Capacitive Sensing Techniques and Considerations

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Executive Summary

Capacitive sensing is emerging as a popular interfacing alternative to switches and knobs in consumer electronics and front panel display applications. For example, the iPod uses capacitive sensing to create a more flexible and intuitive interface than is possible with buttons alone. However, while there are a vast number of ways in which engineers can design with capacitive sensing to create innovative interfaces, engineers must also understand the many ways the underlying technology can be manipulated to maximize sensitivity, accuracy, and responsiveness of the sensors. This article will discuss, in detail, many of the sensing methodologies that transform sensor output into useful data that can be used to determine how a user is interacting with a device. The article will discusses strengths, weaknesses, and implementations of established sensing techniques such as E-field Sensing, Charge Transfer, Force-Sensing Resistor (FSR), Relaxation Oscillator, Capacitance-to-Digital Conversion (CDC), and Dual-Ramp. It will also introduce two new sensing methodologies, Successive Approximation and Sigma-Delta Modulator.

Capacitive sensing as a user input medium is no longer a fringe technology employed on select products. It is now a mature technology employed in thousands of products and millions of units. Significant development has taken place (and continues) as design houses, module manufactures and semiconductor companies all vie for a larger share of the rapidly expanding market and position themselves as a leader in the field. At the heart of this development are the sensing methods themselves, the process by which capacitance is measured and converted into digital values that can be processed, manipulated and interpreted. Charge Transfer, Successive Approximation, Sigma-Delta, and Mutual Capacitance Measurement are the most commonly used sensing methods. Each is described here.

The Problem

Sensing capacitance change from 10pF to 100pF is not difficult. Sensing capacitance change from 10.0pF and 10.5pF is not trivial but does not present significant challenges. Sensing capacitance change from 10.00pF to 10.05pF is quite challenging, especially when doing so in the presence of environmental changes, system-level electromagnetic interference and measurement control circuitry variance. Challenges may be even more severe when also considering power consumption, response time, and usability.

The measured element in capacitive sensing applications is a capacitor formed between a sensor pad (an area of conductive material) and surrounding conductive material, which is typically a ground fill of some density and distance. The capacitance value of a sensor is given by:

$$C = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot A}{d}$$

Where A is the complete area of the entire sensor and associated routing and d is the distance between the sensor/routing and the surrounding conductors. As conductive objects (such as a finger) move in proximity to the sensor, they alter the electrical field lines of the capacitive sensor and change the capacitance that is measured by the control circuitry.

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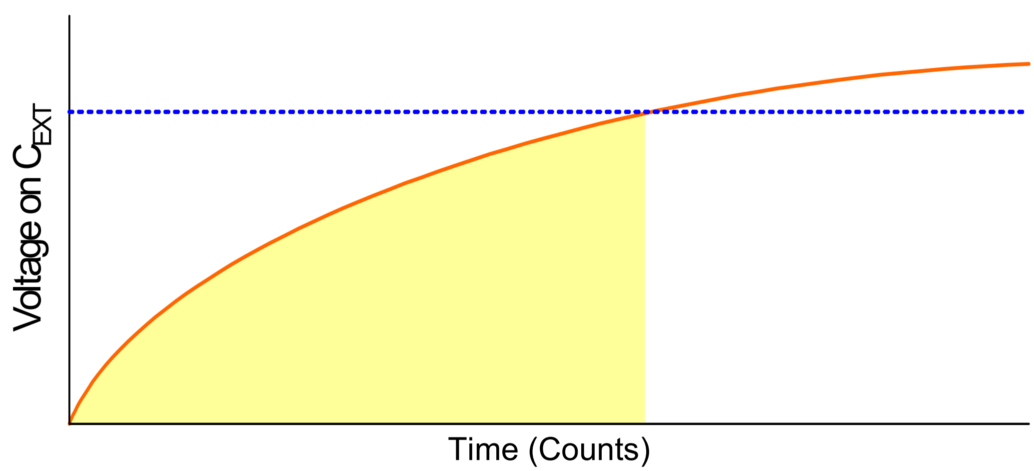
Charge Transfer

Charge Transfer is one category of capacitive sensing using charge amplification and filtering to measure the sum of all the individual charge contributors around a given sensor. A waveform is generated and converted to a representative capacitance value through a combination of timing and filtering means.

Charge Transfer is not a term specific to capacitive sensing. It refers to the transfer of charge from one location to another through a series of switches. This same technique is used in MEMS for physical measurements. Charge Transfer for capacitive sensing uses a switched capacitor network to accumulate charge onto an integrating capacitor. The potential across the integrating capacitor is then measured against a reference voltage or read using an analog-to-digital converter.

In the first of two non-overlapping phases, a sensor capacitor is connected to a voltage source, accumulating charge on that sensor capacitor. In the second phase, the charge that is stored on the sensor capacitor is discharged into the larger integrating capacitor. This process is then repeated a number of times, thereby increasing the voltage on the integrating capacitor. The amount of charge that is transferred to the integrating capacitor in each subsequent phase two cycle decreases exponentially. The sensing circuitry is a simple structure where the voltage across the integrating capacitor is compared to a fixed reference voltage.

Charge Integration with Constant Switched-Capacitor Voltage



When the reference voltage is reached, the time or the number of transfer steps to reach that voltage is measured. The output is inversely proportional to the size of the sensor capacitor. Larger sensor capacitors charge the integration circuit faster and require fewer switching operations to reach the threshold voltage.

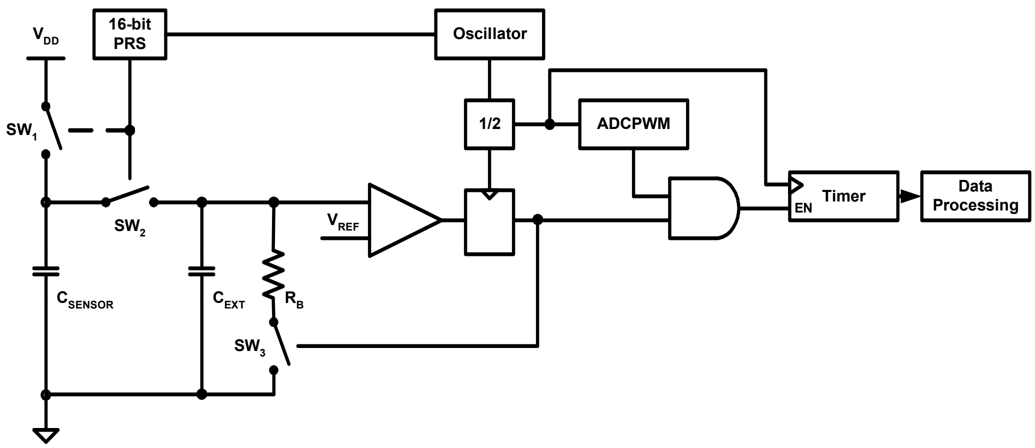
Alternatively, one can replace the comparator with an analog-to-digital converter. In this construction, charge from the sensor capacitor is transferred to the integration capacitor for a prescribed number of cycles. After this number of cycles is completed, the voltage on the integration capacitor is measured and the output of the ADC is proportional to the size of the sensor capacitor.

This sensing method is fairly robust and has a comparatively high signal to noise ratio. However, the implementation of charge transfer in existing capacitive sensing ICs is not without its drawbacks. Most capacitive sensing devices on the market today do not include multiplexing circuitry. The lack of such circuitry means additional pins, resistors and capacitors are required for sensing and tuning of sensitivity for each sensor element. The reference voltage must be created with external components (resistors). Additionally, existing Charge Transfer devices require high-quality dedicated voltage regulators to ensure a clean supply voltage for noise immune and error-free switched capacitor operation.

Sigma-Delta Modulation

Sigma-Delta Modulation also uses a switched capacitor network to charge a large “bus-modification” capacitor. In this topology, however, the external capacitor is not charged from an initial voltage to a reference. Rather, the voltage across the external capacitor is modulated about the reference voltage in charge up and charge down steps. The duration of these steps is compared relative to each other by looking at a comparator bit-stream density. If the density is high enough, the sensor is read as “on.”

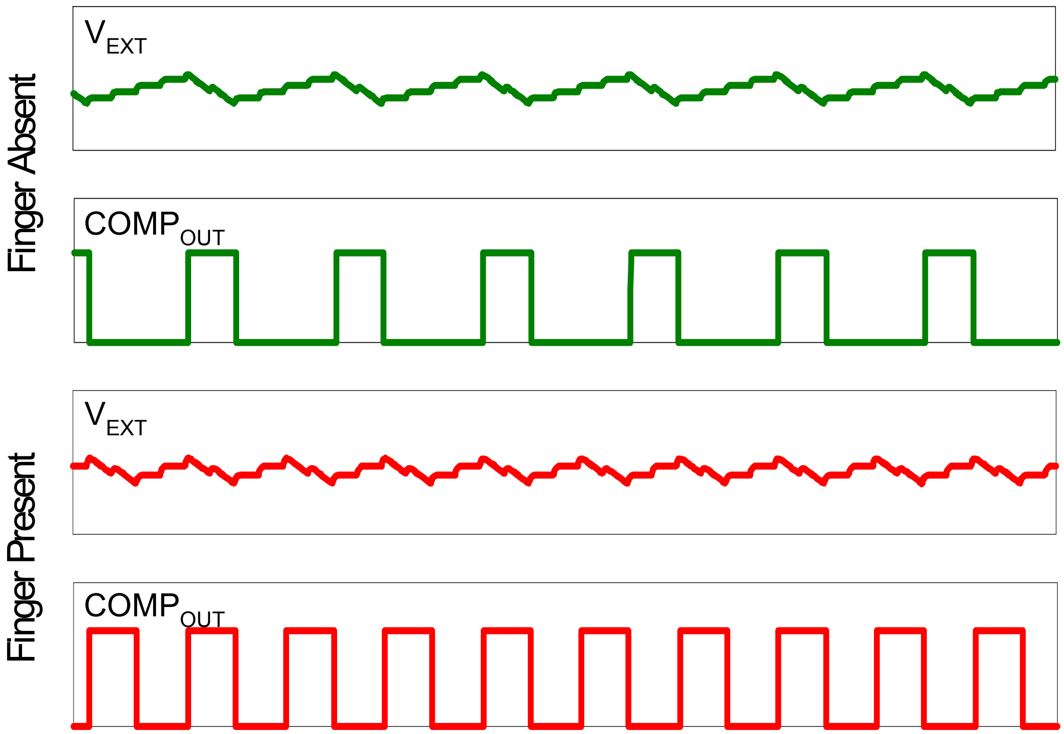
CSD Block Diagram



The sensor capacitor serves as a switched capacitor resistor equivalent to the analog input, which is attached to a large external capacitor often through internal circuitry. As the charge in the external capacitor increases, so does the voltage across it. This voltage is also one input of a comparator. When the input of the comparator reaches the threshold voltage, a discharge circuit (resistor to ground) is connected and charge is bled off of the external capacitor at a rate determined by the starting voltage across the capacitor and the bleed resistor value. As the voltage across the external capacitor decreases, it again passes the threshold voltage and the resistor to ground is disconnected. The voltage across the external capacitor increases again and the cycle is repeated.

The charge/discharge cycle of the external capacitor is manifested as a bit stream on the comparator output. This bitstream is ‘ANDed’ with a pulse-width modulator to enable a timer. The timer output is used for processing the level of capacitance change and determining the sensor activation state.

Comparator Input/Output Waveforms



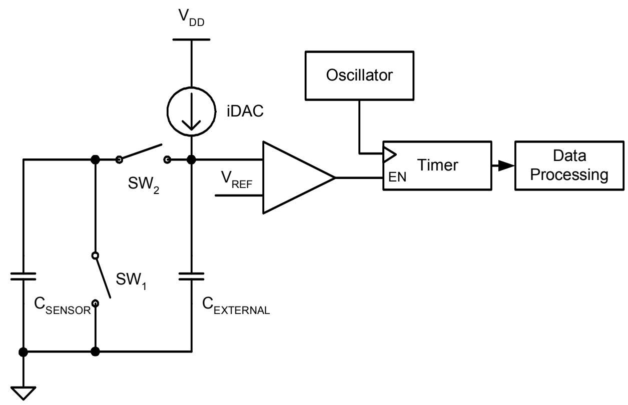
An added benefit of this example of the Sigma-Delta Modulation sensing method is pseudo-random control of the switched-capacitor network. A pseudo-random sequence generator (PRS) – rather than a fixed-frequency clock – can be used to clock the switched-capacitor network. This reduces the electromagnetic inference susceptibility and radiated emissions of capacitive sensing circuits, particularly useful in automotive, white goods and industrial applications. The PRS does increase the time necessary for scanning individual sensors, limiting its usefulness in high-speed applications.

The size of the external bus-modification capacitor can be tuned to further improve the noise resistance of the measurement circuit. In fact, an external capacitor may not be required in some instances, but if the bus capacitance is low enough and the input impedance high enough, the circuit may experience electromagnetic interference that disrupts normal operation. While larger capacitance values will improve the overlay noise performance, they can limit the sensitivity or increase the scan time to a point where the external capacitor size becomes prohibitive. Cypress Semiconductor discusses design guidelines for external capacitor values in the applications notes and reference code descriptions.

Successive Approximation with Single-Slope ADC

Capacitive sensing with Successive Approximation and a Single-slope ADC uses a similar switched-capacitor network to the two previously described sensing methods. A current DAC (iDAC) is connected to the bus with the external capacitor and the switched capacitor network to charge the external capacitor and comparator input to a threshold voltage. The time necessary to charge the external capacitor to the threshold voltage is measured and compared to a stored value to determine sensor activation state and level.

CSA Block Diagram

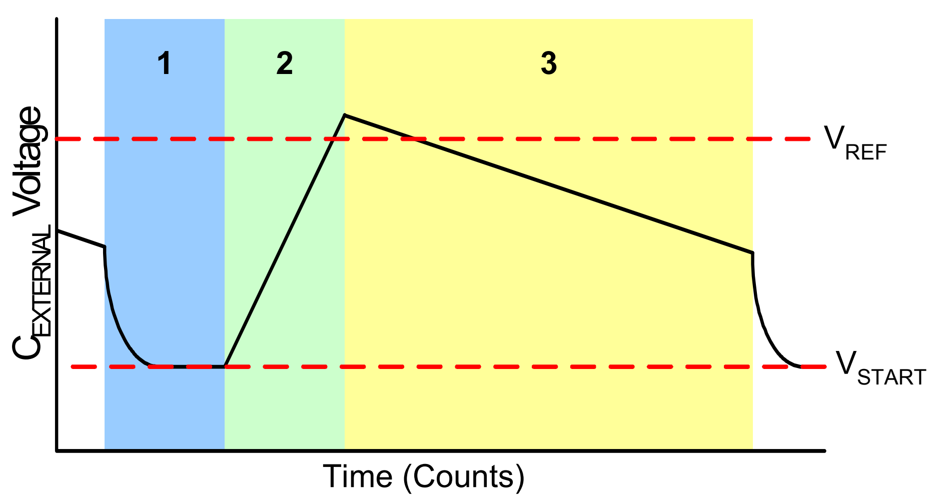


Successive approximation is used to determine the correct iDAC value to maintain a voltage on the external capacitor while the switched-capacitor equivalent resistance discharges the external capacitor to ground. This value is stored and used as the charge current for a single-slope ADC. The switched-capacitor circuit runs as the iDAC charges the bus (Phase 1). The result is a start voltage for the single slope ADC that is dependent on the size of the sensor capacitor from the switched-capacitor circuit.

$$V_{start} = \frac{1}{f \cdot C_X} \cdot iDAC$$

The switched capacitor is then disconnected from the bus and the external capacitor is charged from Vstart (Phase 2). Lower starting voltages lead to longer charge times as the same current from the iDAC flows into the external capacitor and increases the voltage at the same rate.

Charging Figure



Voltage on the external capacitor is then reduced through a low-pass filter in series with the capacitor network to the input of the comparator. This time is used by the control circuitry to process the data and make decisions based on the capacitive inputs. The change in counts from a single scan to a stored value is calculated during Phase 3. If the change is large enough, a sensor activation is determined.

The Successive Approximation sensing method as it is achieved in available circuitry requires the fewest number of external components; a single capacitor is used in most applications and may not be necessary depending on the application needs. The internal capacitance of the bus to which the comparator, iDAC and sensor capacitor are attached is may be enough to achieve the required level of noise immunity. Additionally, the Successive Approximation sensing method is not affected by power-supply transients as the switched-capacitor is an equivalent resistor to ground and the iDAC is sourced from internal references, not directly by VDD. Devices that implement Successive Approximation are limited with reqard to extra-capacitive sensing capabilities. They are optimized for capacitive sensing, but are capable of basic digital functions such as LED control.. Successive Approximation is being made available in more universally capable devices and devices with more program memory, analog and digital function, and higher I/O counts.

Compensation

It is imperative that any capacitive sensing implementation account for system-level variance and interference due to temperature, humidity, electrostatic discharge (ESD) and other stimuli. Stresses such as temperature change and humidity have gradual effects on the system and must tracked to ensure that changes in the control circuitry performance with regard to temperature are taken into account as well as the changes in capacitance of the system. As materials increase in temperature, they expand, increasing both A and d in the equation for capacitance. Additionally, the dielectric constant for the sensing overlay and substrate are temperature dependent. As stated previously, such changes are gradual. In many cases it takes minutes to change the system temperature a single degree. Minutes equates to thousands of scans in any of the described sensing methods. This allows the control circuitry to respond to changes in such a way that no perceivable difference is present to the user or the host controller.

Events such as ESD have more dramatic, yet brief, impacts on a capacitive sensing system. If the device hardware is designed properly, these impacts disappear after only a few scans and can be ignored through detection algorithms designed to recognize the particular and repeatable signature of an ESD event.

Devices such as Cypress's Programmable System-on-a-Chip (PSoC®) allow designers control over most parameters of the compensation to find a balance between the system's ability to respond to changing environments and the usability requirements for the product.

Capacitive Sensing continues to evolve and the sensing methods described here are not the final word in sensing methods. New ideas are being tested all the time as designers seek to lower power consumption, increase sensitivity, decrease scan times and deal with ever more harsh environments.

References

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