Capacitive Touch Sensors

Application Fields, technology overview and implementation example

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Intended audience:
Decision Makers, System Integrators and Development Engineers who have to deal with man machine interfaces. Especially with input devices and control panels which feature different kind of elements like buttons, control dials or slide controls.

Attendees will be informed on:
Advantages and limitations of capacitive touch sensor solutions. The benefits and drawbacks of different HW and SW approaches. How to achieve robust and reliable systems which work in rough environments. Flexible usage of capacitive touch elements in housings and in combination with displays (touchscreen). Capacitive Touch Sensor implementation example Fujitsu FMA1127

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Abstract:
Today, capacitive touch sensors are widely used in consumer products like MP3 players, mobile phones and other portable devices. More and more the technology is utilized in further application fields such as household appliances as well as automotive and industrial applications. There are several reasons for this development.

1) Attractive product design: Users are able to design appealing products to distinguish from competitors. Touch sensors allow much more flexible designs as conventional mechanical buttons and sliders.
2) Durability: Touch elements do not contain moving parts like mechanical input devices. Thus no wearing out of these parts.
3) Robust housing design: It is easier to design devices for rough environments. Compared to conventional solutions, no holes or other openings are necessary where humidity and dust could enter the device
4) Cost: The manufacturing of the housing is simpler and cheaper because no openings and sealings are necessary.

As manifold as the application fields for capacitive touch sensors, are the technical solutions.
It is possible to implement a touch sensor in software with a Microcontroller together with some external components. The other end of the range is defined by fully integrated hardware products.
All methods detect the change of capacitance, if an electrode is touched by a human finger.
Though this principle is the same for all methods, every approach feature specific advantages and drawbacks.
The paper presents various capacitive sensing approaches and discusses the properties current consumption, response time, cost and reliability of these methods.

An important aspect of touch user interfaces is reliable and robust operation. Since environmental parameters like humidity and temperature can influence the sensor behavior, it might be necessary to compensate these factors. Otherwise the system might become instable and false touches are detected. Methods to overcome this problem in actual applications will be presented in the paper.

Since more and more applications feature a display, touch sensors in combination with screens are discussed in a third part of the paper. If the sensing electrodes are transparent, they can be placed onto a display and the user is able to control a device by pressing virtual buttons directly on the screen. Capacitive touch screens offer some advantages compared to resistive solutions which are very common in the industry and widely used already.

Literature:
A Full-Digital Multi-Channel CMOS Capacitive Sensor
B.-J. Moon, D.-Y. Jung, J.-W. Chung, C.-Y. Joung,
J.-S. Hong, S.-J. Lee, Y.-H. Shin
SoC Research Center, ATLab Inc.
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What is capacitive touch and what can it be used for

In many cases, machines, home appliances and electronic devices have to be controlled by human beings. It is part of everyone’s daily life and we are familiar with switches, push buttons, keyboards, knobs and slider controls. Since some time, a new species of control elements invades our life. It started in consumer products like mobile phones and MP3 players but moves into all kind of devices now. Those talks are about touch sensors. Simple electrodes underneath the housing replace

mechanical input devices with moving elements. The shape and layout of these sensor electrodes can be designed in a very flexible way, leading to appealing, modern product designs with enhanced usability. A wide range of elements can be implemented with touch sensor electrodes: simple buttons and keyboards, linear or circular sliders, transparent touch elements on displays or even buttons on wooden surfaces. As the sensor electrodes are placed inside the device, no openings are required. The housing is more robust and cost-effective and ideally suited for rough environments where dust and moisture could creep into the device. Especially for medical applications or devices used in clean environments like in the food industry, capacitive touch control enables hygienic casings.
Conventional mechanical buttons or potentiometers with moving parts have a certain lifetime. Sooner or later they are worn out and do not work reliable anymore. Due to the lack of moving parts, capacitive touch is much more durable. However for highly stressed elements, the surface resp. overlay cover material of the touch electrode has to be considered. Glass or acryl may be better suited as plastics. For single, isolated buttons, even metal can be used, not for complete front covers however as the sensor pads must be isolated from each other.
One positive aspect of the moving parts in conventional push buttons or switches is the tactile feedback to the user. By touching a surface, the user does not "feel" if the push button was triggered. This can be compensated by using optical, acoustical or, a bit more complex, vibration feedback.

Basic Principle

The simplest form of a capacitor consists of two conductors, e.g. two metal plates, separated by an insulator. The following formula shows the parameters which influence capacitance:

$$C = \varepsilon \frac{A}{d}$$

$\varepsilon = \varepsilon_0 * \varepsilon_r$

Where C is the capacitance
ε_r is the relative permittivity, also called dielectric constant, of the insulating material between the plates
ε_0 is the permittivity of free space (8.854x10-12 F/m)
A is the area of the plates
d is the distance between the plates

relative permittivity εr	
air/vacuum:	ε=1
PE:	ε=2
wood:	ε=3
ABS:	ε=4
glass:	ε=7
water:	ε=80

Table 1

The larger the area of the plates, the larger is the capacitance. The smaller the distance between the two plates, the higher is the capacitance. The insulating material determines the dielectric constant. Table 1 list some common materials and their permittivity.

The electrode of a touch sensor represents one plate of such a capacitor. The corresponding 2nd plate is represented by the environment of the sensor electrode (to form a parasitic capacitor C_0) and another conductive object, like a human finger for example (to form touch capacitor C_T).
This capacitor, i.e. the sensor electrode, is connected to a measurement circuit. The capacitance of the sensor pad is measured periodically. If a conductive object approaches or touches the electrode,

the measured capacitance will increase. This change is detected by the measurement circuit and converted into a trigger signal.
Considering the formula above, one can see that a bigger pad and a thinner overlaying cover material, leads to a bigger touch capacitance C_T and as a result, a bigger capacitance difference between touched and untouched sensor pad. In other words, the size of the electrode and the covering material influence the sensitivity of the sensor.

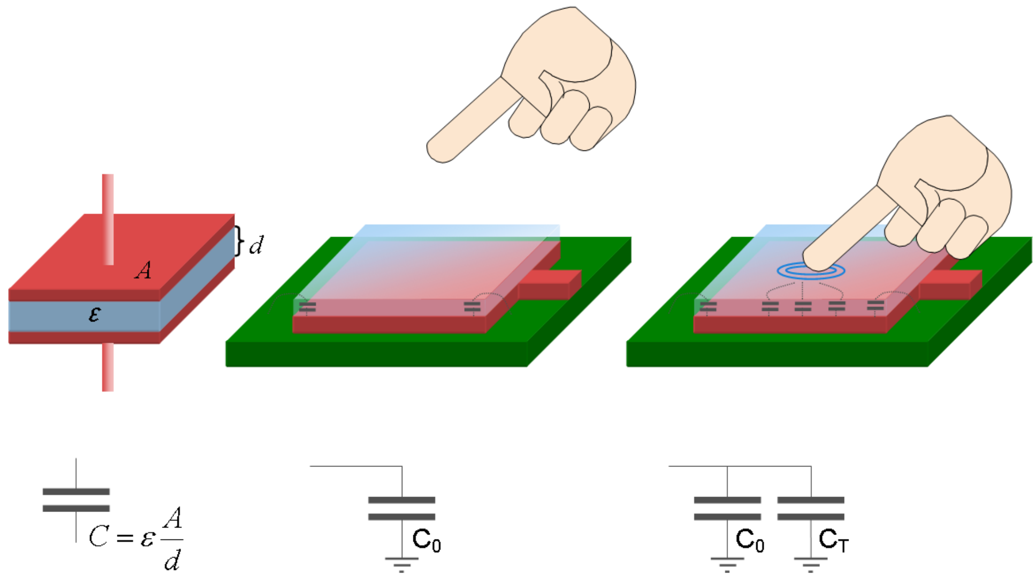


figure 1 Touch Sensor Principle: untouched sensor pad with parasitic capacitance C_0, touched sensor pad with additional touch capacitance C_T.

Measurement Methods

Capacitive measurement methods have been used for a long time in many applications to determine physical values like distance, pressure, liquid level, acceleration etc.. Capacitive touch sensors are just another application field. Numerous different methods exist to measure capacitance: shift of resonance frequency, frequency modulation, amplitude modulation, charge time measurement, time delay measurement, duty cycle, etc.
Most methods require analog-intensive circuits and inherit the related problems like crosstalk, coupling and noise sensitivity. A digital approach is less area and power consuming, compared to analog solutions.

As example for a digital method, the following paragraphs describe a RC-delay line differential design. The circuit measures the difference between a reference and the capacitor to be sensed. This method was developed by ATLab, Inc. of South Korea and is implemented in the application specific standard product FMA1127 for capacitive touch applications, offered by Fujitsu Microelectronics. The method could be used for other measurement applications as well.

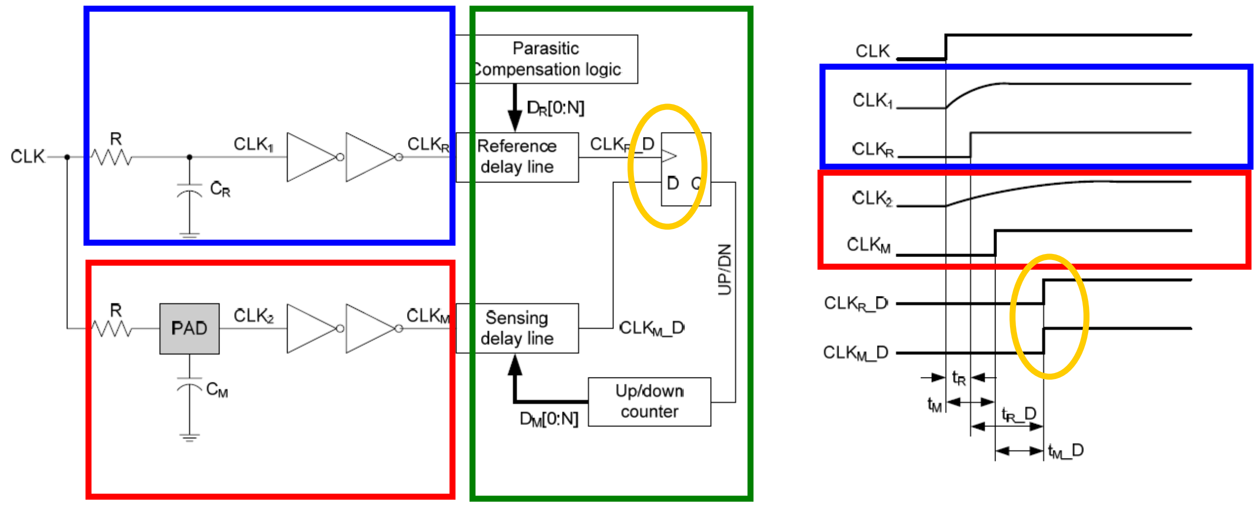


figure 2 Block diagram of RC-delay line capacitance measurement method

The system consists of two RC–delay lines and a time to digital converter. One RC-delay line is the internal reference, the other RC circuit is the measurement line with attached external capacitance C_M. Both RC-delay lines are supplied with the same clock signal CLK. In the FMA1127 implementation, a maximum clock frequency of 20kHz was selected. This allows fast response times but has no negative effect on EMI behaviour of the system.

Depending on the RC element capacitance values C_R and C_M, the CLK signal edges are delayed. This time delay is proportional to the capacitance. Each delayed CLK signal CLK_R and CLK_M is fed into configurable, fully digital delay lines. The digital control values D_R[0:N] and D_M[0:N]of the delay lines are set in a way that the output signals are in phase. I.e. the delay line output signals CLK_{R_D} and CLK_{M_D} arrive at the Flip Flop, shown in figure 2, at the same time. The control circuit includes an up/down counter which adjusts the sensing delay control value until the output is in phase to the reference clock $CLK_{R\_D.}$ By comparing the digital control values D_R[0:N] and D_M[0:N] it is possible to determine the difference between reference and measured capacitor. Thus the capacitance difference, i.e. the corresponding time difference, is converted into a digital value. C_M is proportional to D_R[0:N] - D_M[0:N].

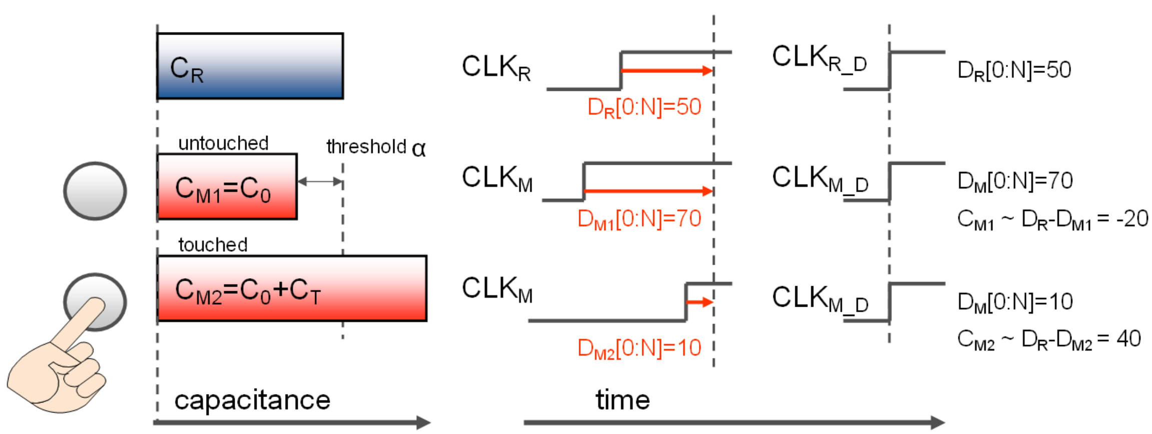


figure 3 Timing diagram of RC-delay line capacitance measurement method

In a touch sensor application, the to be sensed capacitance C_M will change depending on the presence of a finger or other conductive object, while the reference C_R is static (neglecting temperature drift, etc.). A touch is detected if C_M changes from a low ($C_{M1} = C_0$) to a higher value ($C_{M2} = C_0 + C_T$) within a short time period. In order to avoid false detections, the increased C_M must exceed a certain threshold, called α. As C_M is proportional to the digital control signal $D_M[0:N]$, the calculations can be performed in the digital domain as shown below.
If the reference delay line value $D_R[0:N]$ is configured during the initialisation phase to be α steps above the untouch sensing line value $D_{M1}[0:N]$, the touch descison is positive as soon as the difference between reference and sensing line value becomes ≥ 0.

$C_{M1} = C_0$ - parasitic capacitance only
$C_{M2} = C_0 + C_T$ - parasitic plus touch capacitance
$C_T = C_{M2} - C_{M1}$
$C_{M1} \sim D_R[0:N] - D_{M1}[0:N]$
$C_{M2} \sim D_R[0:N] - D_{M2}[0:N]$
$C_T \sim D_{M1}[0:N] - D_{M2}[0:N] \geq \alpha$ - sensor pad is touched
$C_T \sim D_{M1}[0:N] - D_{M2}[0:N] < \alpha$ - sensor pad is untouched

Example:
threshold $\alpha = 20$

$C_{M1} \sim 50 - 70 = -20$ (smaller than ref)
$C_{M2} \sim 50 - 10 = 40 \geq 0$ -> touched
$C_T \sim 70 - 10 = 60 \geq 20 = \alpha$ -> touched

Further Processing

In the simplest case, the sensor circuit just detects a touch of the sensor pad and performs a yes/no decision. Buttons can be implemented in this way. For more sophisticated elements like sliders with higher resolutions, the “strength” of the touch, i.e. the quantity of C_T has to be evaluated as well. In a linear slider design, several sensor pads are located close to each other. By touching the slider, more than one pad is influenced by the finger. Typically distributions of C_T may be similar to the one shown in figure 4, are measured on the slider channels. Depending on the pad size and layout, the resolution of such a 5 channel slider can be as high as 100 steps by applying interpolation to the measurement results.
The described delay to digital converter method features sensor channels with a C_T resolution of 78fF and a dynamic range of 7.8pF, leading to 100 steps per channel. Hence it is excellently suited for interpolation algorithms. Usually the complete dynamic range of several pF is not used in practice. A finger may add a capacitance between 1 to 2 pF maximum, depending on the cover thickness and material.

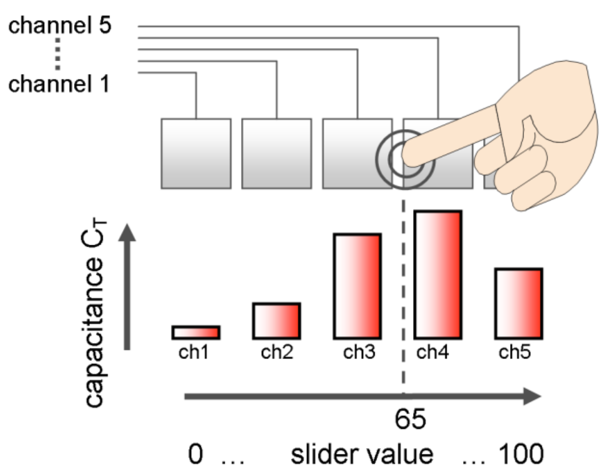
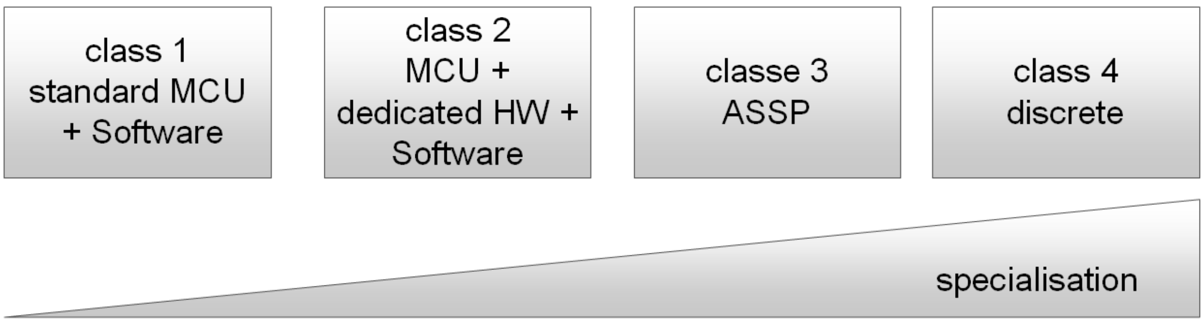


figure 4 Capacitive touch slider implementation with interpolation

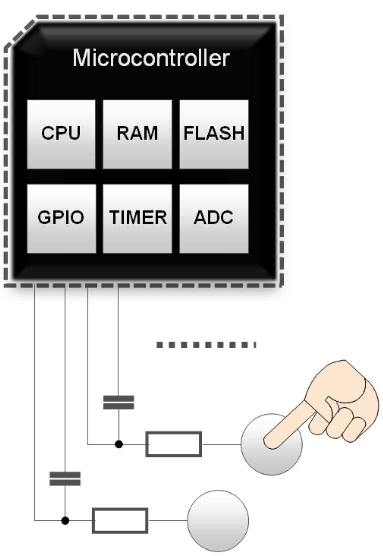
Implementations

The described capacitance measurement methods can be implemented in different ways. Four implementation categories can be defined, ranging from software based solutions, using general purpose microcontrollers, up to specialised discrete hardware implementations. In between, more specialised microcontrollers with dedicated touch sensing peripherals and application specific standard products can be classified. For capacitive touch applications classes 1 to 3 are commonly used, while discrete solutions are mainly implemented in other capacitive sensing applications to measure distances, presure etc.



Each class has its strength and weakness. Depending on the application requirements, the user has to select the best fitting approach.
The most important properties of touch sensors are response time, current consumption, robustness, design effort and cost. Response time defines the delay between the touch of e.g. a button and the corresponding response of the system. Robustness has two meanings. First, the system shall work reliable. I.e. no false triggers must occur and intended touches shall be detected reliable under all conditions like different temperatures, humidity etc.. Second, the system must withstand a certain level of stress, like ESD, overvoltage and so on, without being damaged. Development of a touch solution takes more or less time. The underlying architecture determines the design effort and is another criterion for selecting a particular implementation class. Last but not least, cost of the parts has to be considered.

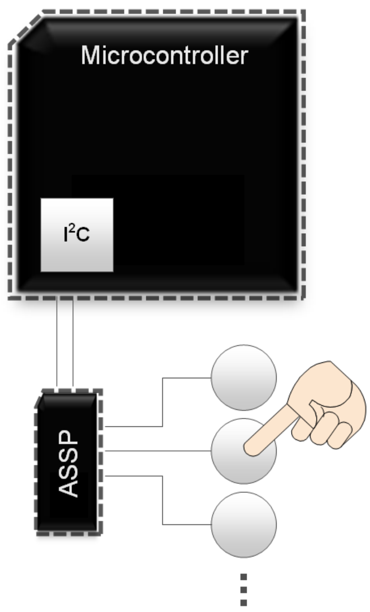
Microcontroller with standard peripherals like GPIOs, timers and A/D converters



These software based solutions make use of the standard peripherals of a microcontroller to implement capacitive sensing methods like charge time measurement. The advantage of this approach is the possibility to use virtually every available microcontroller. If the embedded system offers unused resources, the capacitive touch functionally does not generate additional cost. However a significant part of the resources is occupied by the touch implementation. The software libraries need 4KB to 8KB Flash memory and 10% to 20% of the CPU load, or more if several sensor channles are implemented. Each sensor channel occupies 2 or 3 pins of the microcontroller. In addition, timers, A/D converter channels or other analogue resources like comparators are used by the software. The performance of such a solution is limited, response times are in the range of several

milliseconds. In some cases, the interrupt handling has to be evaluated carefully, as the sensing algorithms does not allow interruption. Some microcontroller vendors offer capacitive touch software libraries for their products to enable developers a quick start. The responsibility and the task to design a reliable touch solution however is on the designers side.
If only a small number of sensor channels is required and the performance requirements are low, this approach might be an option.

Application Specific Standard Product



Such a system consists of 2 devices: the system host controller and a slave which handles the capacitive touch sensing in hardware. The usage of a ASSP is even more flexible as the first implementation class with general purpose microcontrollers since existing applications must not be modified significantly. Just an interface, like a serial I^2C is required to connect the devices. The disadvantage of a ASSP solution is the additional component which generates cost and requires PCB area. Putting the additional resources into perspective which are required for software solutions (many GPIO pins, Flash memory for the library, etc., maybe even a bigger device is necessary) the cost adder for the ASSP may be less significant. The performance of an ASSP is much better than other solutions, especially when several sensor channels are required. Of course a dedicated hardware implementation offers faster response times than software algorithms. Also the current consumption balance tends to be lower with an ASSP. Another advantage is the easy and fast integration. Sensing pads are connected directly to one pin of the device, no additional external components have to be dimensioned. As the reliable operation comes in hardware, the designer can concentrate on the application. The development effort is lower compared to software methods.
Fujitsu's FMA1127 is an example for an ASSP solution. It is connected to any host Microcontroller via an I^2C interface. The delay to digital capacitive sensing method is implemented and achieves short latencies in the range of 200µs. The average active current consumption for 12 channels is around 120µA.

Microcontroller with dedicated capacitive touch peripherals

Some microcontrollers feature special hardware modules for capacitive touch sensing. These modules reduce software development effort and increase performance. They are a compromise between purely software based and more hardware focused ASSP solutions.

Reliable operation

In contrast to mechanical contacts, capacitive touch sensors do not require force to trigger a button. The presence of conductive material is sufficient. Therefore, the risk of unintended, false triggers is higher. In particular, water and moisture, which is a good conductor, are potential problems.

Many capacitance measurement methods require a reference ground plane, located nearby the sensing pad. A fingertip forms the capacitance between the sensing pad and the reference ground. Since the human body consists of around 70% water, a drop of water on such a pad layout is very similar to the fingertip and leads to false triggers. Reducing the sensitivity is no option because intended touches shall be detected reliable.

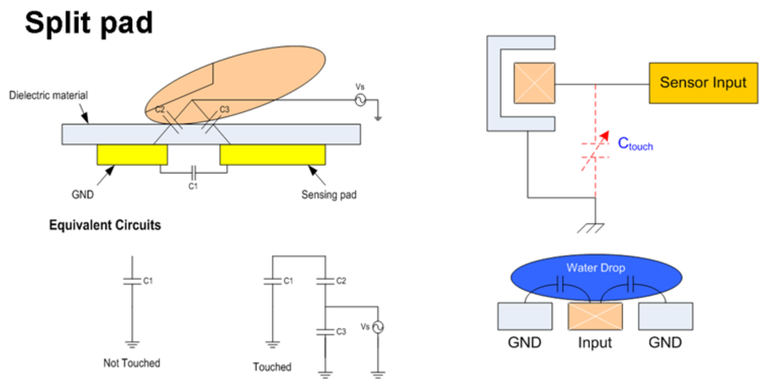


figure 5 Split sensing pad

There are proposals to distinguish between water and intended touches by additional guard sensing pads, special pad layouts with shield electrodes and software algorithms. However the best solution to overcome this problem is to get rid of the reference ground electrode. The differential measurement approach discussed earlier and implemented in Fujitsu's FMA1127/25 touch sensor controllers, use single pads only. With a resolution of 78fF, the sensitivity of the circuit is high enough to sense the self capacitance of the touch pad, which is influenced by the human body. No reference ground plane is required. Furthermore all sensor channels of the device are operated synchronously. This avoids cross coupling effects.

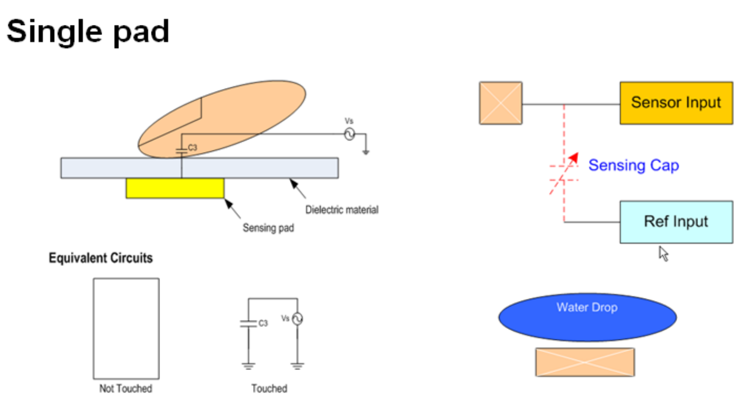


figure 6 Single sensing pad

Another aspect of reliable operation is the compensation of long term effects. Parameters like temperature, humidity etc. influence the measurement result. If these effects are not taken into account and be compensated, the sensitivity of the sensor changes over time. Under bad conditions, this can even lead to false triggers. Some methods register slow capacitance changes and assure a stable sensitivity. This feature is available on FMA1127 and called AIC – automatic impedance calibration.

Touch Screens

The lack of mechanical components enables the implementation of capacitive touch based control elements on LCD panels. As the sensing pads are placed above the display, the user can touch directly onto the screen. Thus it is possible to generate context dependent, virtual buttons and other user friendly, intuitively control elements.
Usually the sensing pads are made of a thin layer of Indium Tin Oxide (ITO) which is deposited on a glass or transparent foil. ITO is conductive and optically transparent at the same time. However for increased conductivity, the ITO film thickness has to be increased which has a negative impact on transparency. I.e. thicker, better conductive layers become slightly visible. The sheet resistance of a typical ITO layer is in the range of some hundreds of Ohms/square. Depending on the track layout, the series resistance between a sensing pads and the connector can reach tens of kOhms.

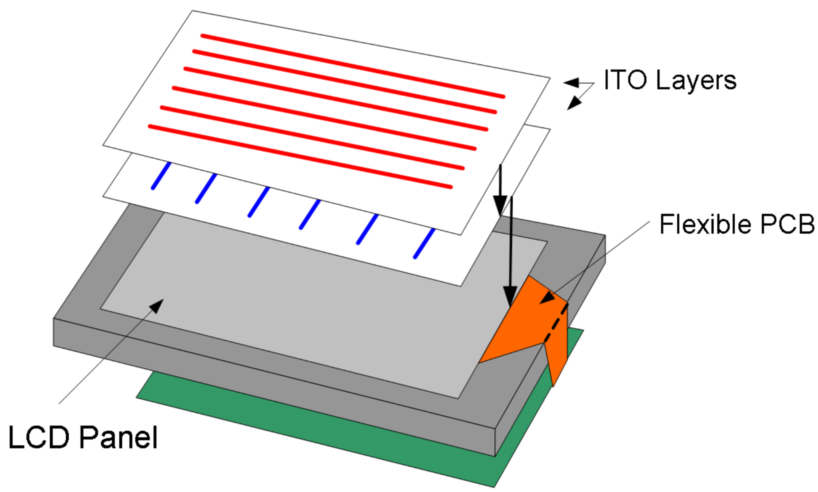


figure 7 Capacitive touch screen with matrix arrangement

For some touch screen applications, several discrete sensing areas on the screen, e.g. 10 or so, are sufficient while for other applications, the position of the finger must be determined in a higher resolution, e.g. 640 x 480 positions or higher. In the 1st case a layout with one ITO layer is sufficient to form the sensing pads. In the 2nd case, two isolated layers ore more are necessary to form a matrix. In such an arrangement one touch activates two channels: one row and one column.
In both cases it is possible to apply interpolation techniques to increase the resolution as described above.
Due to the different requirements, many vendors provide dedicated products for button/slider implementations on one hand and touchscreen applications with high resolution on the other hand.

figure 8 Capacitive touch screen with discrete sensing pads, consisting of one ITO layer

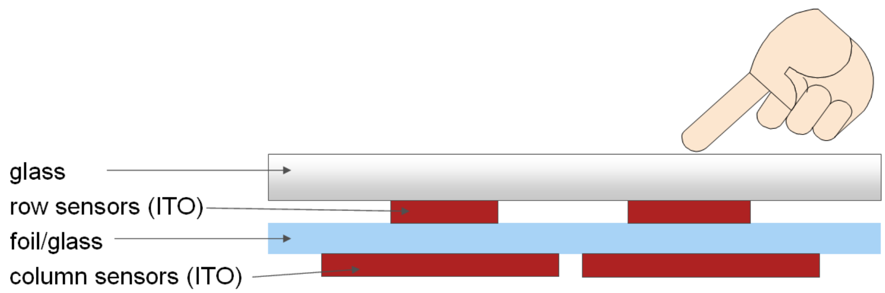


figure 9 High resolution capacitive touch screen with matrix arrangement, consisting of two ITO layers

Resistive touch screens are used for a longer time than capacitive solutions because of the simpler control circuits. Two conductive planes, also made of ITO material, are separated by tiny spacers. The upper layer is deposited on a flexible foil. Pressure leads to a contact between the two conductive layers. In pressed state, the layers form a voltage divider. By evaluating the voltages at this divider, a control circuit determines the position of the contact. In two steps 1st the X and 2nd the Y coordinate is calculated. Resolutions up to 2000 to 4000 steps per dimension are possible.
The major weak point of this approach is the flexible foil. It wears out over time, it is sensitive to physical stress and the optical characteristics are inferior to glass. Frequently used resistive touch screens may look dull after a while and show scratches.
Capacitive touch screens feature a robust glass cover and have a much higher endurance. Thus the surface of a capacitive touch screen looks premium and lasts longer.
A second advantage of capacitive touch screens is the ability to detect multi touches. This opens new applications like scaling or rotating pictures by moving two fingers over the screen.

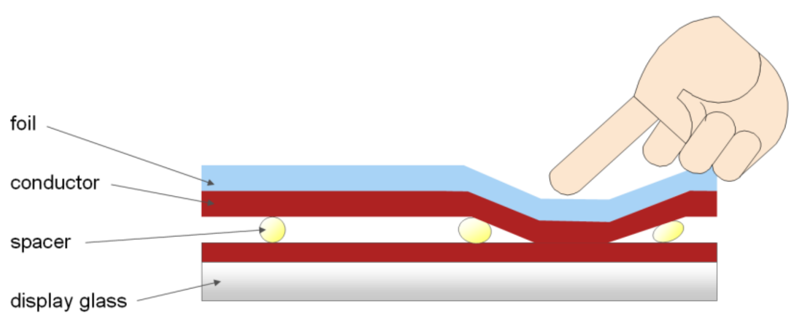


figure 10 Layout of a resistive touch screen with flexible foil as upper layer

Summary

Capacitive touch sensing will become increasingly popular, not only for consumer products but also white goods and industrial applications, for reasons of usability, robustness and cost efficiency. The technology and available products are mature and allow the design of reliable solutions.
The discussed example implementation Fujitsu's FMA1127 is an ASSP with a robust digital capacitive sensing method which offers high performance and easy, fast integration into embedded systems.