AN367

UNDERSTANDING CAPACITIVE SENSING SIGNAL TO NOISE RATIOS AND SETTING RELIABLE THRESHOLDS

1. Introduction

This application note is written to assist embedded designers as they create and compare the performance of capacitive sensing systems. These systems require a thorough understanding of signal, noise, and threshold levels to insure proper operational conditions of the end product.

1.1. Definition of Terms

- ***INACTIVE***: a capacitive sensor switch state that occurs when the intended conductive object is not nearby. ***INACTIVE*** mode is often referred to as off, idle, or baseline; however, baseline is not explicitly a state.
- ***ACTIVE***: a capacitive sensor switch state that occurs when the intended conductive object is within the desired activation range.
- **Signal-to-Noise Ratio (SNR)**: a quality measure of desired signal level divided by undesired noise.
- **Threshold**: a system configuration set point that allows a change in parametric state when crossed by a signal of interest.
- ***INACTIVE*-to-*ACTIVE* Threshold**: a user defined trigger level for changing the state of a switch from ***INACTIVE*** to ***ACTIVE***.
- ***ACTIVE*-to-*INACTIVE* Threshold**: a user defined trigger level for changing the state of a switch from ***ACTIVE*** to ***INACTIVE***.
- **Safe Zone**: a region between the ***ACTIVE*** and ***INACTIVE*** noise bands where switch thresholds may be set without fear of false threshold activation or sluggish switch response.
- **Hysteresis**: a system stabilization method provided through a combination of two thresholds that, after the initial crossing, requires both thresholds to be crossed to trigger a change in parametric state.

2. Calculating Simple SNR

Signal-to-Noise Ratio is a quality metric that provides the developer with a rough measure of the likelihood of false switching and a means of comparing the relative performance of various implementations.

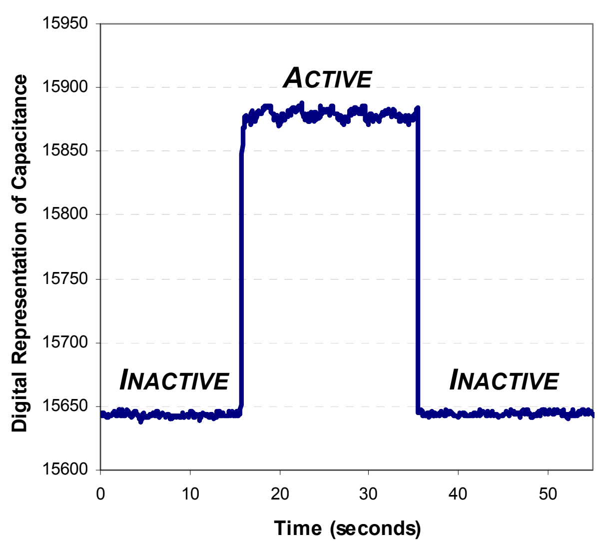

Figure 1. Typical Capacitive Sensor Output

The graph in Figure 1 illustrates a typical capacitive sensor output. The vertical axis is the measured digital representation (counts) of the capacitance of the sensor versus time. The distinct rise in the waveform indicates the presence of a conductive object near the capacitive sensor. The relative change in digital counts from ***INACTIVE*** to ***ACTIVE*** is the 'signal'. The 'noise' riding on the ***INACTIVE*** and ***ACTIVE*** levels in the sensing system comes from many sources.

The traditional approach to calculating SNR is to measure the average ***ACTIVE*** level, subtract the average ***INACTIVE*** level, and divide that result by the peak level of noise witnessed on the ***INACTIVE*** level. This can be measured in digital counts or capacitance.

$$SNR = \frac{[Avg_A - Avg_I]}{Noise_I}$$

An example using digital counts:

$$SNR = \frac{[15878 - 15643]}{10} = 23.5$$

While this measure is sufficient for comparing the relative sensing quality of one implementation to another, the result of this calculation should not be used to set and maintain thresholds. The simple SNR calculation ignores the ***ACTIVE*** mode noise impact and the trigger thresholds.

3. The Impact of Noise

In a capacitive sensing system, the embedded designer needs to be prepared to protect the product from false switching. Measuring the signal and setting thresholds seems straightforward; however, it is not as simple as it appears. The first line of defense against false triggering is to understand the level of noise relative to the level of signal and the chosen thresholds.

3.1. Measuring Noise

Measuring the noise is a simple process of accumulating samples in both ***INACTIVE*** and ***ACTIVE*** states, determining the two averages, and calculating the respective standard deviations for every sensing element. The suggested sample size is at least 1000 for calculating the standard deviation in capacitive sensing systems. It is not unusual for the ***ACTIVE*** mode noise to exceed the ***INACTIVE*** mode noise as the human body often introduces AC line noise into the capacitive sensor. The ***INACTIVE*** mode data is generally a normal (Gaussian) distribution. In typical systems, the ***ACTIVE*** mode noise is also sufficiently normal for sensor margin calculation purposes.

A histogram provides the most meaningful illustration of the ***ACTIVE*** and ***INACTIVE*** variation. An example is provided in Figure 2.

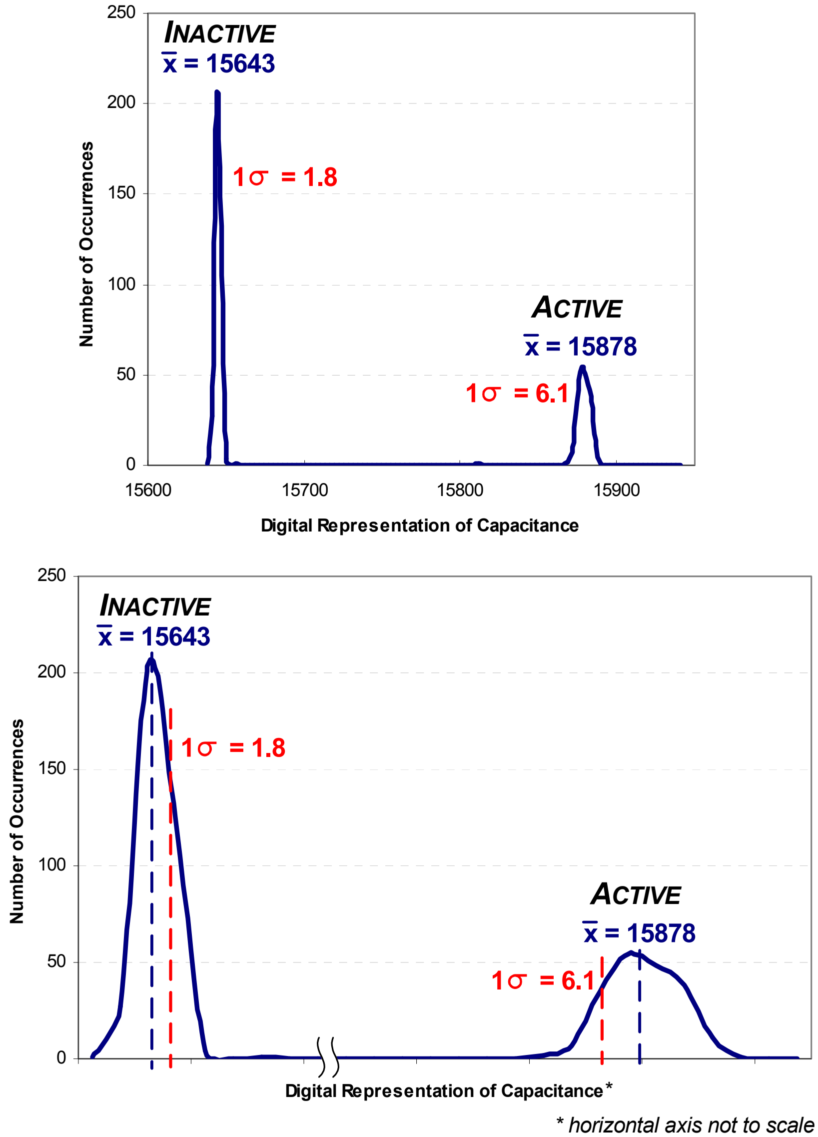

Figure 2. Histogram of Typical Capacitive Sensor Output

In cases where the data is not normal, the contributing noise factors should be investigated and, if possible, corrected. Non-normal ***ACTIVE*** noise is often due to signal variation caused by minute changes in the location or pressure of the conductive object. Alternatively, if the noise is too non-normal, the embedded designer may choose to measure the peak noise level over a very large number of samples. The thresholds should be sufficiently separated from the measured peak noise to protect from false switching.

4. Threshold Recommendations

Setting sensing level thresholds is an important task. Choosing a single threshold for both ***ACTIVE*** and ***INACTIVE*** switching may cause unwanted instability if the signal hovers near the threshold. For this reason, it is suggested that hysteresis be implemented with dual thresholds. Since not all capacitive sensing devices are capable of dual thresholds, some single threshold devices can provide similar results by dynamically adjusting the threshold.

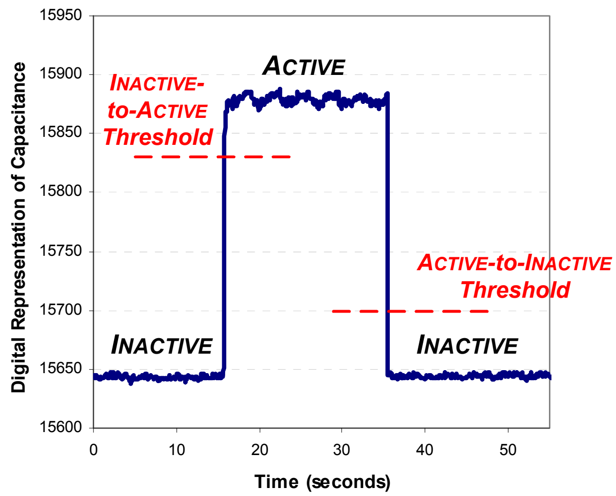

Figure 3. Typical Capacitive Sensor Output with Thresholds

Referring to the two thresholds as upper and lower should be avoided as some applications may require an ***ACTIVE***-to-***INACTIVE*** Threshold that is higher than the ***INACTIVE***-to-***ACTIVE*** for product safety reasons. For example, a laser product that is enabled only when in contact with human skin requires the ***ACTIVE***-to-***INACTIVE*** Threshold to be higher on the vertical axis than the ***INACTIVE***-to-***ACTIVE*** Threshold. Without hysteresis, the region between the two thresholds would be an undefined state where the laser could be either on or off.

A histogram serves as a more meaningful illustration of setting thresholds away from the ***ACTIVE*** and ***INACTIVE*** noise distributions. However, a histogram does not portray the inherent hysteresis of the switch as clearly as other representations.

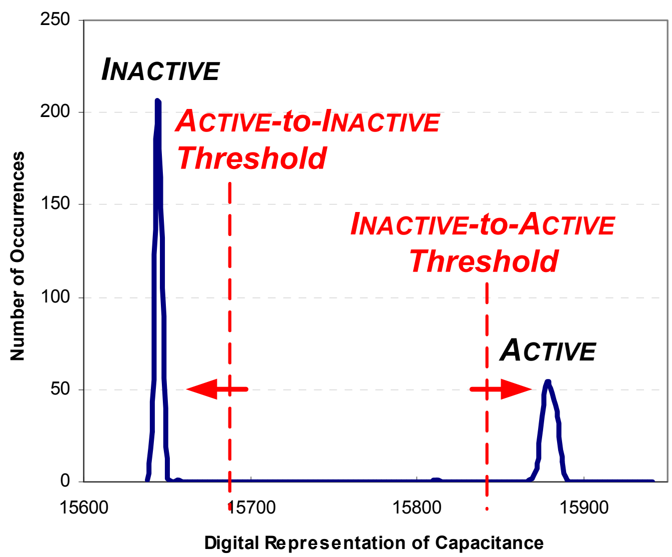

Figure 4. Histogram of Typical Capacitive Sensor Output with Thresholds

Setting thresholds is an important step in the development process. Determining the ***INACTIVE***-to-***ACTIVE*** Threshold is a compromise between avoiding ***INACTIVE*** state noise from triggering a false ***ACTIVE*** and responding too sluggishly to true ***ACTIVE*** signals. Threshold setting is highly dependent upon the application; the following procedures are recommended as starting points for identifying threshold levels.

4.1. Determining *INACTIVE*-to-*ACTIVE* Threshold

The ***INACTIVE***-to-***ACTIVE*** Safe Zone is a range from 3.3 standard deviations of noise above the ***INACTIVE*** average to 1 standard deviation of noise below the ***ACTIVE*** average. With the Safe Zone identified, set the ***INACTIVE***-to-***ACTIVE*** Threshold to 75% away from the ***INACTIVE*** edge of the safe zone.

In equation form:

$$\mathrm{SafeZone}_{\mathrm{ItoA}} = (\mathrm{Avg}_A - \sigma_A) - (\mathrm{Avg}_I + 3.3 \times \sigma_I)$$

$$\mathrm{InitialThreshold}_{\mathrm{ItoA}} = (0.75 \times \mathrm{SafeZone}_{\mathrm{ItoA}}) + \mathrm{Avg}_I$$

As an example, the ***INACTIVE*** average from the data in Figure 1 is 15643, the ***ACTIVE*** average is 15878, the ***INACTIVE*** standard deviation is 1.8, and the ***ACTIVE*** standard deviation is 6.1. Using the equations above, the ***INACTIVE***-to-***ACTIVE*** Safe Zone is:

$$\mathrm{SafeZone}_{\mathrm{ItoA}} = (15878 - 6.1) - (15643 + 3.3 \times 1.8) = 222$$

$$\mathrm{InitialThreshold}_{\mathrm{ItoA}} = (0.75 \times 222) + 15643 = 15809$$

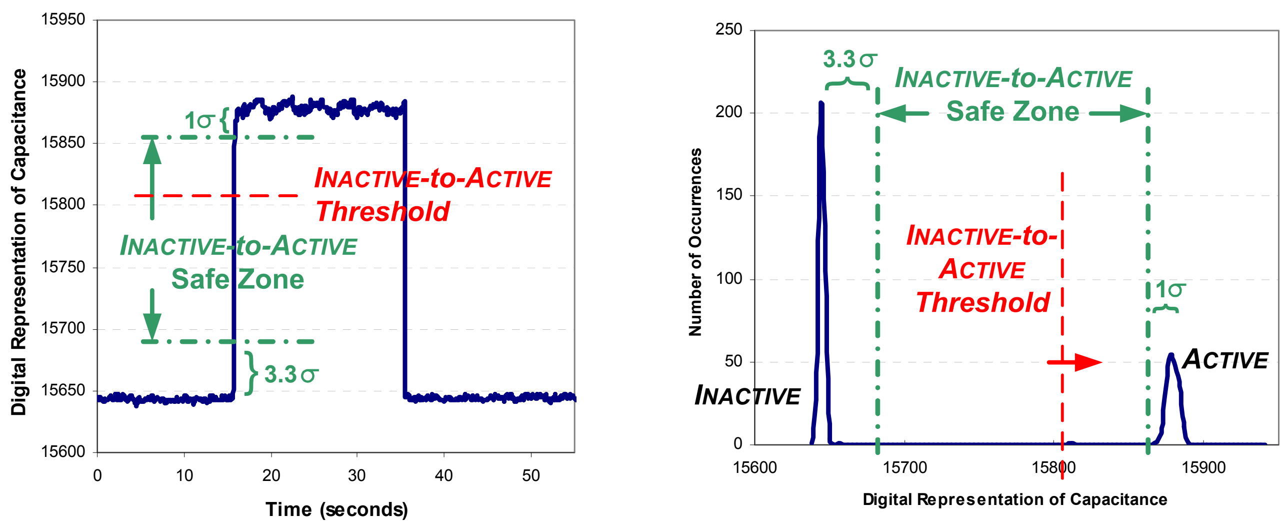

Figure 5. Typical Capacitive Sensor Output with *INACTIVE*-to-*ACTIVE* Safe Zone

4.2. Determining *ACTIVE*-to-*INACTIVE* Threshold

Conversely, the ***ACTIVE***-to-***INACTIVE*** Safe Zone is a range from 3.3 standard deviations of noise below the ***ACTIVE*** average to 1 standard deviation of noise above the ***INACTIVE*** average. With the Safe Zone identified, set the ***ACTIVE***-to-***INACTIVE*** Threshold to 75% away from the ***ACTIVE*** edge of the safe zone.

In equation form:

$$\mathrm{SafeZone}_{\mathrm{AtoI}} = (\mathrm{Avg}_{\mathrm{A}} - 3.3 \times \sigma_{\mathrm{A}}) - (\mathrm{Avg}_{\mathrm{I}} + \sigma_{\mathrm{I}})$$

$$\mathrm{InitialThreshold}_{\mathrm{AtoI}} = \mathrm{Avg}_{\mathrm{A}} - (0.75 \times \mathrm{SafeZone}_{\mathrm{AtoI}})$$

As an example, the ***INACTIVE*** average from the data in Figure 1 is 15643, the ***ACTIVE*** average is 15878, the ***INACTIVE*** standard deviation is 1.8 and the ***ACTIVE*** standard deviation is 6.1. Using the equations above, the ***ACTIVE***-to-***INACTIVE*** Safe Zone is:

$$\mathrm{SafeZone}_{\mathrm{AtoI}} = (15878 - 3.3 \times 6.1) - (15643 + 1.8) = 212$$

$$\mathrm{InitialThreshold}_{\mathrm{AtoI}} = 15878 - (0.75 \times 212) = 15719$$

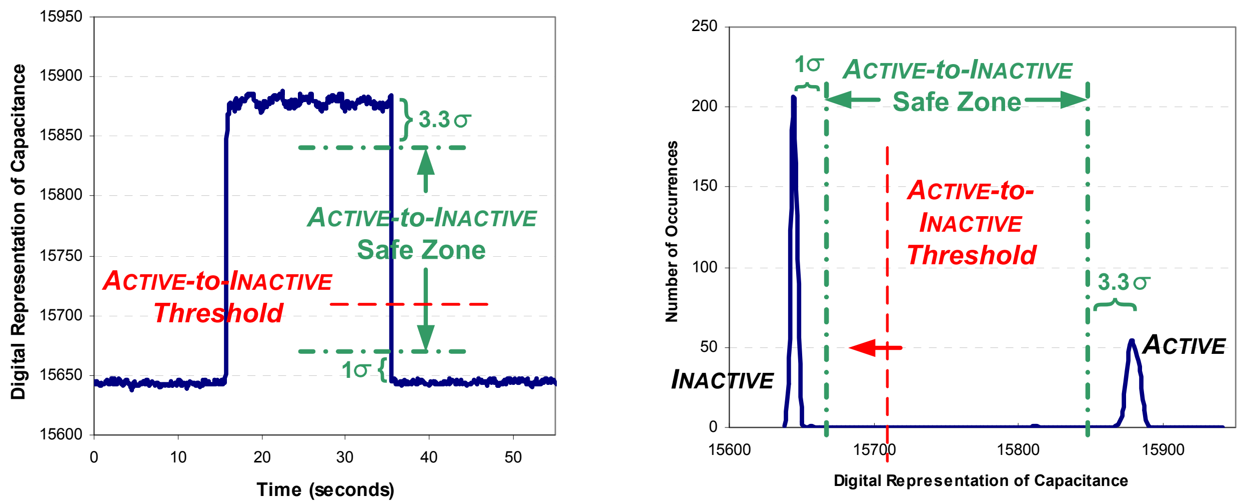

Figure 6. Typical Capacitive Sensor Output with *ACTIVE*-to-*INACTIVE* Safe Zone

Ideally, the signal and noise levels in the system provide far more than 3.3 standard deviations of margin to the threshold levels. At the edge of the Safe Zone, 3.3 standard deviations of margin only provides 1 in 1000 samples violating the Safe Zone. Once the thresholds are set, the margin of safety from false switching can be determined by calculating the number of digital counts between the threshold level from the current switch level (***ACTIVE*** or ***INACTIVE***) and dividing by the standard deviation of that switch level.

A product with 5 standard deviations of margin above the ***INACTIVE*** level would be expected to maintain a proper ***INACTIVE*** state in 99.99994267% of the samples. Other common confidence intervals are provided in the following table.

Standard Deviation (σ) Multiplier	Equivalent Percentage
2x	99.45%
3x	99.73%
3.3x	99.90%
4x	99.993666%
5x	99.99994267%
6x	99.9999998027%
7x	99.9999999997440%

A product with 6 standard deviations of margin would be expected to maintain a proper ***INACTIVE*** in 99.9999998027% of the sensed samples. The ***ACTIVE***-to-***INACTIVE*** Threshold can be adjusted to improve the margin.

Using the data from Figure 1 and the calculated ***INACTIVE***-to-***ACTIVE*** Threshold from section “4.1. Determining Inactive-to-Active Threshold”, the margin between the ***INACTIVE*** average and the ***INACTIVE***-to-***ACTIVE*** Threshold is:

$$\text{ThresholdMargin}_{\text{ItoA}} = \frac{\text{Threshold}_{\text{ItoA}} - \text{Avg}_{\text{I}}}{\sigma_{\text{I}}}$$

$$\text{ThresholdMargin}_{\text{ItoA}} = \frac{15809 - 15643}{1.8} = 92\sigma$$

For a noise data point to trigger the ***INACTIVE***-to-***ACTIVE*** Threshold, it would have to be more than 92 standard deviations away from the ***INACTIVE*** average.

4.3. Additional Protections from False Switching

While a 6x standard deviation (99.9999998027%) sensing confidence initially appears more than sufficient for most applications, it would not be sufficient enough for the launch switch on a nuclear missile, for example. Statistically, it is extremely unlikely that two or more noise-induced samples beyond the threshold would appear sequentially. Therefore, it is important for the sample-interpreting device (predominantly an MCU) to accept a switch change as valid only if multiple sequential samples are received above or below a given threshold. This additional safety factor, or other real-time data analysis, should render the noise as inconsequential.

4.4. Capacitive Sensing API

The Capacitive Sensing API provides code that implements the dual threshold detection method described in this application note. The Capacitive Sensing API package includes a Human Interface Studio application that displays capacitance values measured by a device and allows the configuration of ***INACTIVE***-to-***ACTIVE*** and ***ACTIVE***-to-***INACTIVE*** Threshold levels in real-time. Refer to Silicon Labs application note AN366 for more information on the Capacitive Sensing API.

5. Other Areas of Consideration

5.1. Improving Margin Through Baselining

There are a variety of system factors that can impact the sensing margins. Variations can occur in any of the following aspects of a touch sense system:

- Temperature
- Humidity
- Supply voltage
- PCB, Flex, Substrate, or glass
- Overlay variation
- Air Gap
- Adhesive
- Sensing IC

Many of these factors change over time and adjustments to the ***INACTIVE*** baseline become necessary. Designs with critical switching requirements should be tested for specific variation impact.

5.2. Improving Margin Through System Layout

The greatest impact on margin is often the mechanical design of the capacitive sensor and its connections. For optimal SNR, embedded designers must implement optimal sensor layouts. Here are some key areas of concern:

- Minimizing stray capacitance
- Maximizing sensor size within the constraints of neighboring sensors and overlays
- Minimizing overlay thicknesses
- Avoiding conductive overlays that span beyond the sensor area
- Avoiding air gaps

For additional information on capacitive sensing and layout considerations, see Silicon Labs Application Note AN338 “Capacitive Touch Sense Solution.”

NOTES:

Contact Information

Silicon Laboratories Inc.
400 West Cesar Chavez
Austin, TX 78701
Tel: 1+(512) 416-8500
Fax: 1+(512) 416-9669
Toll Free: 1+(877) 444-3032

Email: productinfo@silabs.com
Internet: www.silabs.com