Capacitive Sensors Overview

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This document provides background on the theory and design of capacitive sensors.

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1. Overview

This document describes the basic operation and design of sensors using Cirque's Gen6 platform. A good sensor design has acceptable sensing distance and SNR along with allowing for unit-to-unit sensor variations, temperature variations, and humidity variations. This document addresses the different measurement techniques, sensor guidelines for each measurement type, and configurations and settings that can be used to maximize each sensor type.

1.1. Measurement Types

There are two types of measurements possible with the Gen6 solution: mutual capacitance and self-capacitance.

- Mutual cap drives a signal on one electrode (the transmitter, or TX) and senses charge movement on another electrode (the receiver, or RX).
- Self-cap drives a signal and senses the charge movement on the same electrode.

Most button and proximity applications generally use Self-cap. Touch pad and touch screen applications generally use Mutual cap.

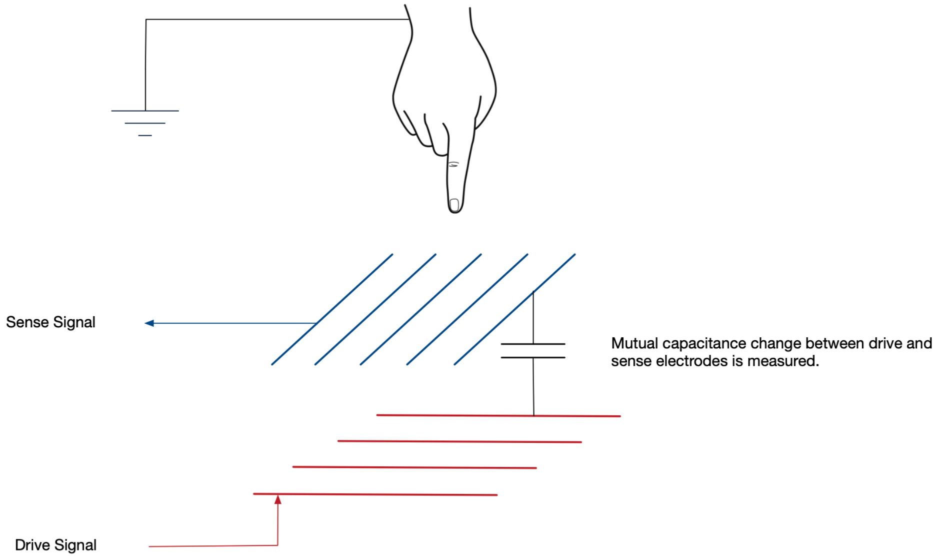


Figure 1: Mutual Capacitance Sensor

With a mutual cap sensor, the transmit electrode’s voltage is toggled. That creates a changing electric field around the electrode that radiates in all directions. The RX sense electrode measures the charge movement caused by the change in electric field and reports that as the measured value. Any objects within this electric field (i.e. a finger) will change the amount of charge movement and thus are also measured.

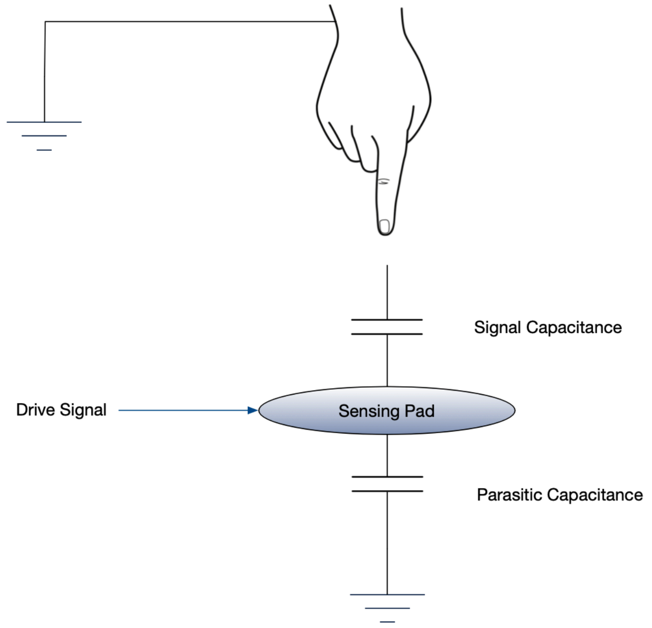


Figure 2: Self Capacitance Sensor

With a self-cap sensor, the amount of charge needed to toggle the voltage on an electrode is measured. The changing electric field on that electrode radiates in all directions and interacts with all nearby objects. Any change in the nearby objects will change the amount of charged needed to toggle the electrode's voltage.

1.1.1. Key Differences and Advantages of Both

Mutual Capacitance:

- Mutual cap focuses the effect to the closest point between transmit and receive. It helps resolve the position of nearby objects because the sensor is most responsive where drive and sense are near each other (typically where they cross).
- Mutual cap sensors can be made into a two-dimensional array of electrodes. This array can be used to sense multiple objects simultaneously. This is why mutual cap is used in touchpads and touch screens. For example, 8 drive electrodes and 8 sense electrodes can be made into an 8x8 array and 2D images can be assembled from the measured values for that array.
    - **NOTE:** Different firmware platforms may be better suited to one sensing type over another. Because of the complexity of calculating and traversing an array of data, mutual cap arrays are typically paired with Cirque's Gen6 tracking FW platform while self-cap sensors are typically used with the CustomMeas FW platform.
- Mutual cap is not very sensitive to capacitance to ground so ground planes can be used to shield and add directionality. Mutual cap is primarily sensitive to capacitance between transmit and receive. This can give more flexibility in routing.

- Transmit lines and receive lines have the most sensitivity where they are in close proximity or crossing over to each other. This means that if the routes are shielded or isolated, a sensor can be created that is only sensitive inside the sensor area and not sensitive in the routing.

Self-Capacitance:

- Self-cap only requires one wire because it can transmit and receive on the same line. Self-cap will sense object position anywhere near the sensing line or electrode.
- Self-cap is generally better for sensing proximity of nearby objects.
- Self-cap is sensitive to parasitic capacitance to ground. Shielding the self-cap routes from the finger ground can be used but the more ground that is used, the more offset it will require.
- A technique called driven shield can be used to reduce the offset caused by parasitic capacitance to ground effects. Detailed information about driven shield is in section 5.2.1 below.

2. ADC Configurations

The Gen6 solution contains 16 Analog to Digital Converters (ADCs) so it can be configured to measure 16 unique electrode results simultaneously. Each ADC has a 16-bit range.

When setting up a measurement, there several items that can be configured to optimize for best results. These are described below.

2.1. Toggle Frequency and Aperture

The toggle frequency is adjustable from 128khz up to 551khz. The toggle frequency controls the speed of the measurement and can be adjusted to allow for the signal settling time needed by the resistance and capacitance of the sensor (the RC time constant of the sensor).

During a measurement the voltage on electrodes will change in a square-wave pattern at the toggle frequency. With each transition in the wave pattern the amount of charge movement is precisely measured. For self-cap the charge movement is measured on the electrode that is toggling. For mutual cap one electrode is toggled while another (nearby) electrode senses the induced charge movement.

In both cases, the amount of charge movement will change when the finger or other objects enter the sensing area

The following diagram shows the interaction between the toggling electrode and the measured change caused by the human. In this particular example, self-cap is used so the electrode is both a TX and RX.

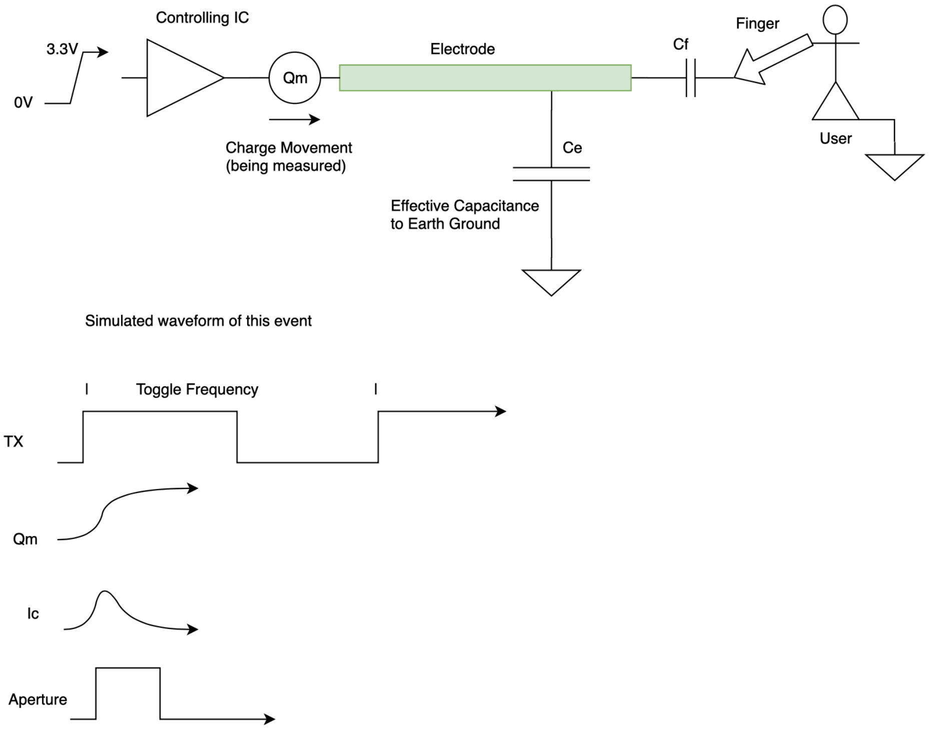


Figure 3: Self Capacitance Event Diagram

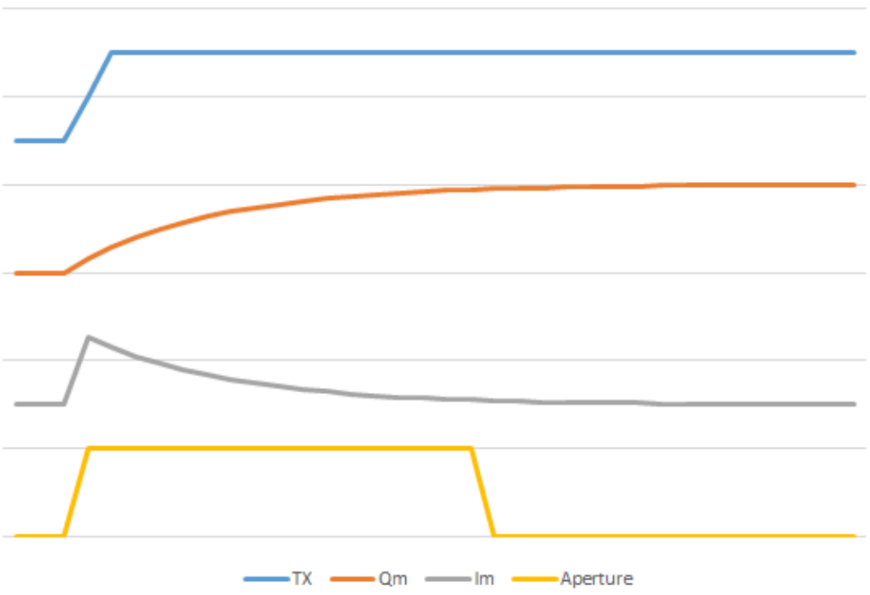


Figure 4: Toggle Event Waveform

The above waveform shows the timing of the TX voltage toggling at the toggle frequency, with the charge movement and aperture window.

In both self-cap and mutual-cap measurements, the charge will change when the finger or other objects enter the sensing area. In essence, the finger changes the capacitance of the system. The amount of time it takes for the charge to move is determined by the combination of resistance and capacitance of the sensor.

The Cirque CustomMeas solution allows the system to be tuned for different RC time constants over a wide ranges of sensor configurations. The toggle frequencies can go very slow if the time constant is long. Or the frequencies can go very fast if time constant is short and very fast measurements are desired.

In addition to measurement frequency, the amount of time that the measurement allows for the accumulation of charge (called the “aperture window”) can be adjusted using the aperture setting. For a given toggle event, the full event can be measured (aperture = 39) or only a portion of the toggle event can be measured (anything less than 39). This gives flexibility to gather the charge for a given multiple of the RC time constant.

The typical method to set aperture is to set it short and then increase the value one count at a time until the signal no longer changes significantly. Aperture should be long enough to let in all the signal from the sensor, but not longer than is needed. Apertures that are too long will result in a 1 to 3dB loss in SNR.

2.2. Gain

Gain is the amplification of the signal. The higher the gain value, the more that the measured signal will be amplified. In CustomMeas firmware there are 16 different gain settings, each with successively more amplification. Increasing the gain effectively decreases the range of capacitance difference that are available.

2.3. Offset

Offset is a hardware method that is used of cancel out the effects of extra capacitance and give the ADC more range to measure the finger.

For example, if sensor has a lot of capacitance (between transmit and receive in the mutual cap case or between electrode and ground in the self-cap case) the initial value may be 25000 counts without a finger at the lowest gain. This only leaves a small amount of the ADC range left to measure the finger, and if the gain is increased that value of 25000 will be amplified by the gain amount. So likely an increase in gain will result in the ADC value reaching the top of its working range (the AD will be “railed out”) and always return its highest value (about 32500).

This is where offset is helpful. Using internal offset, a negative 25000 counts of signal can be added to the existing 25000 counts of signal. This puts the ADC close to zero and allows the user to turn the gain up and get more sensing resolution.

As gain increases the AD will sense finer changes in capacitance but have a narrower range of capacitance it can work with. Offset can be adjusted to position that narrow sensing range almost anywhere along the range of capacitances the sensor needs. The following diagram shows the relationship between capacitance being measured and gain and offset.

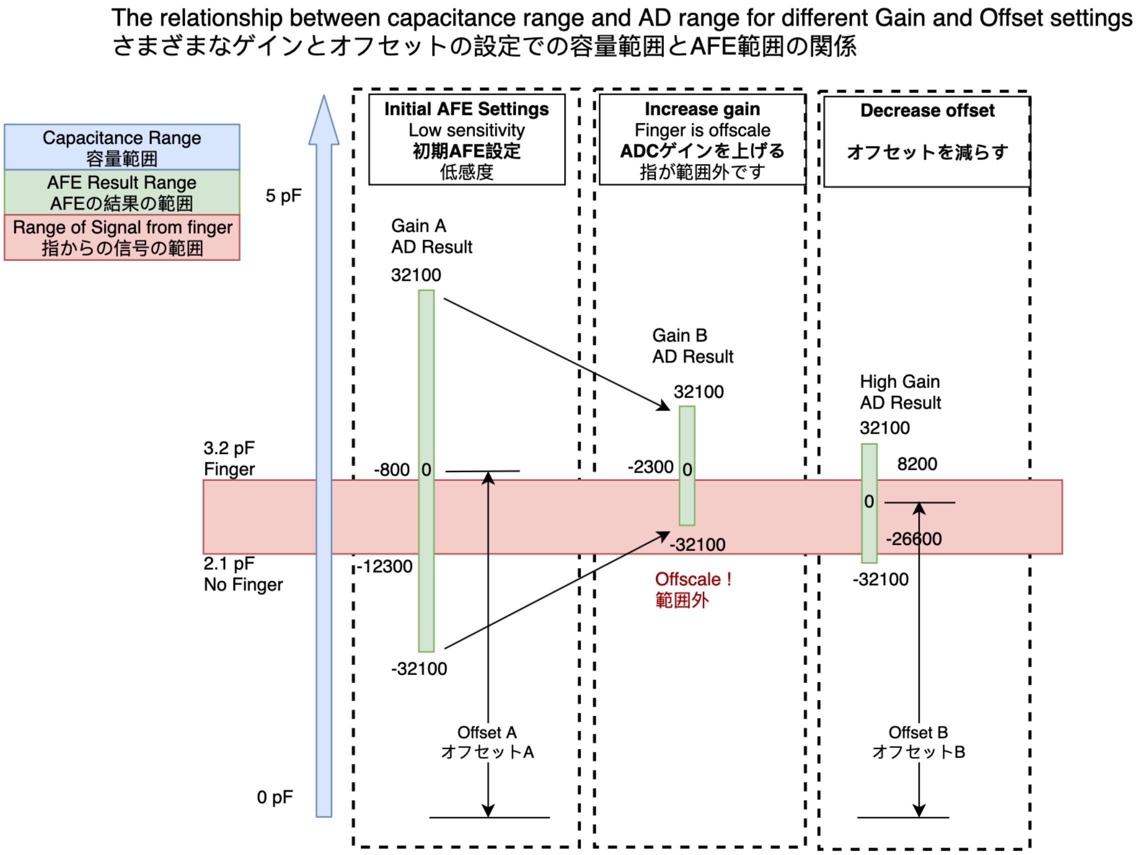


Figure 5: AD range with gain and offset details

NOTE: Capacitive range values shown are examples and will vary depending on specific sensor design and implementation.

Note that using offset has an influence on measurement charge/discharge time. Large offset amounts take extra time for the measurement to settle. This means that offset and gain should be tuned in conjunction with aperture and toggle frequency. Or in other words, after offset and gain are tuned, the aperture and toggle frequency should be re-checked and tuned because adding offset can cause the measurement time to slow.

3. Tuning a Sensor

Four key parameters need to be set to “tune” the IC to give the best possible measurements for a sensor: Gain, Offset, Frequency, and Aperture. Those four parameters are interrelated so adjusting them often requires several rounds of fine-tuning.

The goal of tuning is to have enough measurement range to monitor the variation from a hand or finger and leave enough of the measurement range unused to account for other variations in the surrounding environment. Variations such as temperature change, humidity, movement of nearby objects, and mechanical deformation all need to be accounted for.

The following steps can be followed when tuning a capacitive sensor. Start by setting the frequency low, the aperture open (high), the gain low, and the offset low.

> Increase the frequency until you start to see a large change in measurements. Slow down the frequency to be just below that threshold of change.
>
> Decrease the aperture window until you see a change in measurements. Increase the aperture to be just above the threshold of change.

1. Apply each source of variation and record how much change occurs in the ADC with that source applied.
2. Evaluate the sums of all of the sources of variation (both min and max) and make sure the ADC will stay within its measurement range. See below drawing.
3. If the ADC is well within its measurement range consider increasing the gain, adjusting the offset, re-adjusting the frequency and aperture, and re-evaluating all variation sources until you have consumed a safe majority of the available measurement range.

In other words, start at low gain and turn the gain up if there are large amounts of ADC range not used by the sources of variation.

It is important to allocate enough range for each of the sources of variability. This typically means measuring the variation across multiple systems and estimating the range of variation you are likely to see.

It is common to leave some of the measurement range as "margin" for the variation. This will account for unknown sources of variation.

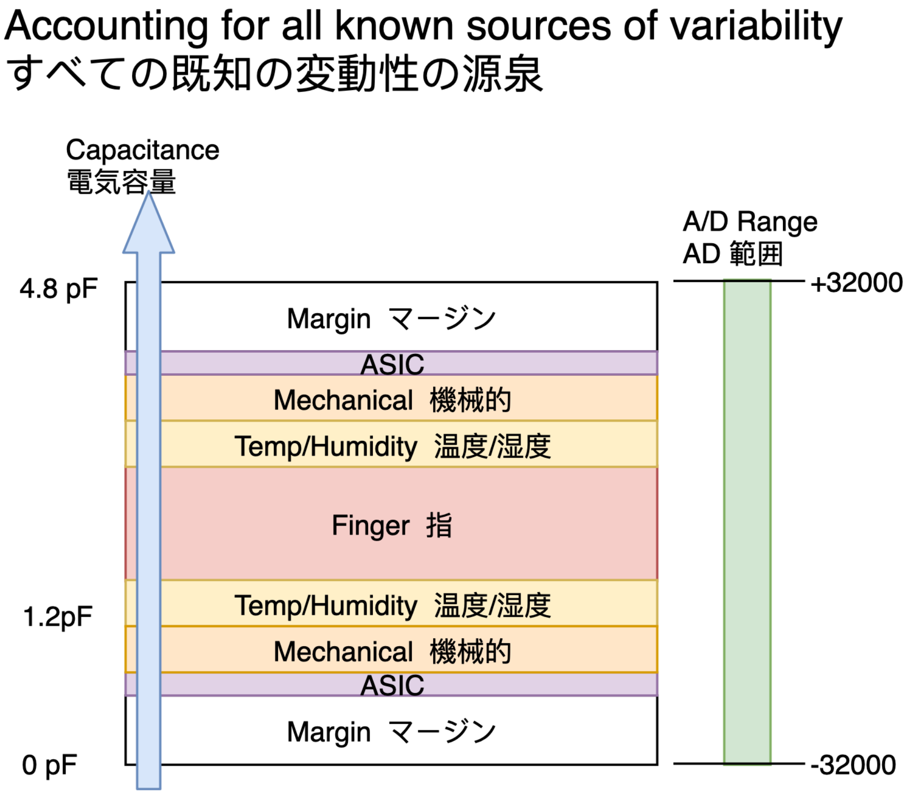


Figure 6: Diagram of accounting for sources of variability

NOTE: Capacitive range values shown are examples and will vary depending on specific sensor design and implementation.

4. Compensation

It is common to keep (and periodically update) a base-line value for a measurement. That value is called the "compensation value" (Item 2 in the figure below) and it is used to isolate changes in the environment from changes in the hand position.

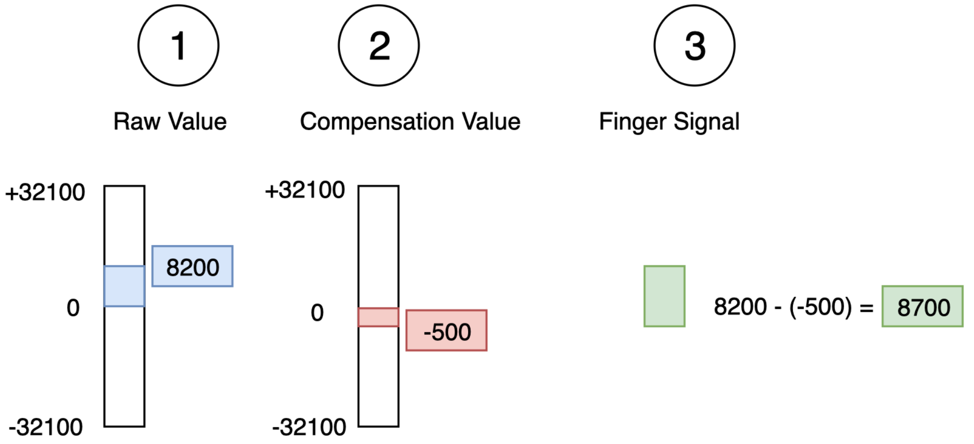


Figure 7: Compensation Diagram

When a new measurement is made (item #1 – raw value) the compensation value (item #2) is subtracted from the new measurement. This produces the "finger signal" (item #3) that is relative to the background value

If the compensation value is captured when no object is near the sensor then when an object approaches the sensor it's easy to see the change that occurs. Anytime the hand is known to be away from the sensor the compensation value can be updated.

The compensation process is very helpful in isolating changes in the background of a sensor from changes in the hand position, but it does create some issues. First, if the raw measurement is beyond the ADC's measurement range the raw measurement is “off scale” or “railed” (stuck near +32k or -32k) then the finger signal will be stuck at zero (case #2 in the table below).If the raw measurement is almost off scale, then the finger signal will seem to respond but will be limited to a small value. This can seem like reduced sensitivity (case #3 in the table below).

It is important to monitor the range of the compensation values. If you see unusual compensated values, it's best to look at the raw measurements and verify the ADC readings are well within range

Case	Situation	Raw Value	Compensation Value	Compensated Value	Result
1. Normal Case	Powering up, no finger nearby	-521	0 (Not yet set)	-521	This is the first measurement. Copy raw value to the compensation value.
	No finger nearby	-510	-521	11	The signal is really small but not zero (due to noise).
	Finger is approaching	318	-521	839	Compensated value is getting larger, finger is approaching.

	Finger has arrived	4195	-521	4716	Compensated value is very large, finger has touched the sensor.
	Finger leaves	-485	-521	36	Compensated value is small but not zero (due to noise or a slight change in temperature/humidity/shape of the sensor, etc.)

Table 1: Normal Compensation Procedure

Case	Situation	Raw Value	Compensation Value	Compensated Value	Results
2. Railed Signal Case	Powering up, no finger nearby, ADC railed	32135	0 (Not yet set)	32135	Signal is railed out. Copy raw value to the compensation value.
	No finger nearby	32135	32135	0	Compensated value is exactly zero and likely won't show any noise or variation.
	Finger arrives	32135	32135	0	Compensated value is still zero.
3. Nearly Railed Signal Case	Powering up, no finger nearby, ADC almost railed	31500	0 (Not yet set)	31500	Signal is nearly railed. Copy raw value to the compensation value.
	No finger nearby	31489	31500	-11	Compensated value is really small but not zero (due to noise).
	Finger arrived	32135	31500	635	Compensated value is NOT the correct size because there is no room in the measurement range to measure it properly.

Table 2: Compensation with "railed" signals

5. Hardware Design Guidelines

5.1. Common Sensor Design Principles

Sensors are crafted to help electric charges between objects interact. Those charges interact using electric fields. Building a good sensor involves creating the needed strength of electric field at a given point in the sensing area.

Two common parameters for any sensor affect the electric field: length and width. Increasing an electrode length or width will increase the field strength. Strong electric fields will have better SNR at a given distance.

Narrow and short electrodes can only sense a short distance. Long or wide electrodes can sense a longer distance. In general, make the electrode width and length be about the distance you want to sense.

A third sensor design parameter also exists: electrode density. Electric fields from each part of an electrode will add together (at any given point in space). If you use a hatch pattern for the electrode it will create a field that almost the same strength as a solid pattern for objects at a distance but will have less electric field strength for objects nearly in contact with the sensor. In general, hatch electrodes to reduce having too much signal nearby yet still have signal when an object is farther away. For more details see section 5.3 below.

5.2. Mutual Capacitance Sensors

Mutual cap sensors focus a capacitance effect to a point in space. A variation in the measurements of a mutual cap system indicates something changed near that point in space. You can control how broad or narrow that point will be (the area of sensitivity) by the shape and path of the electrodes. In the diagram below, as an object approaches 'A' the Drive/Sense interaction will change. The change in relationship will be concentrated near the point 'A'.

Shielding is commonly used to help focus the area of sensitivity. Typically, the drive signal is shielded from (or kept well away from) the sense everywhere except the point of focus.

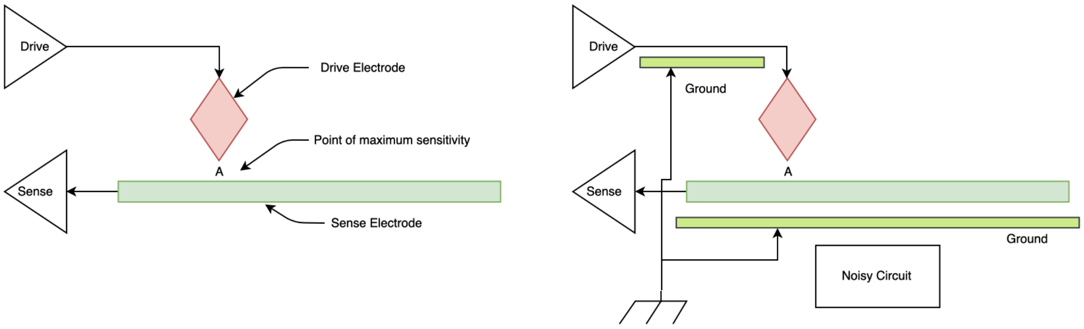


Figure 8: Mutual Capacitance Sensor and Shielding Diagram

It is possible to "defocus" the area of sensitivity by adding additional interaction points. For a given object size this technique can be used to trade-off position accuracy for SNR. An object with a size that spans A to B will be easier to detect but the exact position will not be known.

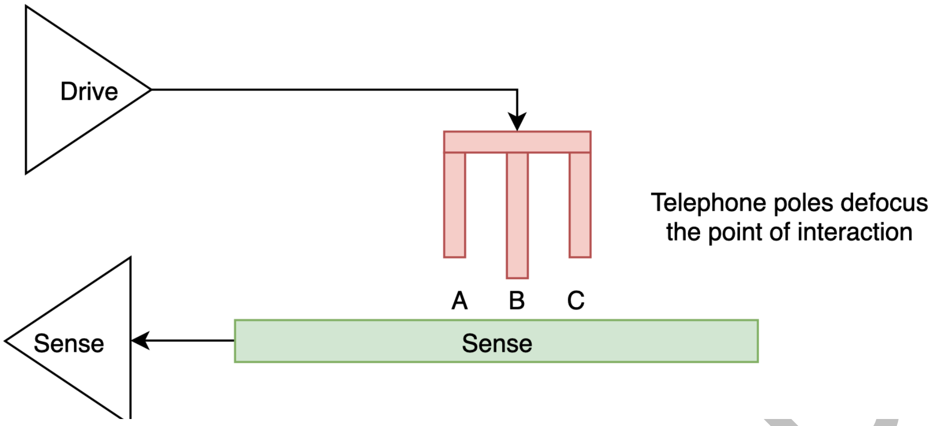


Figure 9: Techniques to defocus sensitivity

Sensors typically have multiple electrodes to help detect and track an object over a surface (or in a volume of space). Many drives can interact with a sense line. Many sense lines can interact with a drive line. This allows creating large sensing surfaces.

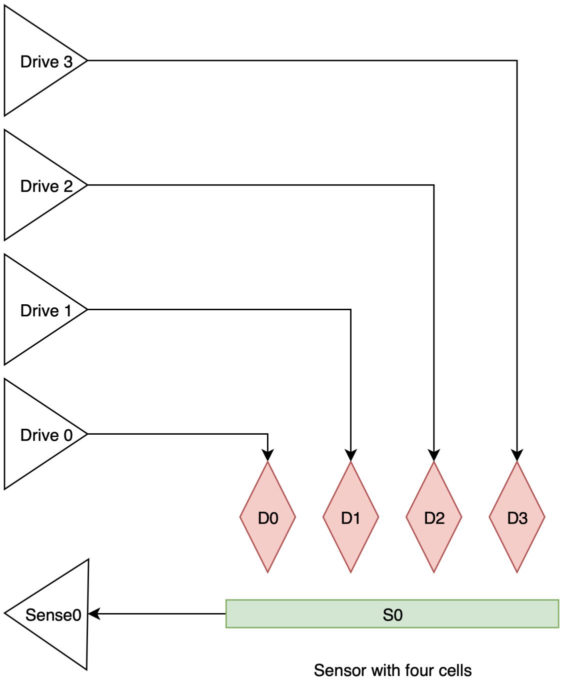


Figure 10: Diagram of a sensor with four cells

Cells are often arranged in XY grids. Common cell patterns include "plain", "telephone pole", and "diverging diamonds".

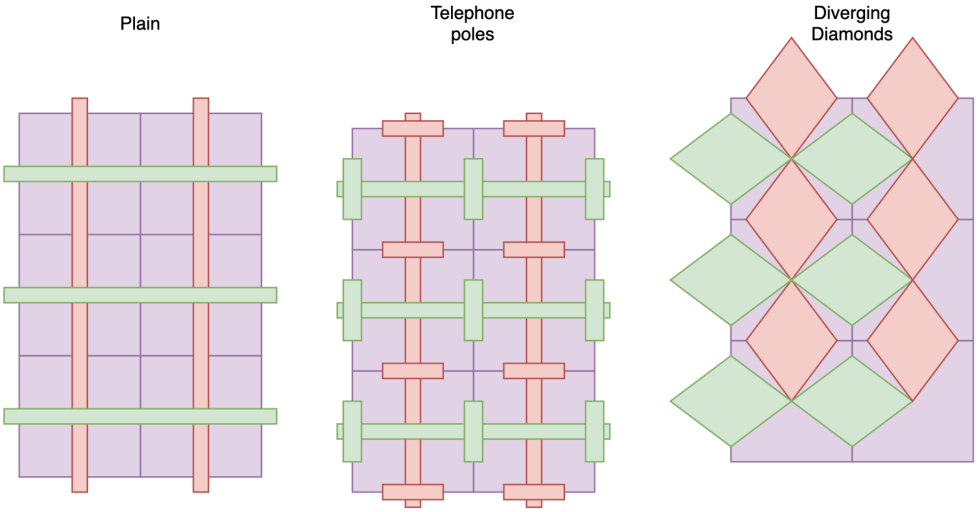


Figure 11: Examples of different mutual cap sensor patterns

Typically, plain line sensors have the lowest SNR and highest potential accuracy for determining an object's position in between cells. Telephone poles give more SNR with less accuracy and diamonds give the highest SNR with least amount of positional accuracy. For applications where the spacing between electrodes is small relative to the size of object tracked, diamonds or telephone poles can be used and will still give excellent accuracy.

5.3. Self-Capacitance Sensors

Self-cap measurements will change if any change occurs anywhere near the electrode. The change is not focused to a point in space (like it is with mutual cap) but is spread around the vicinity of an electrode.

Because the sensors generate electric fields, the general design practice for maximizing sensitivity is the bigger the sensor, the more inherent signal it will create and the better its proximity reach will be. Very small electrodes will require a very high gain to sense a long distance but increasing the electrode size will allow lower gain settings to work at the same distance with better SNR.

One design technique that can be used to create good reach but also improve linearity of the response is to hatch or hollow out the sensing area. With a solid sensing area, the sensor will be at maximum sensitivity when it is actually touched. This creates a somewhat exponential response to the finger. If the sensing area is hatched or hollow, the finger touch will not create as big of a response, but the proximity response will be close to the same. This allows for a more linear response to touch and proximity. Examples sensors and their predicted response is shown in figure 12 below.

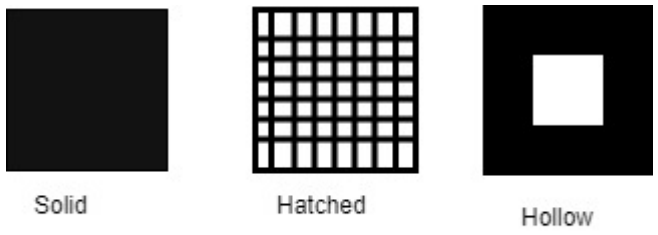


Figure 12: Self Cap Sensor Fill Examples

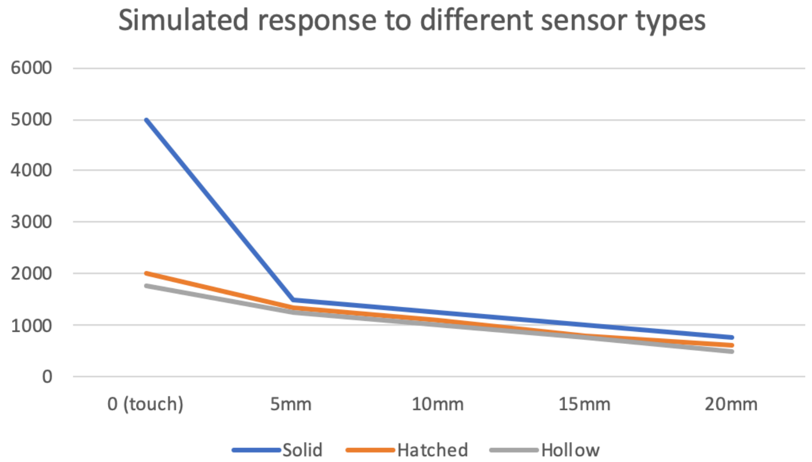


Figure 13: Simulated Response to Different Self Cap Sensor Fill Types

Self-cap measurements can be thought of as capacitance measurements between the electrode and ground (or the world at large). This means using ground to shield the electrodes (to help control or focus the area of sensitivity to a specific point) is more difficult to do. The shield will increase the measured charge. There is a limited measurement range so if the shield increases the measured charge too much the measurement will rail out (or “clip”). Gen6 platforms support a technique to eliminate the large signal added by shielding the electrode: Driven Shield.

5.3.1. Driven Shield

The Gen6 platform allows the use of a driven shield with self-cap designs. Driven shield sensor designs may require multiple layers. The top layer (layer closest to the object to be sensed) is the electrode. The next layer (layer opposite the object to be sensed) is the driven shield. The Olympus IC will drive both the electrode and driven shield with the same voltage. See figure 12 below.

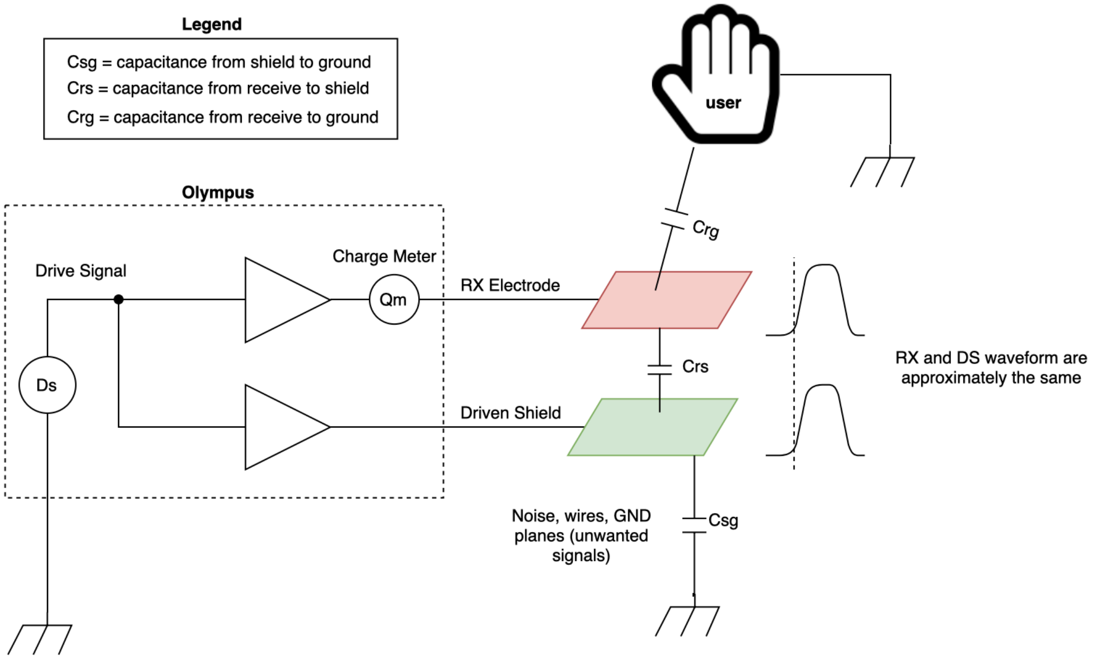


Figure 14: Driven Shield Operation Diagram

The driven shield will effectively shield the electrode from ground without adding any signal to the electrode. The driven shield (DS) does the work to charge and discharge Cds (the capacitance to earth ground). This effectively removes the signal offset from the electrode (RX) and makes it possible to increase the gain of the charge meter (Qm). This makes it possible to design high-gain self-capacitance systems that can tolerate large changes in capacitance to earth ground.

While the voltage (electrode to driven shield) is always 0.0V the capacitance Crs should be kept small to maintain high sensitivity.
Small Crs = Good (more sensitive)

To achieve small Crs, increase the distance between RX and DS (PCB thickness). This works because parallel plate capacitance is proportional to area/distance.

Large Crg = Good (more sensitive)

To achieve large Crg, increase the area of the RX sensorTo achieve large Crg, increase the area of the RX sensor.

Ar = RX area
As = Shield area

Ideally, RX area is the same as shield area, however the shield area can be slightly larger than the RX area for additional shielding. It is important to not make the shield area significantly larger than RX area, as this can reduce sensitivity. The greater the distance between RX and shield, the greater the ratio shield/RX area can be.

When designing sensors that include a driven shield it is necessary to route the driven shield so that it encloses (or shields) the electrode everywhere except where the user will interact with the electrode. Consider how the driven shield routes from the IC to the connector and from the connector through the FPC to the user. This often means having groups of electrode traces surrounded by driven shield traces.

Any electrode on the Gen6 controller may be programmed as a driven shield. Electrode <0> is special in that it has an option for a stronger driven shield output buffer. This allows it to drive larger capacitive loads.

It is necessary to match the DS type with the RX type you are using. For example, use DS with RX (voltage-to-voltage mode), use DS+ with RX+ (in-phase rail-to-voltage mode), and use DS- to shield RX- (out-of-phase rail-to-voltage mode). Using DS/RX or DS+/RX+ is the simplest solution. The DS-/RX- is used to design differential self-cap sensors that requires changing some secondary settings.

It is best to use the same type of DS/RX for any given measurement. If mixing different types of DS and RX in the same measurement a mixture of self-cap (because each RX is toggling in reference to ground) and mutual cap (because different types of DS and RX will be coherent (same frequency and phase) at a different toggling magnitude).

Using DS+ with RX+ is the recommended starting configuration. This will result in the largest signal for the best SNR. If using DS+ with RX+ has sufficient SNR, but signal reduction is necessary due to EMI emissions, reduce the signal coupling to other sensitive circuits. To manage a very large offset (such as with a very large sensor area), DS and RX is recommended.

5.4. Overlay Materials

General guidelines should be followed when considering the material that will cover the sensing pads in the device (typically plastic or glass):

- Ensure that no carbon or other conductive material is present in any material or paint that will be placed over the sensor.

- The dielectric constant of any overlay material will have an effect on the electric fields of the capacitive sensor and will impact the total proximity sensing distance. Higher dielectric material will better concentrate the electric fields and reduce signal loss (see table 3 below).

- The sensor should be directly adhered to the device surface using high quality adhesive film. Because air has a low dielectric constant, any air gaps between the sensor and the surface will reduce proximity sensitivity.

- Conversely, material below the sensor will ideally feature a low dielectric constant to better reduce parasitic capacitive coupling on the backside of the sensing pad.

Material	Dielectric Constant
Air	1
Typical Trackpad Overlay (Lexan)	3
ABS Plastic	2.4 - 4
Glass	8 – 10

Table 3: Example Dielectric Constants

A general guideline is to keep the overlay surface thin with the highest dielectric constant possible within the constraints of the products industrial design. This will help to maximize the range and sensitivity of self-capacitance proximity sensing.

6. Routing Guidelines

6.1. Mutual Cap Routing Guidelines

As explained above, mutual cap routes (TX and RX) should be separated from each other with either distance (trace spacing) or ground until they reach the sensing area.

The sense line electrode connections to the touch controller IC should be shielded with ground from other signals to reduce interference to the analog sensing system. Avoid routing high-speed signals on other PCB layers adjacent to the sense line traces.

6.2. Self-Cap Routing Guidelines

As explained above, self-cap routes are sensitive to capacitance to ground and thus shielding them with ground will create a large offset. However, if they are not shielded by ground, they will sense object movement all along the route. There is a technique to eliminate that ground sensitivity and reduce the sensitivity along the routes using driven shield as a buffer between the electrode(s) and ground. The diagram below shows how this can work.

In this first diagram, multiple electrode sense buttons are routed in groups on an FPC. Each group (of three buttons) is surrounded by a driven shield. The driven shield is surround by a wide ground plane. The ground plane will reduce the sensitivity to touch all along the FPC. The driven shield dramatically reduces the offset introduced by the nearby ground. By keeping the button traces small with a small trace spacing and keeping the ground wide (about as wide as the button trace group) the FPC will only be sensitive in a very close proximity. Notice that this technique was used in the Cirque Proximity Dev Kit (available at www.cirque.com).

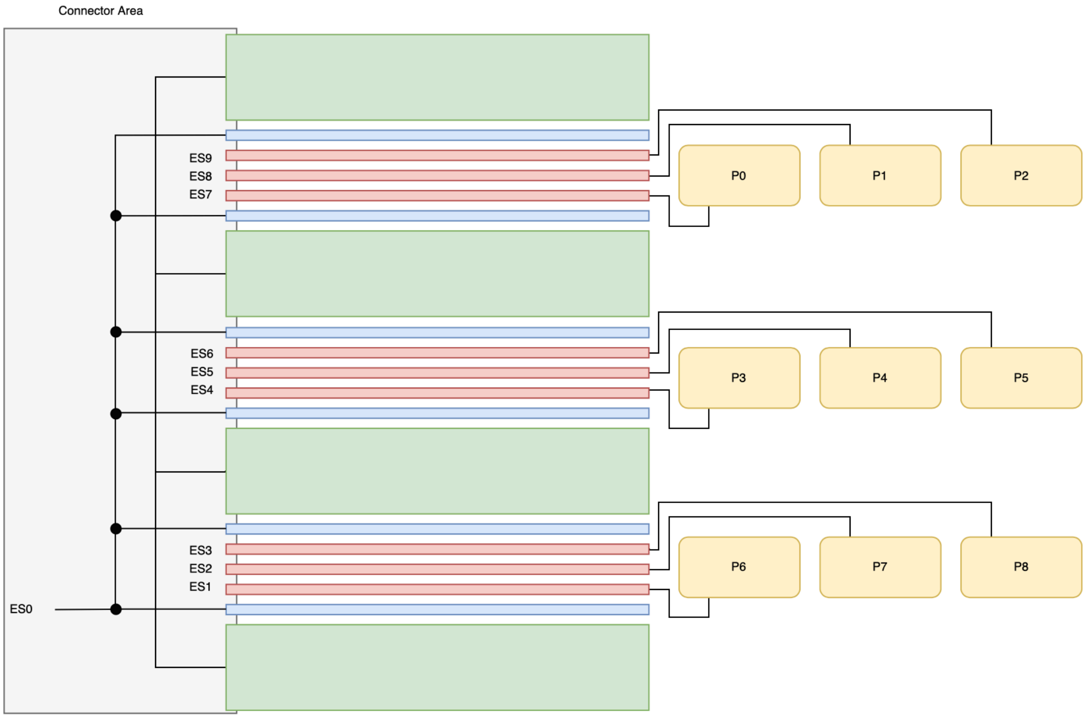


Table 4: Self Cap Routing Example

7. ESD Considerations

Sensors are typically used in devices that are handled by users, so the sensors need to be designed to manage ESD events from the users.

Management occurs in three layers:

- Deflect
- Distribute
- Harden

7.1. Deflect

Any gap or seam that might allow a spark to travel to the sensor should have an exposed ESD ground trace next to it. The ground trace should be exposed (uninsulated) so that it can emit charges as needed during an arc event. That trace should connect back to the ESD/RF ground point of the system (the main power connector or USB connector shield line). The ESD trace can have sharp points near screws, connectors, or seams to help entice the arc to strike it at a specific point.

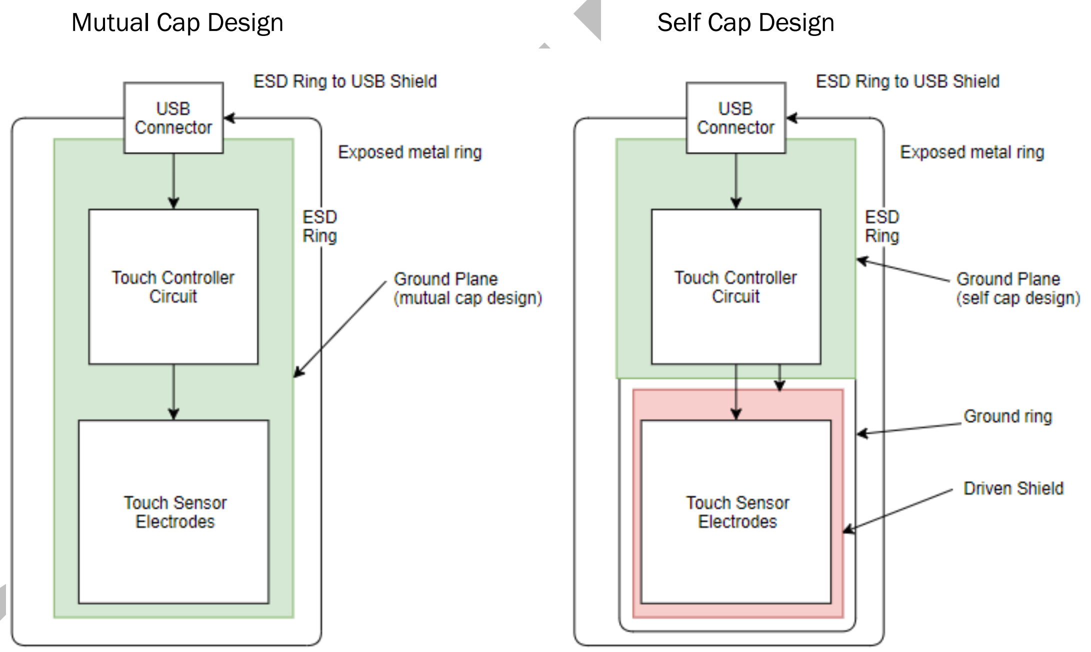


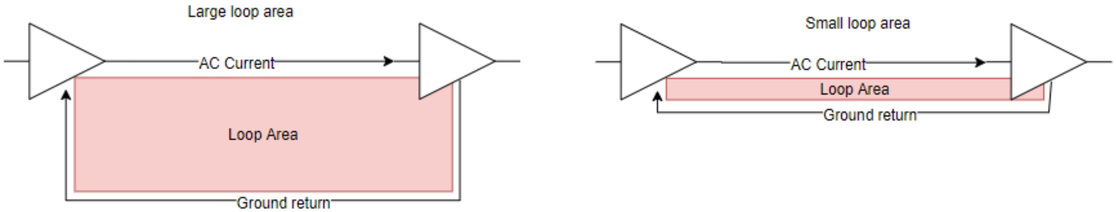
Figure 15: Mutual Cap & Self Cap ESD Protection Diagram

7.2. Distribute

Inside of the ESD ground trace should be a system ground plane (or trace). Any ESD energy that bridges over to the system ground trace should then be spread to the system ground plane and to all system components as uniformly as possible. The ground plane should be uniform with a minimum of voids or gaps in its routing.

7.3. Harden

Any communication or control signals should have the smallest possible loop area (signal to ground) to eliminate differential voltages from being induced by the ESD event. Keep these signals running over a ground plane or running right next to ground.



Use overlay materials that have a dielectric strength (and thickness) high enough to resist conduction at the required ESD voltage.

If it is necessary to add ESD protection to specific electrodes, then be aware the protection circuitry will introduce variability (over temp and supply voltage) and the design will need to allow for that variability.

8. Contact Information

Contact a Cirque sales representative for a complete list of Cirque's OEM products.

In United States & Canada:	(800) GLIDE-75 (454-3375)
Outside US & Canada:	(801) 467-1100
Fax:	(801) 467-0208
Website:	http://www.cirque.com