Capacitive Sensing 101

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Executive Summary

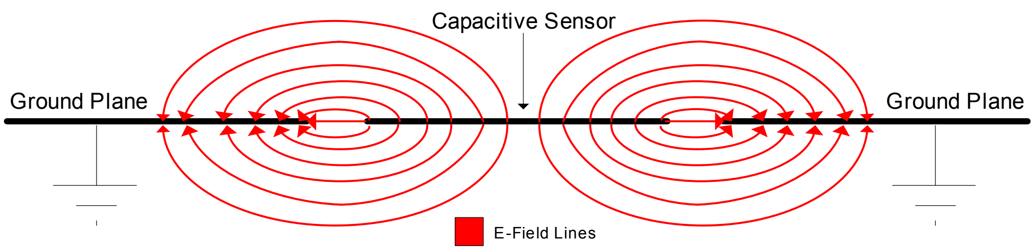
Capacitive Sensing as a human-device interface is becoming increasingly popular. Capacitive sensing can be recognized in many popular consumer products such as laptop trackpads, MP3 players, computer monitors and cell phones, but it is certainly not limited to these applications. More and more engineers choose capacitive sensing for its flexibility, unique human-device interface and cost reduction over mechanical switches.

Designs are likely to experience many different environmental changes, marketing requirement changes and user abuse; choosing a device that is flexible, programmable, and upgradeable is necessary. Without question, the most flexible, programmable and upgradeable device on the market is the Cypress Semiconductor Programmable System on a Chip (PSoC). PSoC is a mixed-signal array which includes analog and digital resources as well as an integrated microcontroller all on the same chip! Choosing a fixed-function device, such as an ASIC, seems like a good idea at first, but overcoming its problems requires spending more money on hardware. A mixed-signal array device allows resolution of most issues with a firmware change. One major advantage of having a flash-based device is that its firmware can be updated after the device has shipped by including a bootloader. Bootloaders are valuable are worth considering on a new design.

Understanding Electric Fields

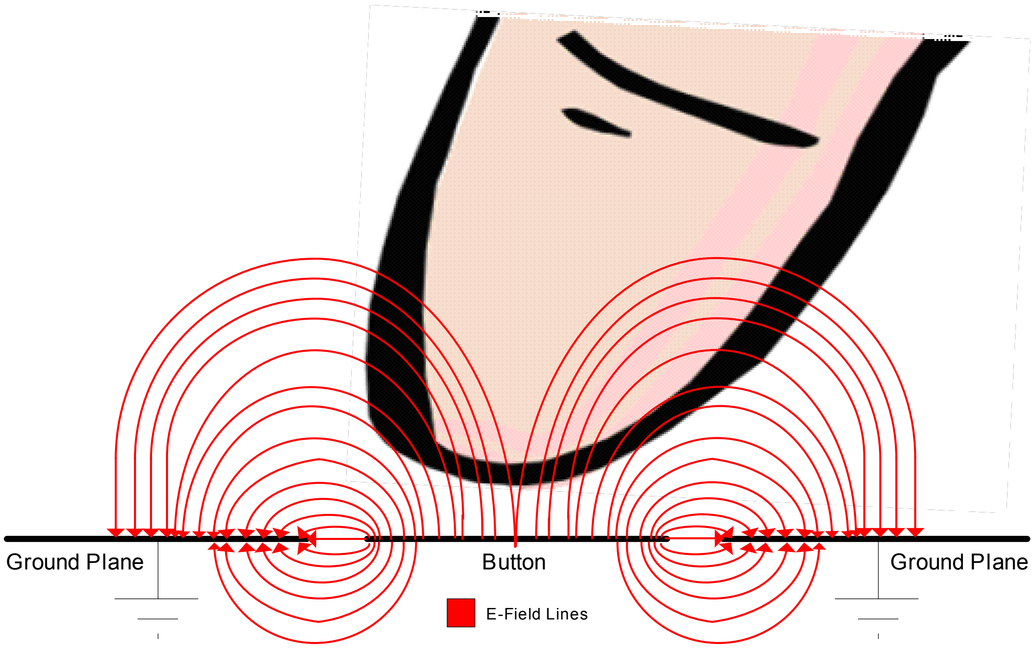
In order to understand capacitive sensing, it is first important to understand some basics about electric fields (E-Fields). It is a fundamental fact that E-Fields take the path of least resistance. *Figure 1* shows a general form of E-Fields in a capacitive sensing design.

Figure 1. E-Fields and Parasitic Capacitance



E-Fields form from the greatest potential to the least potential. *Figure 1* shows E-Field lines from the capacitive sensor to ground. Measuring the capacitance at this point yields the parasitic capacitance. Parasitic capacitance is the capacitance of the sensor, without a conductive object present. *Figure 2* shows the effect of a conductive object in the same system.

Figure 2. E-Fields with a finger present



The conductive object allows an increased number of E-Field lines to travel between the sensor and ground. This greater concentration of E-Field lines results in a greater capacitance measured at the sensor. In human interface devices, the conductive object is typically a human finger, hand, foot, etc.

Measuring a Fixed Capacitance

It is important to understand how to measure a fixed capacitance. One of the most fundamental capacitor equations is shown in *Equation 1*. Differentiating both sides with respect to time, results in *Equation 2*. Since a static capacitance is being measured, $\frac{dC}{dt}$ equals zero and the equation simplifies to *Equation 3*. $\frac{dq}{dt}$ is more commonly called current, i, allowing one final simplification to *Equation 4*. *Equation 4* is another of the most important capacitor equations. Rearranging *Equation 4* yields *Equation 5* which bares a striking resemblance to the formula for a line, y = mx + b. *Figure 3* shows capacitors being charged by a constant current source.

$$q = C * V$$

Equation 1

$$\frac{dq}{dt} = V * \frac{dC}{dt} + C * \frac{dV}{dt}$$

Equation 2

$$\frac{dq}{dt} = C * \frac{dV}{dt}$$

Equation 3

$$i = C * \frac{dV}{dt}$$

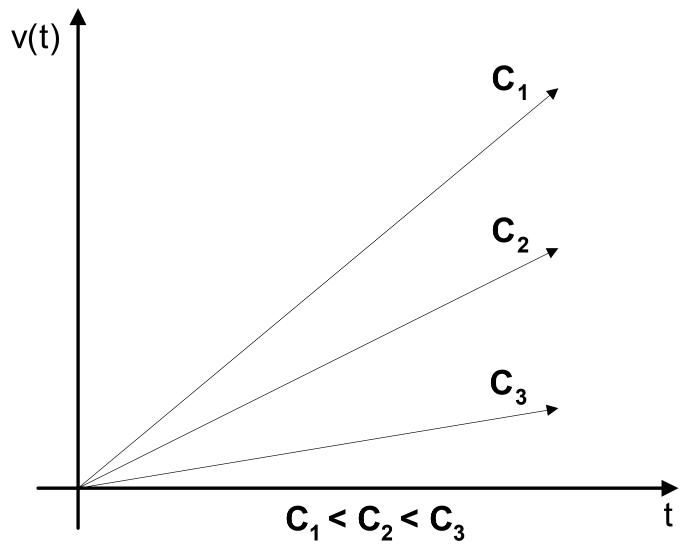
Equation 4

$$v(t) = \frac{i}{C} * t$$

Equation 5

The slope, m, of the line is current divided by capacitance. Applying constant current to the capacitor yields a linear slope. Changing the capacitance and keeping the source current constant causes the slope of the line to change. For the same current, and an increase in capacitance, the slope of the line will become more gradual as shown in *Figure 3*.

Figure 3. Voltage ramp on different capacitors



Measurement Methods

Two measurements are necessary to determine the presence or absence of a conductive object on a sensor: the parasitic capacitance and the capacitance due to the conductive object. Taking *Equation 4* and rearranging it results in *Equation 6*.

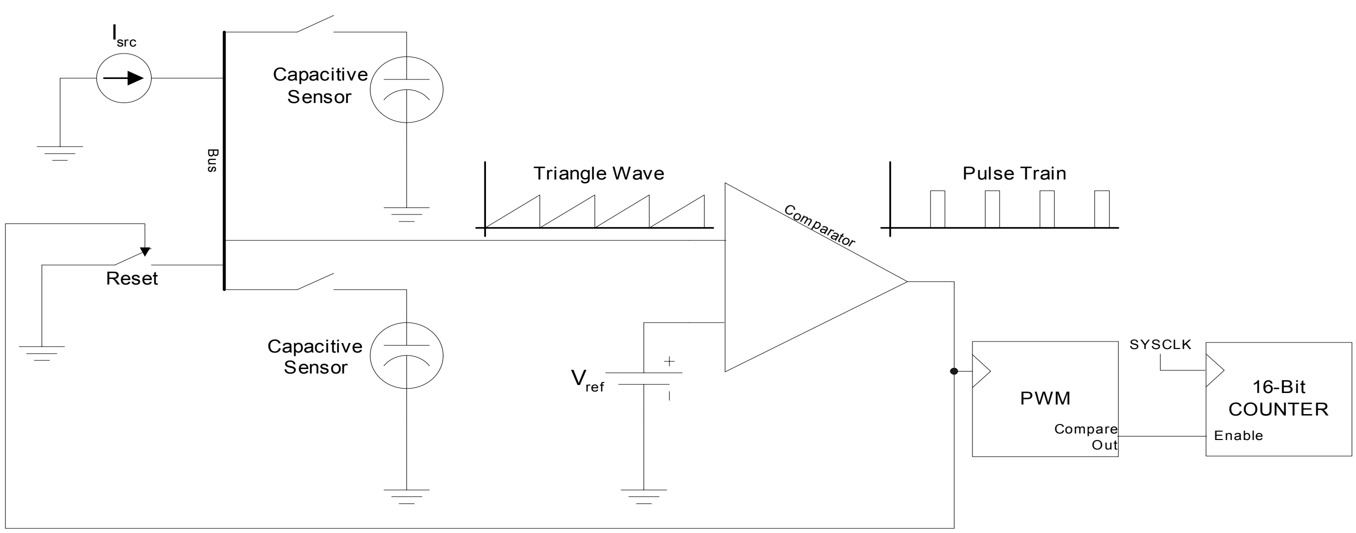
$$C = i * \frac{\Delta t}{\Delta V}$$

Equation 6

If the supply current, i, and the time elapsed, Δt, are known, it is possible to measure the voltage change, ΔV. Once a measurement for ΔV has been made, solving for the capacitance is simple.

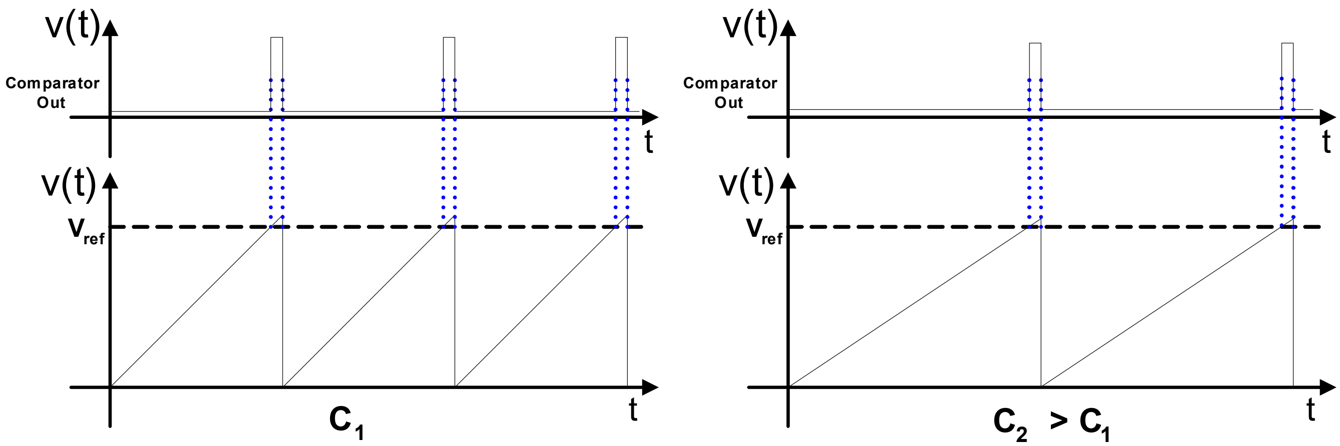
The method utilizing *Equation 6* is simple; a more advanced solution is to use a relaxation oscillator [*Figure 4*].

Figure 4. CapSense Relaxation Oscillator



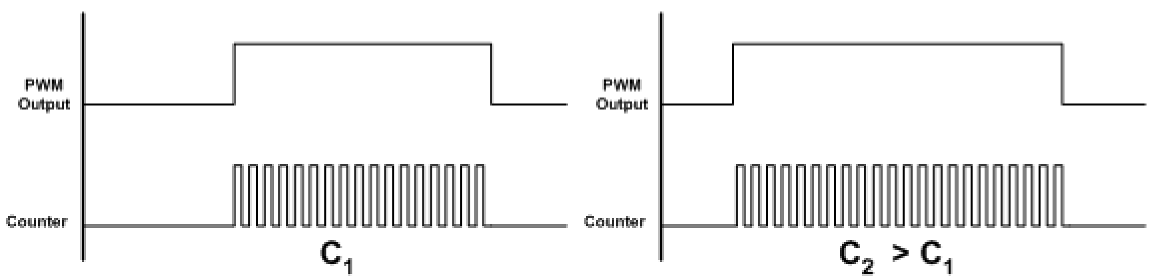
The current source, I_{src}, provides the constant current to charge the capacitor. I_{src} is connected to a bus which allows one or more capacitors to be connected at a time. The reset switch allows the capacitors connected to the bus to be drained. Each capacitive sensor is connected to the bus one at a time. When a sensor is first connected, I_{src} applies constant current to the capacitor to generate the ramp shown in *Figure 3*. Once the voltage reaches a predefined reference level, V_{ref}, the comparator trips and restarts the charging sequence by draining the sensor capacitor to ground. *Figure 5* shows the charging sequence and comparator trip level.

Figure 5. Pulse train frequencies with different capacitors



The pulse train's frequency decreases with a greater capacitance. The pulse train is tied to the clock input of a PWM. For a fixed duty cycle, the PWM is high longer when measuring a greater capacitance. The output of the PWM enables a 16-bit counter. *Figure 6* shows how the PWM enable affects the counter. The counter value is greater for C_2 than C_1.

Figure 6. PWM Enable and Counter



After the PWM disables the counter, the counter value is stored for processing. Now that the counter value has been stored, the circuit has undergone a full analog to digital conversion; the capacitance is stored as a digital value.

Processing the Data

Once the capacitance is stored as a digital value (raw counts), the next step is to process the data. In order for the capacitance value to be meaningful, it must be compared to something else. *Equation 7* shows the capacitance ratio.

$$\Delta C = \frac{C_{conductive}}{C_{parasitic}}$$

Equation 7

The capacitance due to the conductive object, $C_{conductive}$, must be compared to the capacitance occurring naturally in the system, $C_{parasitic}$. In order to keep track of the parasitic capacitance as it changes with time, its measured value is stored in a variable called a baseline. A baseline keeps track of the slow changes in parasitic capacitance due to environmental effects such as temperature changes. A baseline is analogous to analog ground; the baseline does not need to be zero, but it serves as the reference for all capacitive measurements.

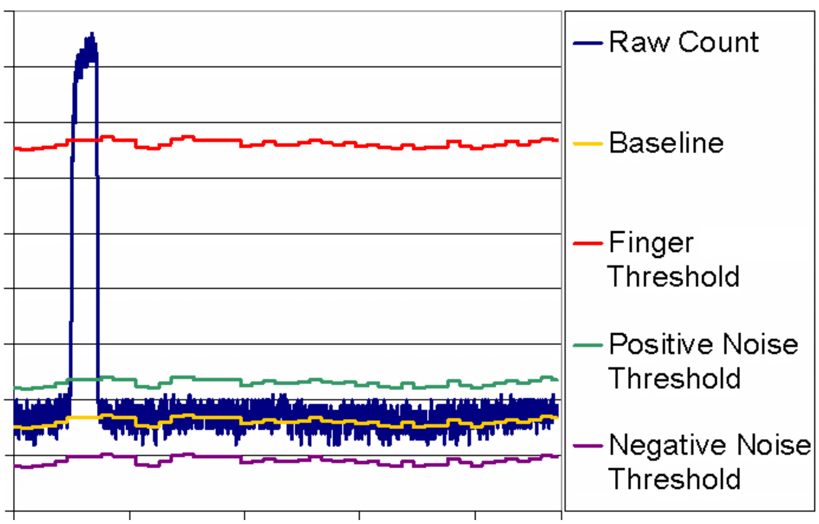
There are multiple methods for storing the measured value into the baseline variable; each method is essentially a low-pass filter. An example is an Infinite Impulse Response (IIR) filter. The IIR filter follows the simple equation shown in *Equation 8*. The CurrentMeasurement variable is equal to the present measured value for the raw counts.

$$Baseline(n) = \frac{3}{4} * Baseline(n-1) + \frac{1}{4} * CurrentMeasurement$$

Equation 8

Once a stable baseline has been established the next step is to define the level at which a finger press will be detected. The best way to detect a finger press is to define two threshold values, one at which the signal is considered to be noise and the other where the signal is considered to be a finger press (or presence of a conductive object). *Figure 7* shows each of the thresholds in a capacitive sensing system. Care should be taken to choose the correct levels of these thresholds as they affect the sensitivity and performance of the system. The thresholds are relative to the baseline. To add hysteresis, detect a finger press when the raw counts break above the finger threshold, and detect the off state when the finger press falls below the noise threshold.

Figure 7. Thresholds in a capacitive sensing system

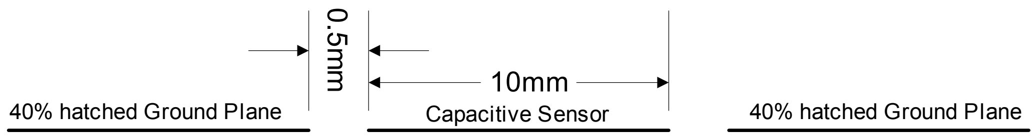


PCB Design Basics

Capacitive sensors can be constructed from many different media, such as copper,ITO and printed ink. Copper capacitive sensors can be implemented on standard FR4 PCBs as well as on flexible material. ITO allows the capacitive sensor to be up to 90% transparent (for single layer solutions).

The size and spacing of the capacitive sensor are both very important to the sensor's performance. *Figure 8* shows the recommended sensor spacing.

Figure 8.



In addition to the size of the sensor, and its spacing relative to the ground plane, the type of ground plane used is very important. Since the parasitic capacitance of the sensor is related to the E-Field's path to ground, it is important to choose a ground plane that limits the concentration of E-Field lines without a conductive object present. *Equation 7*, shows decreasing the parasitic capacitance increases the device's sensitivity (greater ΔC). The recommended ground plane for capacitive sensors is a 40% fill, hatched ground plane. Leave some ground plane intact so that the conductive object is still able to provide a low-resistance path to ground without affecting other circuit elements. For a more detailed description of capacitive sensor layout, please refer to the Cypress Semiconductor Application Note AN2292.

Troubleshooting and Debugging

It is difficult to account for all environmental effects in the initial design phase. There may be some adjustments required for the noise and finger thresholds. Care should be taken to test the system across the full operating temperature range and in noisy environments.

Conclusion

Designing a capacitance sensing system is fairly straightforward. First, pick the type of sensing material (FR4, Flex, ITO, etc). Second, understand the environment the device will operate in. Understand the full operating temperature range, what radio frequencies are present and how the user will interact with the interface. Third, choose an integrated circuit that will be able to handle the demands of a changing environment and is upgradeable. The Cypress Semiconductor Programmable System on a Chip, Mixed Signal Array, is a configurable device which includes royalty-free source code for implementing a capacitive sensing solution. Fourth, do not make compromises with your PCB design that will affect capacitance sensing performance. Make sure to pay attention to the layout guidelines defined in Cypress application note AN2292. Fifth, spend the time to "tune" your system. Make sure the design meets the environment requirements. Finally, be patient while troubleshooting. If you are not familiar with capacitance sensing, take the time to understand it. Cypress Semiconductor makes several capacitive sensing evaluation boards, such as the CY3212 and CY3214. Cypress also provides free source code examples that ship with these evaluation kits. To view the source code online, please visit http://www.cypress.com/capsense/ and click on the "Applications" link.

References

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