ECE Senior Capstone Project 2020 Tech Notes

Capacitive Sensors: How do they work and what can they do?

Fall Prediction Using Anomaly Detection

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Introduction

The capacitor is one of the fundamental building blocks of circuit design due to its ability to store and discharge energy through its electric field. In addition to its energy storage capabilities, the capacitor can also be used to measure a variety of physical quantities. These capacitive sensors, also known as transducers, have gained popularity over the past 20 years due to their high sensitivity and low power consumption (Nei, Bao, & Huang, 2015).

The first half of the tech note examines how different sensors use the properties of the capacitor, such as the dielectric material, the plate distance, and the plate area, to gain information about the environment. Several applications are discussed, including pressure and humidity sensors. The latter half of the paper explores some of the methods used to measure capacitance values so that they can be processed on a digital system. These include both classic techniques, such as measuring the decay of an RC circuit, as well as some modern ones, like using a Σ-Δ convertor.

Capacitor Background

By definition, a capacitor is simply two separated conductive surfaces that generate an electric field when a voltage is applied. The behavior of a capacitor is mainly characterized by its geometry. As a result, capacitors come in a variety of shapes as seen in *Figure 1*. The equation to calculate the capacitance of a capacitor is $C = \varepsilon_r \varepsilon_0 \frac{A}{d}$, where ε_0 is the permittivity of free space, ε_r is the permittivity of the space between the plates, A is the overlapping area of the plates, and d is the separation distance (Avnet, n.d.). The first of these values is a constant, while the other three are chosen by the designer to achieve a desired capacitance. In most cases, once a capacitor is manufactured, these parameters do not change. Capacitive sensors, on the other hand, take advantage of this dependence on geometry to make capacitors whose characteristics vary in response to physical stimulus.

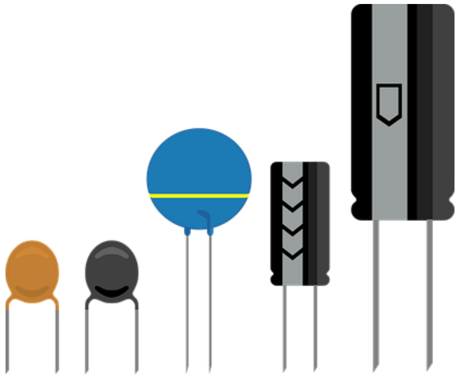

Figure 1. An assortment of different capacitors

Applications

Touch Screen

One of the most common applications is the capacitive touch sensor used in touchscreens. Beneath the part of the screen where the user is supposed to touch, there are two plates that form a capacitor as seen in *Figure 2*. When a finger is brought close to the screen, it enters the electric field of the capacitor and thus influences its dielectric characteristics. Since the human body is composed mainly of water, the finger has nearly 80 times the relative permittivity of the air that it displaced. As a result, the capacitance of the device increases as the finger gets closer to the screen. Once the capacitance exceeds a set threshold, the screen is registered as having been touched (Keim, 2016a).

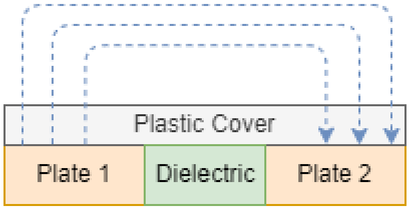

Figure 2. Touchscreen layout

Capacitive Transducer

Another class of capacitive sensors are those that change the distance between the plates. For these sensors, one of the plates is held in place while the other moves freely. The dielectric between the plates is typically a flexible material, so when a force is applied to the movable plate, the distance between plates decreases resulting in an increase in capacitance. These sensors are useful for making measurements of pressure since the change in capacitance can be mapped to the force being applied to the moveable plate.

Humidity Sensor

In addition to the touchscreen, there are a few other capacitive sensors that use changes in permittivity to affect capacitance. One of which is the capacitive humidity sensor, which uses hygroscopic material as the dielectric between the plates (Rotronic, n.d.). This material absorbs moisture from the air which causes its permittivity to go up, therefore, increasing the capacitance. This change in capacitance is then used as a measure of the humidity. Other types of sensors use a similar idea to detect the level of a specific gas, such as hydrogen, in an area (Bindra & Hazra, 2018).

Measurements

Time Constant

However, the capacitance of the sensor is not much use unless the system can measure it. There are several ways to go about doing this, the most direct one being to place a resistor in parallel with the sensor to create an RC circuit. This circuit can then be connected to a microcontroller, which repeatedly applies a voltage to charge the capacitor and then allows it to discharge. The microcontroller can calculate the RC time constant by measuring the amount of time it takes for the capacitor to reach 63% of the applied voltage when charging. From there, dividing by the resistance yields the capacitance of the sensor.

Oscillator

Another approach is to use the capacitive sensor as part of a standard RC oscillator. The frequency of the oscillator is calculated as: $f = \frac{1}{2\pi RC\sqrt{2}}$. Therefore, by having a microcontroller count the number of pulses that elapse over a period, the frequency can be calculated, which in turn leads to a measure of the capacitance

Downsides

While these strategies are straightforward, they both require a circuit for conversion from capacitance to voltage, which is then sampled by an analog-to-digital converter (ADC). The downside is that the location where the sensor goes is usually space restricted, so the conversion circuit must be placed further away. The parasitic capacitance that results from the longer connections then begins to degrade the accuracy of the sensor (Brychta, 2005).

CDC

What is it?

To avoid these issues, designs in industry use a more compact architecture known as a capacitance-to-digital converter (CDC). The main component behind the CDC is known as the Σ-Δ convertor (EDN, 2006). This converter uses oversampling and noise shaping to achieve high accuracy analog-to-digital quantization (Smith 2016).

Oversampling

In any ADC, the noise floor is set by the amount of quantization error. The signal-to-quantization-noise ratio (SQNR) is calculated in dB as $SQNR = 1.76 + 6.02N$ where N represents the number of bits used for quantization. One obvious way to improve the SQNR is to increase the number of bits, however, another more efficient way is to sample the signal at a rate higher than twice the highest frequency. Since the number of bits does not change, the SQNR remains the same, so the total noise power must be the same. However, now that the frequency band is wider, the noise in each frequency bin is reduced so that the total noise power does not change. Therefore, the noise in the region up to the Nyquist frequency is less than what it was before oversampling. So by applying a digital lowpass filter and downsampling, the SQNR is improved without needing extra bits.

Noise Shaping

To further improve the SQNR, the Σ-Δ convertor uses noise shaping in conjunction with oversampling (Smith 2016). By applying noise shaping, the noise power going from being equally distributed among all frequencies to having high power at higher frequencies and low power at lower frequencies. Since the signal is going to be lowpass filtered and downsampled anyways, the SQNR will benefit.

Architecture

The basic architecture of the Σ-Δ convertor can be seen in *Figure 3*.

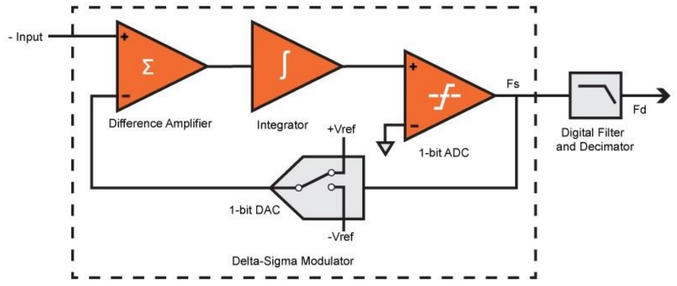

Figure 3. CDC Architecture

The system is composed of a difference amplifier, an integrator, a comparator that acts as a 1-bit analog-to-digital convertor (ADC), and a 1-bit digital-to-analog convertor (DAC). The comparator outputs *1* if the input is greater than *0*, otherwise it outputs *0*. The DAC outputs either a positive or negative reference voltage based on whether the input is *1* or *0*. The system takes the input voltage and sums it with the output of the DAC. This sum is then integrated and passed to the ADC, which returns a bit value. The purpose of the feedback loop is to keep the output of the integrator around 0 (EDN, 2006). After several iterations, the ratio of 1's to the number of bits in the output approaches the ratio of the input voltage to the voltage scale provided by the positive and negative reference voltages. This architecture implements the oversampling and the noise shaping that reduces the SQNR.

Comparison to Σ-Δ

The CDC architecture is almost identical to that of the Σ-Δ convertor and works in very much the same way. The main difference being that in the Σ-Δ system, the circuitry has three constant values which are a reference capacitance, an input capacitance, and a reference voltage (Scarlett, 2014). This leads to the output bitstream representing a ratio between the input voltage and the reference voltage. The CDC is the same, except the input voltage is replaced with an excitation signal which oscillates at a constant rate while the input capacitance varies. The resulting output bitstream now represents a ratio between the input capacitance and the reference capacitance (Brychta, 2005). Since these CDCs are industry standard, manufacturers sell them as systems on a chip, an example being the AD7142 from Analog Devices (Analog Devices, n.d.).

Conclusion

Capacitive sensors are versatile systems which can be designed to measure several different quantities. Their low cost and high sensitivity, when combined with the efficiency of the CDC, make them a popular choice in many designs. In our senior capstone project, we fabricated our own set of capacitance transducers to go in the insole of a shoe. These sensors allowed us to measure the pressure applied by the user when they walked, allowing us to extrapolate data about their walking pattern and their risk of fall. The CDC was a crucial part of reading the measurements from the capacitive sensors quickly and accurately.

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