references to the literature.

It should be noted that a direct quantifiable comparison of these technologies is not possible as each is intended for a different application and as such may require different pressure sensing capabilities, different build parameters and different materials characteristics. However, a broad comparison in terms of the response parameter may prove useful in giving a general overview of the functionality that these technologies are capable of. We define the response parameter as

$$Response = \frac{X_i - X_{min}}{X_{max} - X_{min}} \times 100\%, \tag{6}$$

where X_i is the ith value of a measurable quantity X, for example resistance, capacitance or voltage, and X_{min} and X_{max} are the minimum and maximum values of X, respectively.

Fig.15 shows the response of the various types of pressure–sensitive touch technologies described in this review as a function of applied pressure. Response data for Interlink FSR technology (FSR-Interlink), PyzoFlex® piezoelectric foil (PIEZO-PyzoFlex), in-cell pressed capacitive touchscreens demonstrated by H. Kim and K. Kim (ICPC-K Kim and ICPC-H Kim) and the resistive pressure–sensitive touchscreen patented by Peratech Ltd (RES-Peratech) are compared. For the FSR technology as described in Section 4.5.1, the Interlink sensor is chosen as a representative sample and for the resistive–pressure sensitive touchscreens outlined in section 4.2 only the data for the Peratech touchscreen allows for the touch pressure to be calculated.

Interestingly, the response for both RES-Peratech and FSR-Interlink technology is similar in that they operate over the same range of applied pressure. The response for both ICPC-K Kim and PIEZO-PyzoFlex® is almost linear in the range of pressures tested. Of course it is likely that for higher pressures the response would eventually saturate. The sensitivity of a particular sensor may be defined as the change in pressure (expressed as a percentage of the total pressure range of the sensor) required to produce a 50 % response:

$$Sensitivity = \frac{Pressure_{50\%} - Pressure_{0\%}}{Pressure_{100\%} - Pressure_{0\%}}, \tag{7}$$

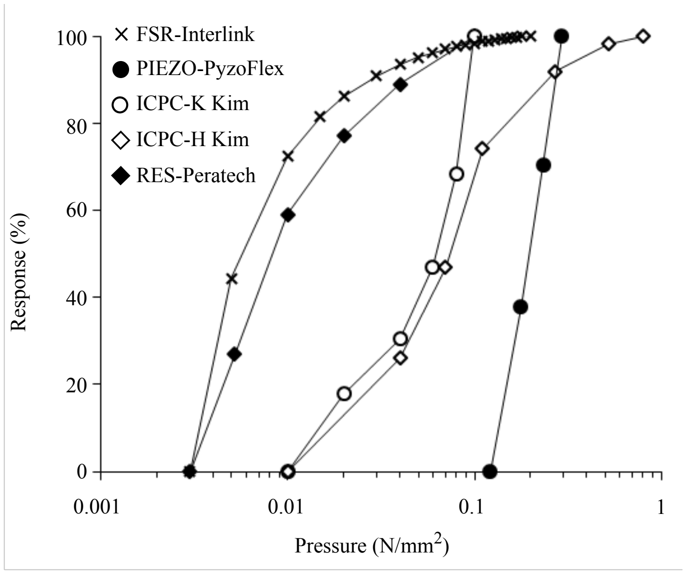


Figure 15: Comparison of sensor response to applied pressure for Interlink FSR technology (FSR-Interlink), PyzoFlex® piezoelectric foil (PIEZO-PyzoFlex), in-cell pressed capacitive touchscreens demonstrated by H. Kim and K. Kim (ICPC-K Kim and ICPC-H Kim) and the resistive pressure–sensitive touchscreen patented by Peratech Ltd (RES-Peratech).

where $Pressure_{100\%} - Pressure_{0\%}$ defines the range of response, that is the difference between the maximum and minimum pressure (or force) able to be detected. The calculated sensitivity values are compared in Table 3. Here we can see the sensitivity for both ICPC-K Kim and PIEZO-PyzoFlex® is around 50 %, indicating a linear response - 50 % of the sensor response is achieved through 50 % application of applied pressure. The other technologies have much lower sensitivity values. This indicates that the sensors are highly sensitive to low values of applied pressure, as only a pressure input typically less than 10 % is required to produce a 50 % response.

For each technology discussed in this review paper, the maximum and minimum force values from the available data (i.e. the range of response) are shown in Fig.16. The region corresponding to a light touch (0.1 N) and a hard press (10 N) is shaded. Both the pressure–sensing resistive touchscreen patented by Peratech Ltd and the FSR technology (in this case demonstrated by Interlink but in practice any of the sensors shown in Fig.12) produce a response for most forces in this range. Whilst the ICPC touchscreen demonstrated by K. Kim and the resistive touchscreen patented by Stantum are sensitive to smaller applied forces below this limit, in practice this is not particularly useful.

Table 3: Sensitivity of selected pressure–sensing tactile technologies

Technology	Sensitivity
FSR-Interlink	1.5
PIEZO-PyzoFlex	45
ICPC-K Kim	59
ICPC-H Kim	8.2
RES-Peratech	5.8

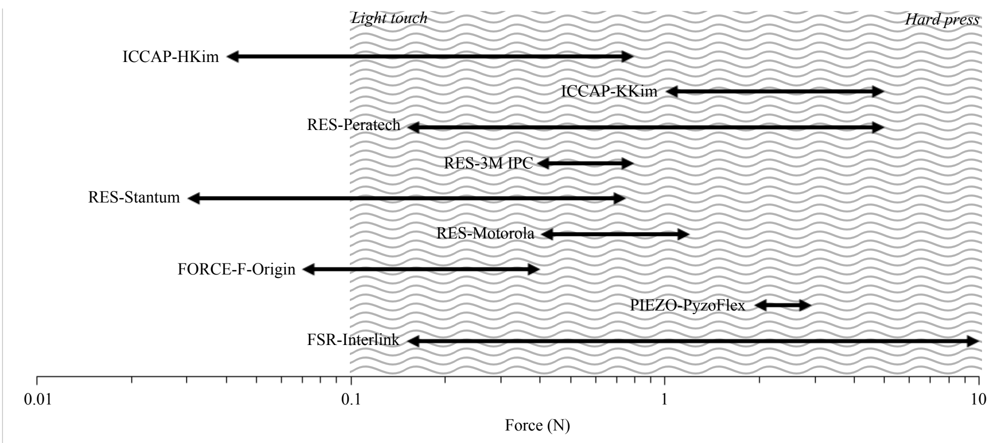


Figure 16: Comparison of the range of forces to which the pressure–sensitive touch technologies described in this review exhibit a response. The force region comparable to a light touch (0.1 N) and a hard press (10 N) is shaded.

In terms of how pressure input may be utilised in computer interfaces, a pressure level may be defined as a range of pressures that will result in a certain reaction. For example in drawing software each pressure level would result in brush stroke of a certain diameter. The diameter would typically become larger for a higher pressure level input. A large sensitivity coupled with a small responsive pressure range means that the defined pressure levels must become narrow. The reaction becomes almost switch-like and access to intermediate pressure levels requires a high degree of user control. However for a smaller sensitivity coupled with a large range of response, broad pressure levels may be defined and it becomes easier for the user to manipulate between the pressure levels.

Another important issue to consider is the cost of implementing the pressure–

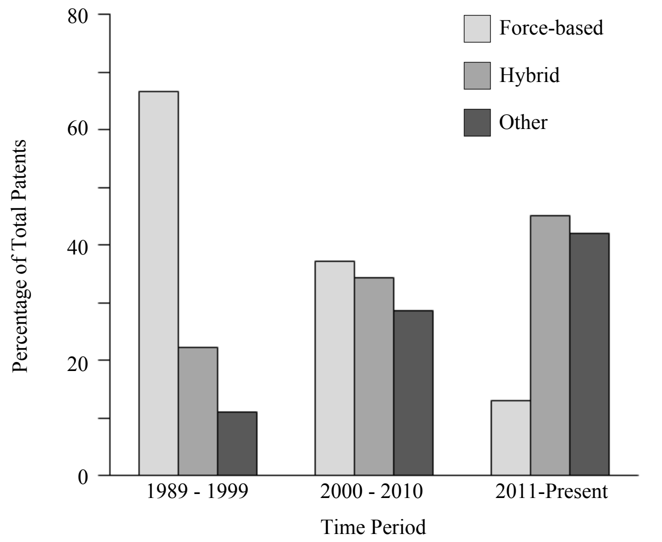


Figure 17: An analysis of patent trends over time. A sample of 75 patents containing the words "force sensitive touchscreen" or "pressure sensitive touchscreen" were analysed. It was found that the majority of the patents described either a touchscreen which used discrete force sensors to measure both touch location and touch force, or a hybrid touchscreen where discrete force sensors were used alongside a location sensing technology, usually projected capacitive. Furthermore, the percentage of hybrid technologies is found to increase over time, whereas the percentage of discrete force-based technology patents decreases.

sensing solution. The addition of a small number of discrete pressure sensors, placed outside the touch module in strategic locations (for example force sensors placed in the four corners underneath the display) is likely to be a low–cost solution as the price of sourcing and incorporating the sensors into the build of the device should be comparatively low. Contrast this with incorporating the pressure sensor within the touchscreen itself – for example the continuous resistive films described in Section 4.2 or even a 2D matrix array of sensors as described in Section 4.1.2. Here, the manufacture costs are likely to be high as new methods and additional steps must be included in the manufacture of the touchscreen. Whilst the resistive pressure sensing layers can be printed, using screen-print techniques for example, the manufacture of the pressed in-cell touchscreen uses photolithographic methods with a high number of manufacture steps.

Analysis of the patent literature can yield information regarding the possible future successes for each technology. Fig.17 shows the patent trends in touch technologies since 1989. A patent search engine was used to search for patents containing the phrase "force sensing touchscreen" and/or "pressure sensing touchscreen". A sample size of 75 patents were analysed in the order they were listed on the search engine. It can be seen that the majority of the patents describe either force-based touchscreens or the hybrid touchscreens described above. Interestingly, it can be seen that the percentage of purely force-based technology patents decreases over time, whereas the percentage of patents detailing the hybrid technology increases. In the category of 'other' the patents may describe resistive pressure sensing technology, FSRs and pressed–capacitive technology. This is perhaps of no surprise, as the leading touchscreen technologies currently use P-Cap or In-Cell P-Cap technology and hybridisation with discrete force sensors is perhaps the simplest compatible method of incorporating pressure sensitivity in such a device.

6. Conclusion

This review describes current and emerging tactile sensing technologies for use in HCI applications where touch pressure can provide a third dimension of user input. Pressure–sensing may be realised by the incorporation of resistive, piezoresistive, capacitive, piezoelectric or inductive pressure sensors.

Whilst some of the pressure–sensing technologies discussed are at present only detailed in the patent literature, or available as prototype only, there are some products available on the market which already utilise pressure–sensitivity. These include the Microsoft Surface Touch Cover Keyboard and the Interlink VersaPad™ laptop trackpad, which contains FSR resistive pressure–sensing technology. Pressure sensitivity is also being developed for transparent touchscreens, for example by the incorporation of a resistive pressure–sensing layer in a resistive–type touchscreen, or by a capacitive pressure sensing array in a pressed 'in–cell' touchscreen. However, currently these technologies are in the research stage only, and whilst at least the resistive solution is under development by some companies there is currently no device on the market utilising this technology. The pressed in-cell approach has been studied by various research groups, for its potential applicability in touchscreens. However, the inherent disadvantages of this technology mean it is unlikely to be commercialised in the near future.

Perhaps the most success (in terms of number of patents and devices which utilise this principle) has been achieved by the addition of discrete pressure sensors outside the touch module, where the sensors do not need to be transparent. For example, the Apple Watch uses this method to distinguish between a light touch and a hard press, and the ForcePad™ trackpad produced by Synaptics, Inc. can detect 64 levels of applied pressure from five fingers simultaneously. Perhaps the main benefit of this approach is that the specific advantages of the touchscreen can be kept, for example the multi-touch functionality associated with P-Cap touchscreens, as the pressure sensors can be integrated underneath any display using any location–sensing interface. Analysis of patent trends show this approach is rapidly gaining traction. For these reasons, the authors believe that this approach may show the most commercial successes in the next few years.

In the words of Apple "[Pressure sensing] is the most significant new sensing capability since Multi-Touch" [106]. Their recent focus on force–sensing in laptop trackpads and wearable technology such as the Apple Watch show that it is only a matter of time before pressure input becomes mainstream in the new generation of human–computer interfaces.

7. Acknowledgements

The authors would like to acknowledge the Technology Strategy Board (TSB), the Knowledge Transfer Partnership scheme, and the Faculty of Science at Durham University for funding this research.

8. Figures

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