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mTouch™ Projected Capacitive Touch Screen Sensing Theory of Operation

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INTRODUCTION

Microchip's mTouch™ Projected Capacitive Touch Screen Sensing technology provides a readily accessible, low cost, low power solution to facilitate implementation of projected capacitive touch screen user interfaces.

Among many other desirable characteristics, projected capacitive sensor technology can provide an easy to use, robust, and feature rich user touch interface. Gestures are an example of a feature that can be supported with this technology.

A development kit (P/N DM160211) can be purchased at microchipDIRECT: www.microchipdirect.com. The source code is available royalty-free for use on Microchip PIC® MCUs.

This document covers the theory of operation behind this exciting patent-pending technology.

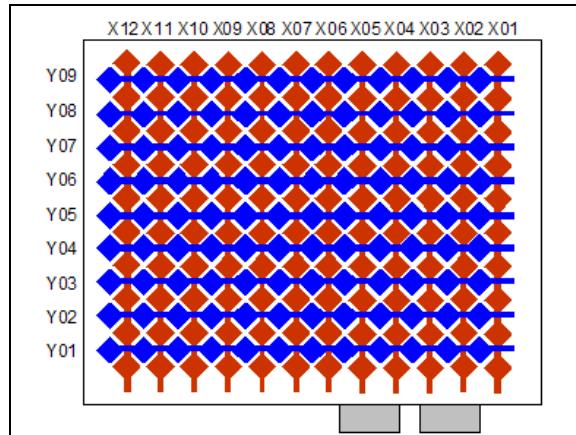
BASIC PROJECTED CAPACITIVE SENSOR

There are number of different projected capacitive sensor constructions and various materials used for each. One of the sensor constructions consists of the following:

- Two layers, each having a multitude of conductive electrodes arranged parallel to each other.
- The layers are fixed in close proximity to each other and electrically insulated from each other.
- The layers are oriented with their electrodes orthogonal to each other.

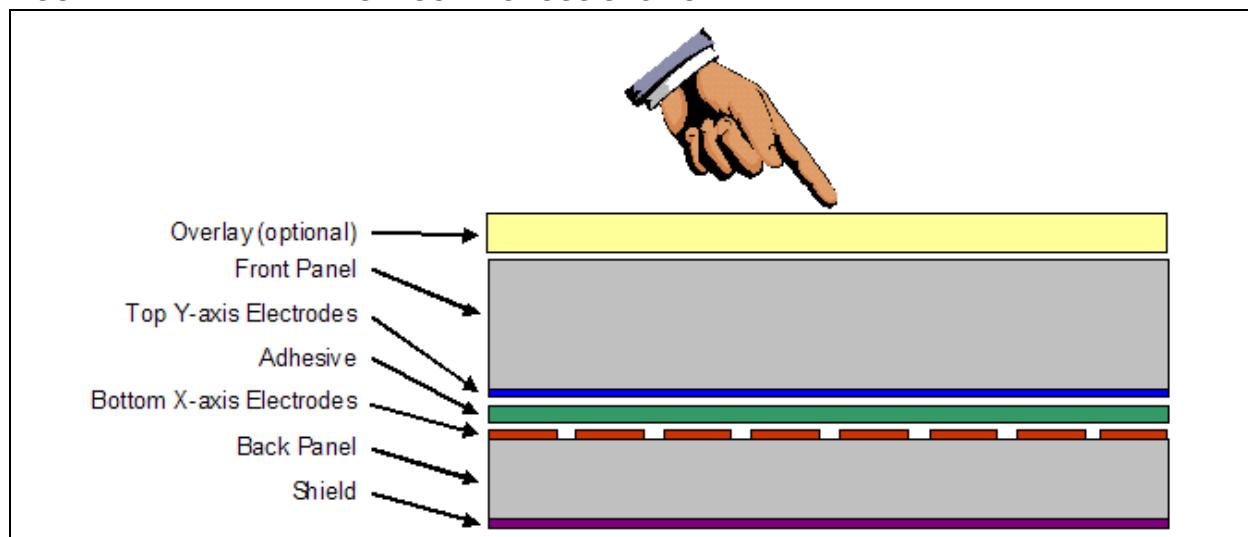
A front view of an example sensor is shown in Figure 1, with 9 top layer electrodes represented in blue and 12 bottom layer electrodes in red.

FIGURE 1: EXAMPLE SENSOR – FRONT VIEW



A cross sectional view of the example sensor is shown in Figure 2.

FIGURE 2: EXAMPLE SENSOR – CROSS SECTIONAL VIEW



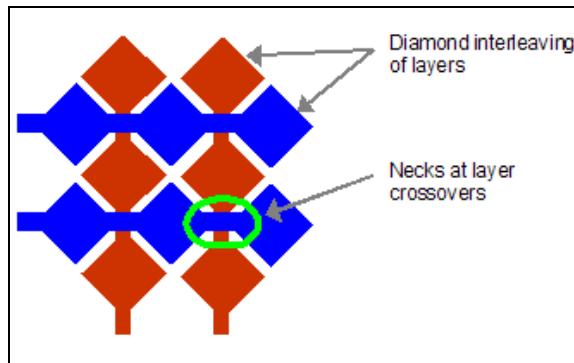
Electrodes

The electrodes are the active conductive elements of the sensor. They are often made of Indium Tin Oxide (ITO) for its transparent and conductive properties. Another example for the electrodes could be copper on a rigid or flexible printed circuit board.

Many electrode patterns can be used to create a projected capacitive sensor. The electrode pattern geometries are an important factor in the overall resolution and touch sensitivity of the sensor.

A common pattern for the electrodes is a series of diamonds interconnected with narrow “neck” sections. The pattern allows for interleaving of the diamonds on the front and back panel layers, such that only a small portion of the back panel electrodes are blocked by those on the front panel. This optimizes the presented electrode surface area (refer to Figure 3).

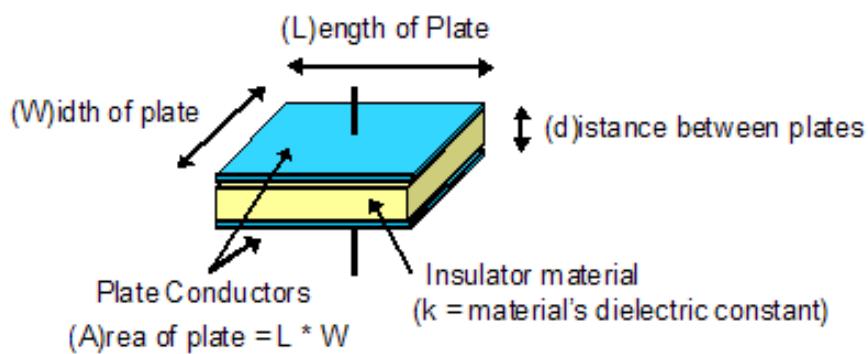
FIGURE 3: DIAMOND ELECTRODE PATTERN ALIGNMENT



CAPACITANCE

Capacitance is the ability of a material to store electrical charge. A simple capacitor model is two conductive plates held separated by an insulator (refer to Figure 4).

FIGURE 4: SIMPLE CAPACITOR



Capacitance (farads) = $k \cdot \epsilon_0 \cdot (A/d)$
where ϵ_0 = permittivity of free space = $8.854e - 12 \text{ F/m}$

The value of capacitance is dependent on:

- Surface area of the plates
- Distance between the plates
- Materials constant for the insulator between plates

Capacitance of Touch

The capacitance of touch is dependent on sensor design, sensor integration, touch controller design and the touch itself.

Some examples of sensor properties that affect its capacitance are:

- Front panel thickness
- Electrode geometry and pitch
- X,Y layer-to-layer spacing
- Rear shielding

The capacitance of the sensor and of the touch can vary significantly, based on the many variables. Some example values are shown in Table 1 to give an idea of scale for discussion.

TABLE 1: TYPICAL PARASITIC AND TOUCH CAPACITANCE

Item	Capacitance
Electrode Parasitic	100 pF
Strong Electrode Touch	0.5 to 1.0 pF
Weak Electrode Touch	0.05 pF

- The Electrode Parasitic capacitance is the capacitance presented by the touch sensor system for an electrode that is not being touched.
- The Strong Electrode Touch capacitance is the change in capacitance from a touch directly over an electrode.
- The Weak Electrode Touch capacitance is the change in capacitance from a touch next to an electrode. In other words, the effect on an electrode next to an electrode which has a touch over it.

Capacitance Measurement Methods

There are a number of methods to measure capacitance. Some example methods are:

- Relaxation Oscillator
- Charge Time vs Voltage
- Voltage Divider
- Charge Transfer
- Sigma-Delta Modulation

CAPACITIVE SENSING MODULE (CSM)

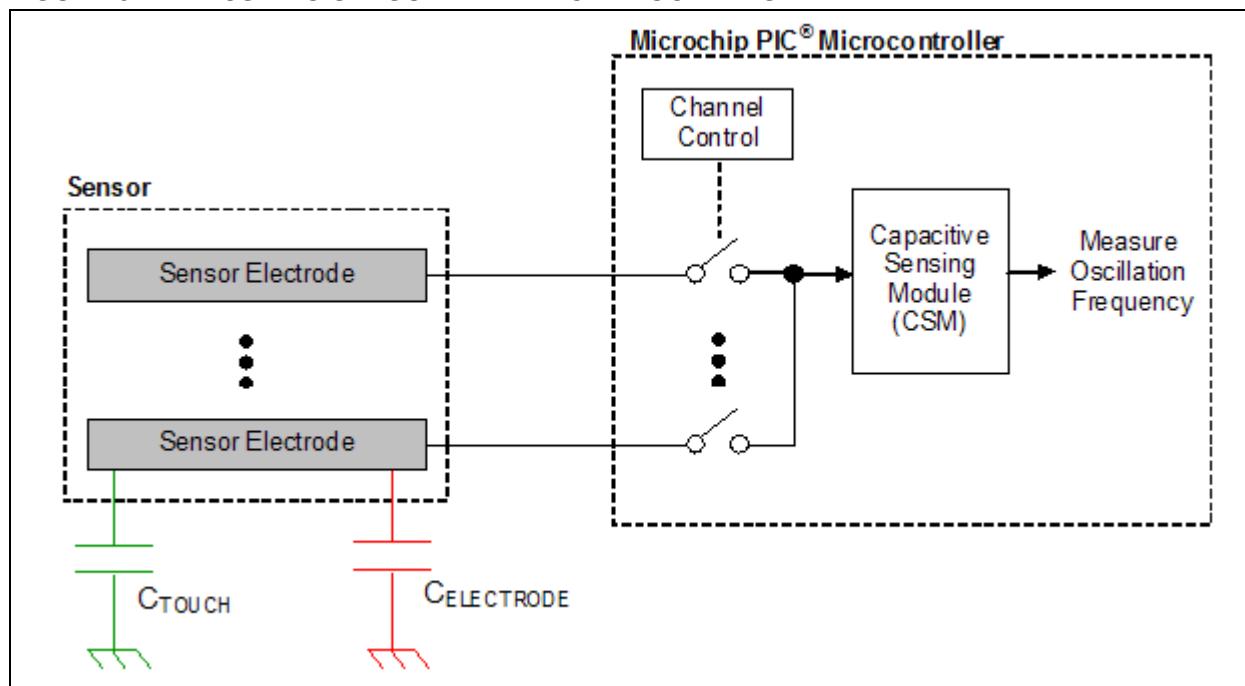
The CSM is a proprietary Microchip hardware module available in a variety of different PIC microcontrollers. The CSM enables the measurement of capacitance, based on the relaxation oscillator methodology.

The CSM produces an oscillating voltage signal for measurement, at a frequency dependent on the capacitance of an object connected to the module. The basic concept is as follows:

- CSM oscillates at some frequency, dependent on the capacitance of a connected sensing electrode.
- CSM frequency changes when a touch is introduced near the sensing electrode because the touch changes the total capacitance presented by the electrode.
- CSM frequency change is used as an indication of a touch condition.

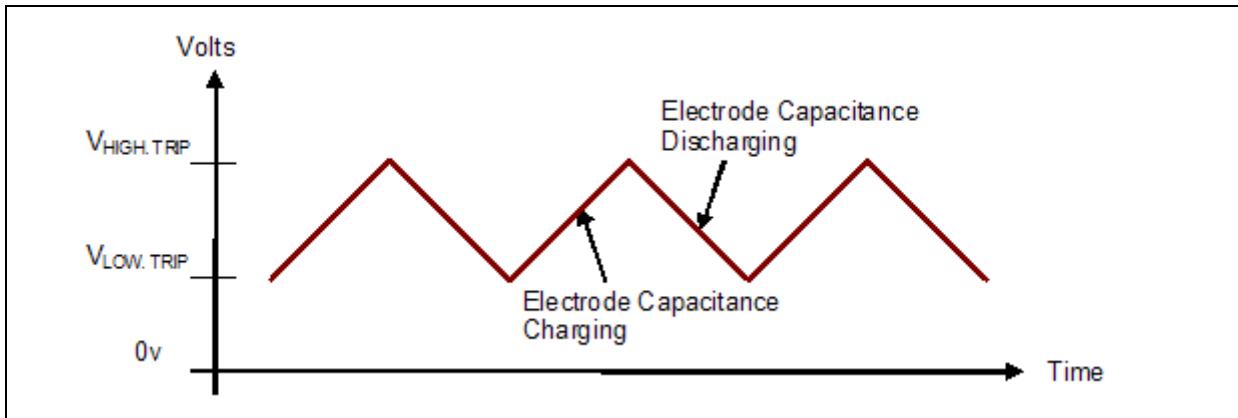
A simplified block diagram of the CSM to sensor interface is shown in Figure 5.

FIGURE 5: CSM TO SENSOR INTERFACE BLOCK DIAGRAM



An example of the CSM measurement waveform is shown in Figure 6. It is a triangle wave because the CSM drives with a constant current source/sink.

FIGURE 6: CSM WAVEFORM



The CSM hardware can be user configured for the oscillating trip point voltage levels and the charge/discharge current.

Trip Point Voltage Adjustment – Changing the CSM's high and low trip point voltages will alter both the CSM waveform's frequency and amplitude. Expanding the trip points to increase the waveform amplitude can improve the Signal to Noise Ratio (SNR). The flexibility to change the trip voltages enables optimization for different applications.

Charge/Discharge Current Adjustment – Changing the CSM's constant current charge/discharge value will alter the CSM waveform's frequency.

Higher current settings can improve the SNR. The flexibility to change the value of the constant current source/sink enables optimization for different applications.

Measuring self capacitance does not easily lend itself to supporting multi-touch events, which requires correlation of multiple X and Y touched electrodes into multiple (X,Y) touch coordinates.

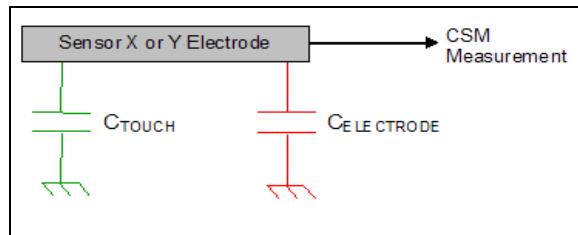
Self Capacitance Measurement Method

1. Connect a desired electrode for measurement to the CSM.
2. Ground all other sensor electrodes.
3. Measure the time duration required for a defined number of CSM cycles to occur.
 - a) Chip timer TMR0 is used to count the desired number of CSM cycles.
 - b) Chip timer TMR1 is used to measure the time duration for the desired number of CSM cycles to occur.
4. Repeat steps 1-3 until all sensor electrodes have been measured.
5. Subtract the measured value for each electrode from a previously acquired "no-touch" baseline value for the respective electrode.
6. Compare the measured electrode change from baseline against a defined touch threshold value.

SELF CAPACITANCE

Self capacitance is defined as the capacitive load, relative to circuit ground, that an electrode presents to the measurement system (refer to Figure 7).

FIGURE 7: SELF CAPACITANCE

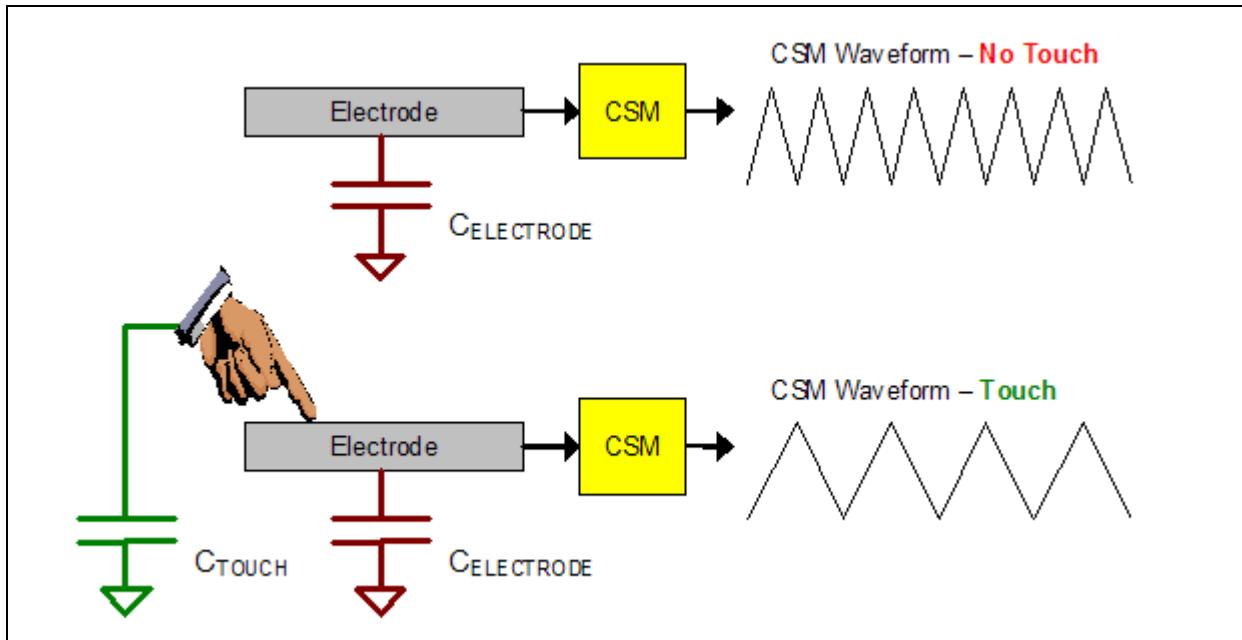


The self capacitance of each X and Y axis electrode on a sensor can be independently measured.

Measuring the self capacitance of each individual sensor electrode provides for the determination of the (X,Y) location of a single touch event in progress.

Self Capacitance Example CSM Waveforms

Example CSM waveforms for no-touch and touch conditions are shown in Figure 8.

FIGURE 8: SELF CAPACITANCE EXAMPLE CSM WAVEFORMS

Self Capacitance Example Measurement Values

The measured self capacitance values are dependent on many variables, such as: sensor, integration of the sensor and controller configuration. Self capacitance example values are shown in Table 2.

TABLE 2: SELF CAPACITANCE EXAMPLE VALUES

Sensor Layer	CSM Cycles Counted	Scan Time per Electrode	Measured Timer TMR1 Counts		
			No-Touch	Touch	Delta
Top	48	400 us	4400	4600	200
Bottom	89	400 us	11000	11200	200

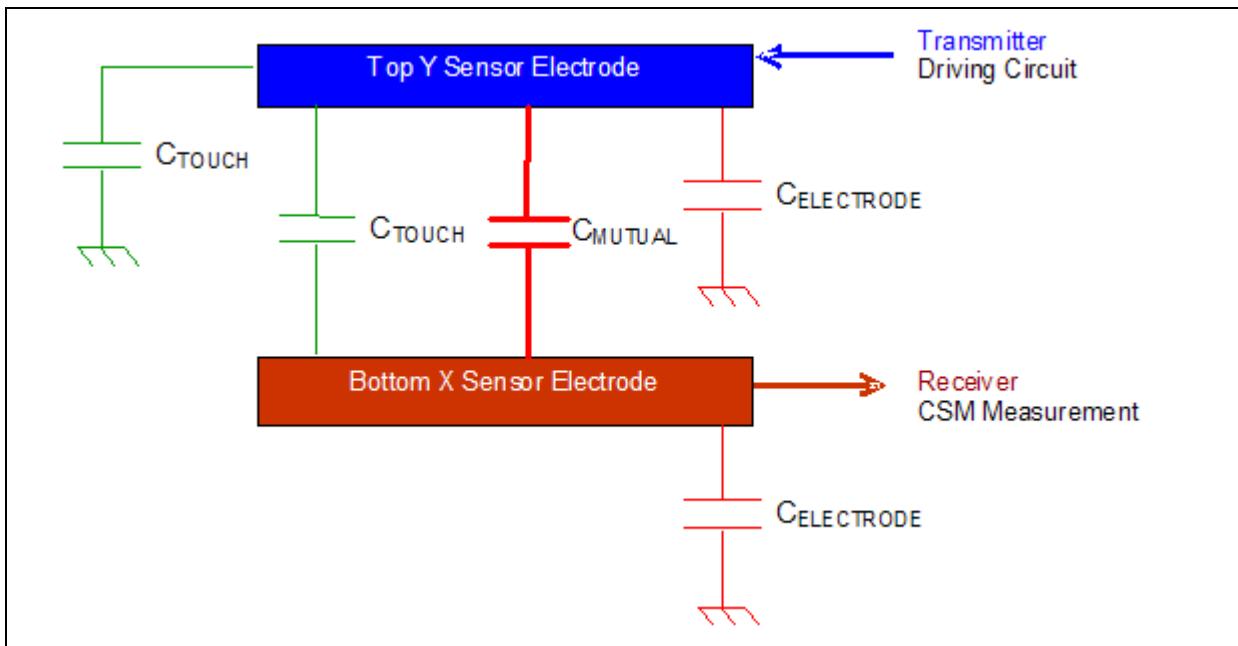
MUTUAL CAPACITANCE

Mutual capacitance is the capacitive coupling between objects. One example is the mutual capacitive coupling between an X and Y axis electrode on a projected capacitive touch sensor.

The mutual capacitance measurement can be implemented with the electrodes on one sensor layer serving as receivers and the electrodes on the opposing sensor layer serving as transmitters.

The capacitance relationships are shown in Figure 9 for a single transmitter electrode and a single receiver electrode on the two opposing sensor layers.

FIGURE 9: MUTUAL CAPACITANCE



A node is defined as the intersection of any single top sensor layer electrode with any single bottom layer electrode. A fully functional multi-touch system can be developed by taking mutual capacitance measurements at each node of the sensor. However, the time required to measure the entire sensor can be dramatically improved by only performing mutual capacitance measurement on dynamically selected nodes. See the “**Self and Mutual Capacitance Measurements Combined**” section for an explanation.

Note: Measurements based on mutual capacitance enable position tracking of multiple simultaneous touch events occurring on a projected capacitive touch sensor. This is accomplished by performing mutual capacitance measurements at receiver/transmitter nodes (intersections) in order to correlate touched X and Y axis electrodes into (X,Y) coordinate pairs.

Overview of How Mutual Capacitive Works

A receiver electrode on the sensor's bottom layer is connected to the CSM, which will oscillate at some frequency based on the capacitance of the connected electrode.

A transmitter electrode on the sensor's top layer is driven with voltage pulses, synchronized to the CSM's frequency.

The transmitter pulses inject current into the receiver electrode's capacitance, through the mutual capacitance between the transmitter and receiver electrodes.

The CSM's frequency slows down because the synchronized pulse current is injected into the receiver electrode's capacitance when the CSM is trying to discharge it.

A finger touch near the node (intersection) of the receiver and transmitter electrodes provides a capacitively coupled ground path, which shunts away some of the transmitter pulse injected current.

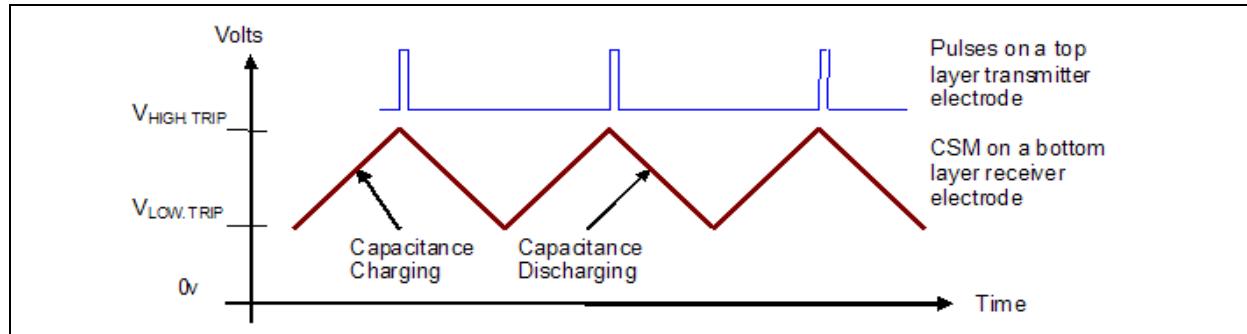
The CSM's frequency speeds up because the finger touch steals some of the pulse injected current from the receiver electrode.

The change in CSM frequency is used as an indication of the touch condition.

Mutual Capacitance Measurement Method

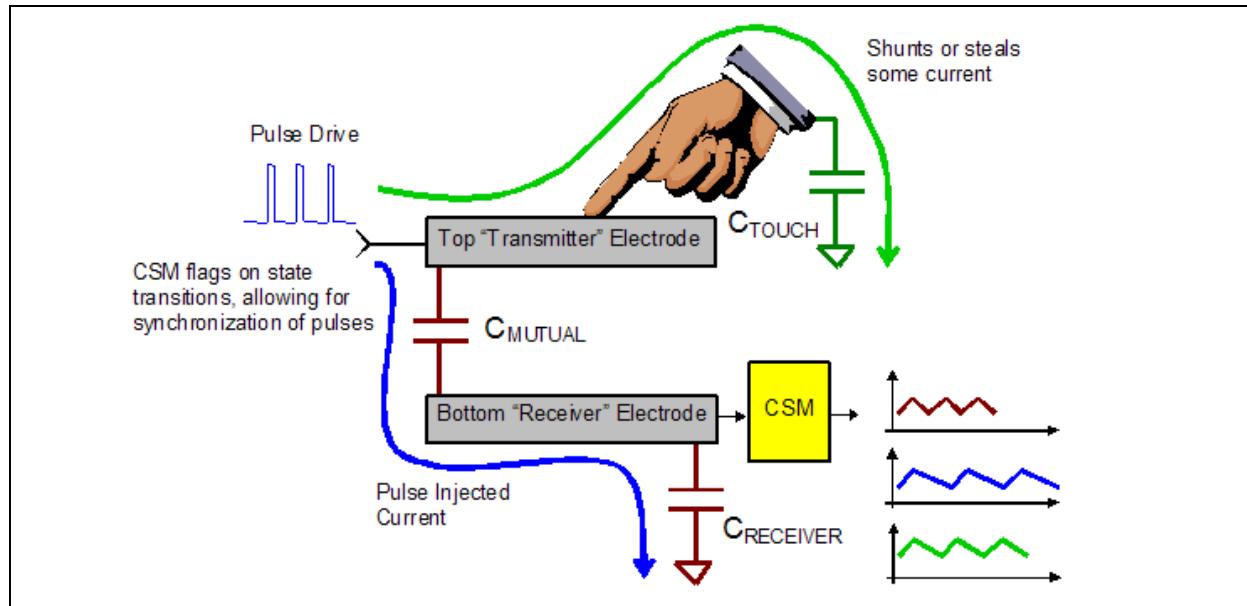
1. Select a receiver electrode on the sensor's bottom layer for measurement and connect it to the CSM. The CSM will oscillate at some frequency, based on capacitance of the connected receiver electrode.
2. Select a transmitter electrode on the sensor's top layer and drive it with a voltage pulse, each time the CSM waveform changes state from charging to discharging. The pulse injects current into the receiver electrode's capacitive load. This slows down the CSM frequency because the pulse is synchronized to when the CSM is discharging the capacitive load of the receiver electrode.
3. Ground all other sensor electrodes.

FIGURE 10: TRANSMITTER PULSE SYNCHRONIZATION



4. Measure the time duration for a defined number of CSM cycles to occur for the selected receiver electrode.
5. A finger touch near the node (intersection) of the selected receiver and transmitter electrodes provides a capacitively coupled "touch" shunting path for some of the pulse injected current. The shunting path steals some of the pulse injected current, which causes an increase in the CSM frequency.

FIGURE 11: CSM AND MUTUAL CAPACITANCE METHOD

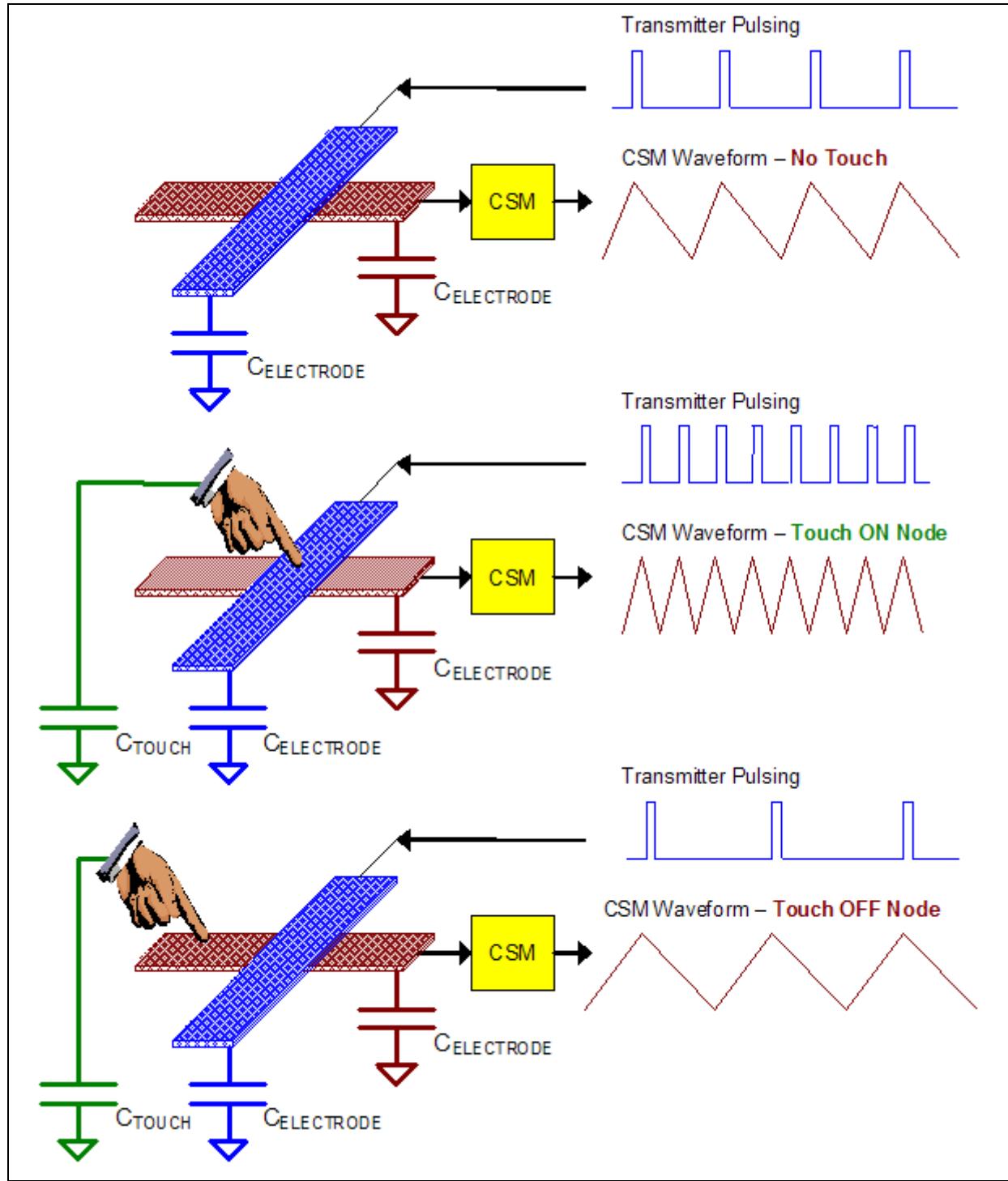


6. Repeat steps 2-5 until each top layer electrode has served as a transmitter for a given receiver electrode.
7. Repeat steps 1-6 until each bottom layer electrode has served as a receiver electrode.
8. Subtract the measured value for each node (receiver and transmitter electrode intersection) from a previously acquired "no-touch" baseline value for the corresponding node.
9. Compare the measured node change from baseline against a defined touch threshold value.

Mutual Capacitance Example CSM Waveforms

Example CSM waveforms no-touch and touch conditions are shown in Figure 12.

FIGURE 12: MUTUAL CAPACITANCE EXAMPLE CSM WAVEFORMS



Note that the CSM frequency increases when a touch occurs at the selected node and decreases when the

touch is away from the selected node.

Mutual Capacitance Example

Measurement Values

The measured mutual capacitance values are dependent on many variables, such as: sensor, integration of the sensor and controller configuration. Mutual capacitance example values are shown in Table 3.

TABLE 3: MUTUAL CAPACITANCE EXAMPLE VALUES

CSM Cycles Counted	Scan Time per Node	Measured Timer TMR1 Counts		
		No-Touch	Touch	Delta
14	1 ms	11000	10850	150

SELF AND MUTUAL CAPACITANCE MEASUREMENTS COMBINED

Performing self capacitance measurements on all X and Y axis electrodes provides a fast system response time, but it does not easily support multi-touch tracking of multiple simultaneous touch events.

Performing mutual capacitance measurements on all X and Y axis electrode nodes (intersections) supports tracking the (X,Y) coordinates of simultaneous multi-touch events, but the system response time is degraded when compared to the self capacitance method.

A unique utilization of both self and mutual capacitance methods provides multi-touch capability with improved systems response time.

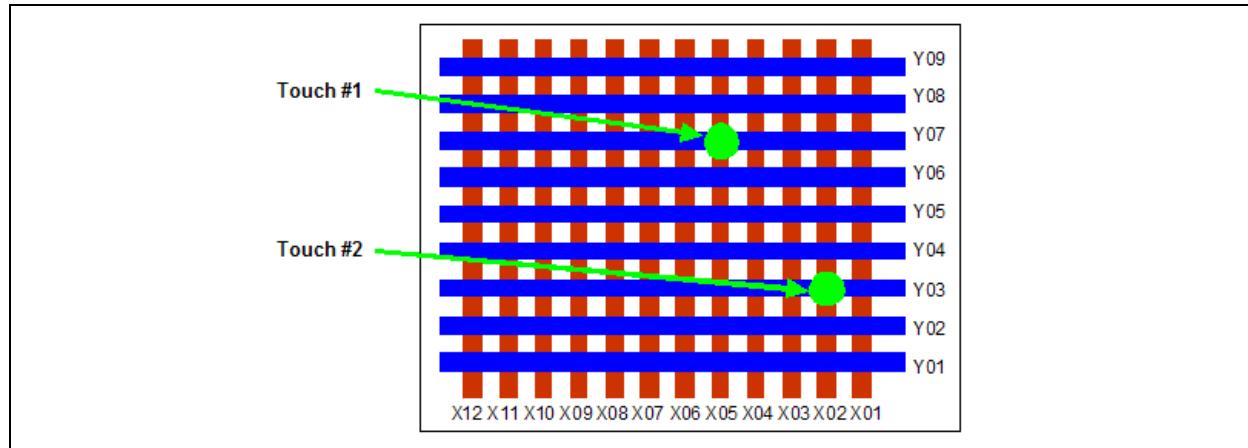
Self on All Electrodes with Mutual to Correlate Touched Electrodes Method

1. Perform self capacitance measurements on all sensor electrodes.
2. Determine which X and Y axis electrodes are experiencing a touch event.
3. Perform mutual (transmitter/receiver) capacitance measurements on only the X and Y electrodes identified as being touched from the self capacitance measurements.
4. Correlated touched X and Y axis electrodes into one or more (X,Y) touch coordinates.

Dual Touch Example

Figure 13 is an example sensor with a simulated dual-touch condition. The location of two touches are represented as green dots.

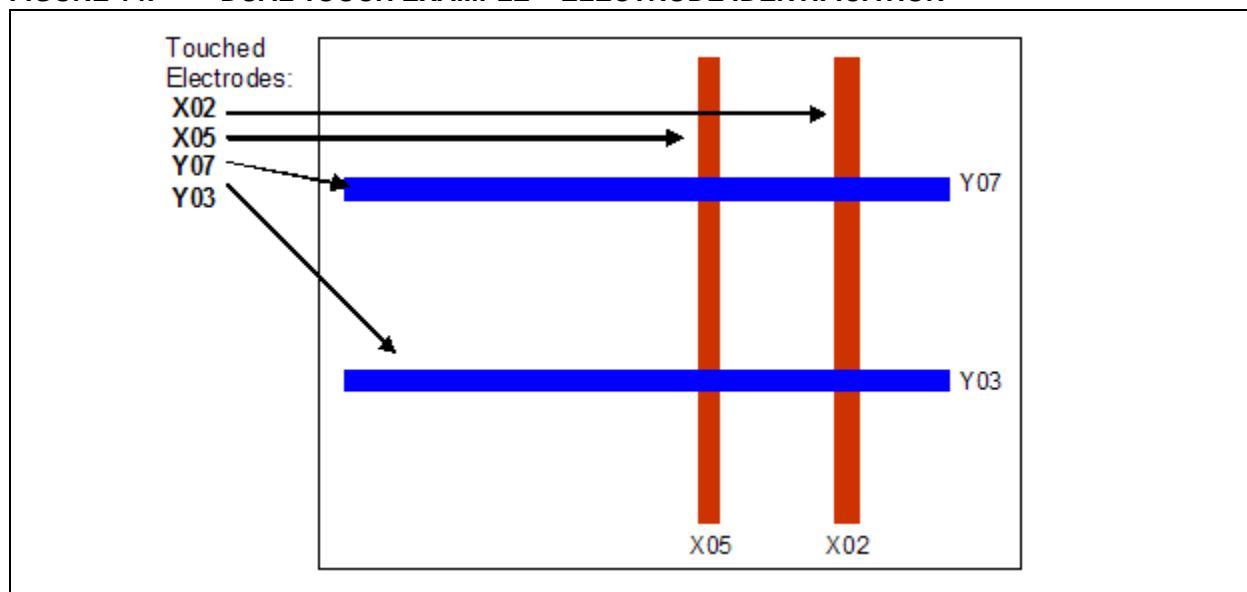
FIGURE 13: DUAL TOUCH EXAMPLE – FULL MAP



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1. Measure the self capacitance of each individual sensor electrode.
 - a) Self capacitance on X01
 - b) :
 - c) Self capacitance on X12
 - d) Self capacitance on Y01
 - e) :
 - f) Self capacitance on Y09
2. Compare each of the 12 X electrode self capacitance delta measurement to a touch threshold value.
 - a) Identify the touched X electrodes as X02 and X05
3. Compare each of the 9 Y electrode self capacitance delta measurement to a touch threshold value.
 - a) Identify the touched Y electrodes as Y03 and Y07

FIGURE 14: DUAL TOUCH EXAMPLE – ELECTRODE IDENTIFICATION



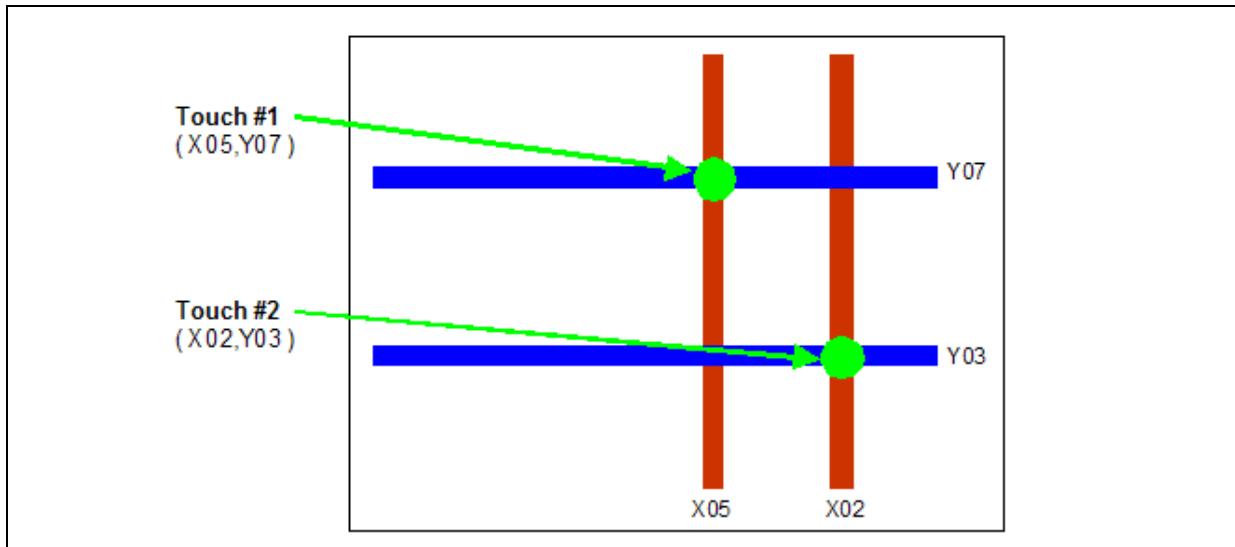
4. Measure the mutual transmitter/receiver capacitance on a subset of the sensor's node set, consisting of the intersections of electrodes X02, X05, Y03, and Y07.
 - a) Mutual measurement 1: Pulse drive transmitter Y07 and measure capacitance of receiver X02.
 - b) Mutual measurement 2: Pulse drive transmitter Y07 and measure capacitance of receiver X05.
 - c) Mutual measurement 3: Pulse drive transmitter Y03 and measure capacitance of receiver X02.
 - d) Mutual measurement 4: Pulse drive transmitter Y03 and measure capacitance of receiver X05.
5. Identify two peaks from the four mutual measurements, in order to correlate the four touched electrodes (X02, X05, Y03, and Y07) into two unique (X,Y) touch locations

TABLE 4: DUAL TOUCH MUTUAL MEASUREMENTS EXAMPLE

Receiver	Transmitter	Mutual Measurement	Peak Mutual	Touches
X02	Y07	20		
X05	Y07	130	X	(X05, Y07)
X02	Y03	110	X	(X02, Y03)
X05	Y03	15		

The touch coordinates for the dual touches have been determined as shown below.

FIGURE 15: DUAL TOUCH EXAMPLE – X AND Y ELECTRODE CORRELATION



BASELINE

Due to parasitic capacitance variations in the touch system that can not be controlled, a touch is determined based on measurement differences from "no-touch" capacitance measurements. The "no-touch" reference values are referred to as the baseline.

The concept is to normalize raw measured touch values using the baseline no-touch values as follows.

Normalized = Raw – Baseline

Note: The baseline reference method is critically important to system operation! It provides "relative", as opposed to "absolute" touch measurement values.

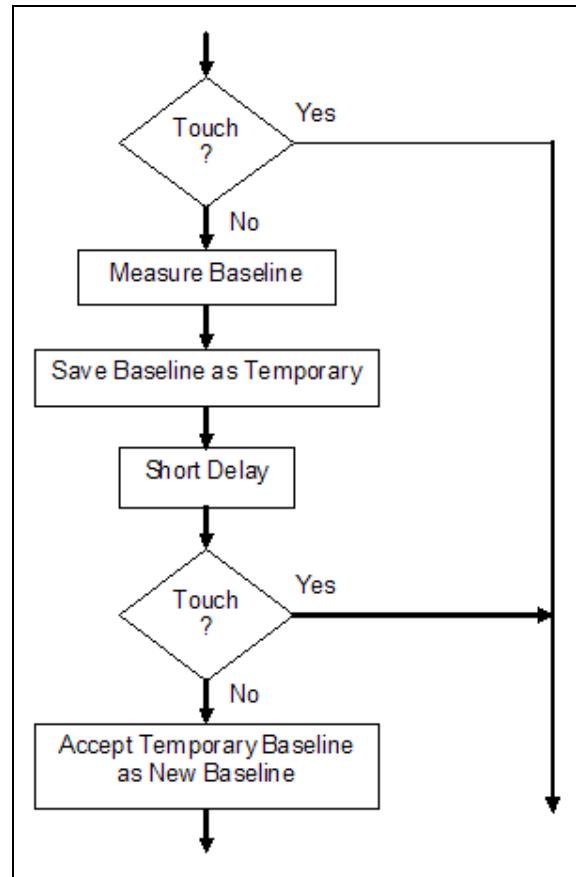
The baseline image contains a measured self capacitance value for every sensor electrode and a measured mutual capacitance value for every sensor node.

A new baseline image of the sensor's "no-touch" capacitance is taken approximately every 800 ms, when there is no touch activity.

A "no-touch" condition is checked to exist at the beginning and end of measuring a new baseline, before it is accepted for use.

The baseline taking logic is shown in Figure 16.

FIGURE 16: BASELINE LOGIC



RESOLUTION

Resolution is defined as the smallest change in the touch location, which can be discriminated. It is the smallest measurable step size of the system.

The coarse resolution of a projected capacitive sensor is the physical distance between electrodes, sometimes called the pitch spacing. For example, if the electrodes are spaced 5 mm apart on the sensor, then the coarse touch resolution is 5 mm.

The coarse electrode pitch on a given sensor usually does not provide the desired level of touch system resolution. The touch resolution can be greatly improved from the coarse sensor's electrode pitch by more finely interpolating touch positions between adjacent electrodes.

Interpolation Method

The basic interpolating steps are as follows.

1. Determine the coarse touch position by identifying the electrode with the peak measured signal.
2. Determine the fine touch position by calculating a ratio of the measured signal strength for the two electrodes that are adjacent to the identified peak electrode.

The design implementation is based on a set resolution between each pair of adjacent electrodes of 128 points. The overall resolution for a sensor layer will be this electrode resolution of 128 times one less than the number of electrodes making up the layer.

For example, a sensor layer with 9 electrodes would have a total resolution of:

$$128 * (9 \text{ electrodes} - 1) = 1024 \text{ points}$$

The center of each electrode has a value that corresponds to incrementing multiples of the 128 point electrode resolution.

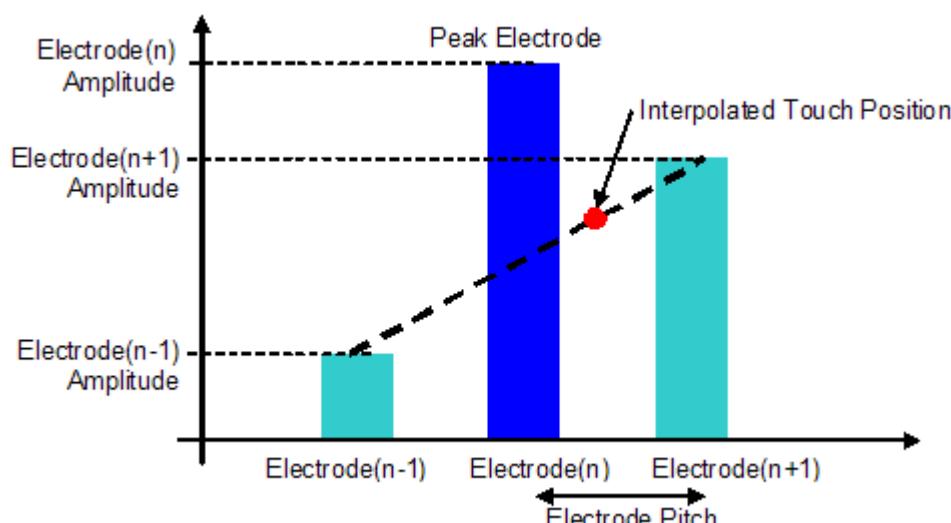
FIGURE 17: LAYER RESOLUTION MAP EXAMPLE

Position Value	Y-axis Electrodes
1024	Y09
896	Y08
768	Y07
640	Y06
512	Y05
384	Y04
256	Y03
128	Y02
0	Y01

The interpolation is calculated as follows:

$$\text{InterpolatedPosition} = \text{Electrode}(n)\text{Position} + \left(\frac{\text{ElectrodePitch}}{2} \right) \cdot \left(\frac{\text{Electrode}(n+1)\text{Amplitude} - \text{Electrode}(n-1)\text{Amplitude}}{\text{Electrode}(n)\text{Amplitude}} \right)$$

FIGURE 18: INTERPOLATING TOUCH POSITION



Conceptually, the resolution can be adjusted by changing the set 128 electrode resolution to some other value. Increasing the electrode resolution will likely require lengthening of the capacitance measurement durations in order to increase the measured signal. The trade off is that higher resolution will slow the speed at which the sensor can be measured and therefore decrease the touch responsiveness of the system.

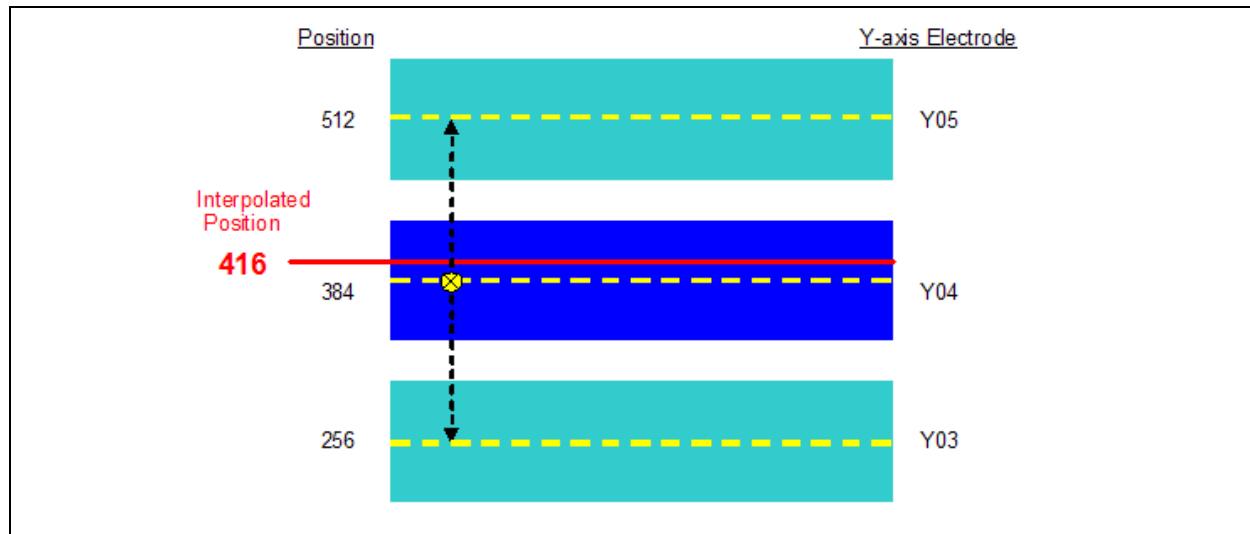
TABLE 5: ELECTRODE INTERPOLATION CALCULATION EXAMPLE VALUES

ID	Position	Measured Value	Peak or Adjacent	Formula ID
Y03	256	25	Adjacent to peak	Electrode(n - 1)
Y04	384	100	Peak	Electrode(n)
Y05	512	75	Adjacent to Peak	Electrode(n + 1)

Interpolated Position:

$$\begin{aligned}
 &= \text{Electrode}(n)\text{Position} + (\text{ElectrodePitch}/2) \cdot (\text{Electrode}(n + 1)\text{Amp} - \text{Electrode}(n - 1)\text{Amp})/\text{Electrode}(n)\text{Amp} \\
 &= 384 + (128/2) \cdot (75 - 25)/100 \\
 &= 416
 \end{aligned}$$

FIGURE 19: ELECTRODE INTERPOLATION CALCULATION EXAMPLE MAP



FILTERING

Many different software filtering algorithms can be implemented to enhance the quality of reported touch positions. Software filtering, however, can sometimes be a trade off with the controller's code space, RAM space, and the time required to resolve touch events on the sensor.

Sampling Filter

A sampling filter collects a number of capacitance measurement samples, then calculates the average value of the sample set. This can be an effective filter, but many applications may not need it to be implemented.

EXAMPLE ELECTRODE INTERPOLATION CALCULATION

An example interpolation calculation is shown in Figure 19 for a condition in which electrode Y04 has been identified as having the peak measured amplitude for the Y-axis layer.

Integration Filtering

An integration filter is achieved by adjusting the length of time the capacitance is measured. This is done by increasing the number of CSM cycles that are counted for the time-based measurement.

Increasing the number of CSM cycles that are counted increases the level of the integration filtering, but it comes at the expense of taking more time to perform the measurements.

Touch Detection Filter

A touch detection filter compares a measurement sample to a defined touch threshold value. The measured sample is only accepted if it passes the test against the threshold value.

Coordinate Filtering

A coordinate filter collects a number of sequential reported touch coordinates and averages them together into the next coordinate to be reported. It is a FIFO (First In, First Out) or "ring buffer" type of filter, applied to touch coordinates.

A good balance of responsiveness and smoothing can be achieved by performing a rolling average of approximately 4 coordinate values.

Touch coordinates are sent from the controller to the host system in a 5-byte data packet. The packet contains: multi-Touch ID #, Pen-Up/Down touch status, X-axis coordinate, and Y-axis coordinate.

The touch coordinate report data packet is shown in Table 6.

TOUCH REPORTING PROTOCOL

TABLE 6: TOUCH COORDINATE REPORTING PROTOCOL

Byte No.	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
1	1	T1	T0	0	0	P2	P1	P0
2	0	X6	X5	X4	X3	X2	X1	X0
3	0	0	0	0	0	X9	X8	X7
4	0	Y6	Y5	Y4	Y3	Y2	Y1	Y0
5	0	0	0	0	0	Y9	Y8	Y7

T<1:0>: Multi-Touch Point ID Number

00 = Touch #0

01 = Touch #1

P<2:0>: Pen/Touch Status

000 = Pen-up

001 = Pen-Down

X<9:0>: X-axis Coordinate Value

0000000000 = 0

:

1111111111 = 1023

Y<9:0>: Y-axis Coordinate Value

0000000000 = 0

:

1111111111 = 1023

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