RX200, RX100 Series

Overview of CTSU operation

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Introduction

This document gives an operational overview of the capacitive touch sensing unit (CTSU) associated with a variety of RX and Synergy MCUs, including functioning principals and waveforms describing its operation in mutual and self-capacitive modes.

Target Device

RX230, RX231, RX130, and RX113.

Contents

1. The components of capacitive touch

Renesas’ capacitive touch solution takes advantage of interactions a human body has with an electrostatic field generated by the microcontroller unit (MCU) to determine user input. The peripheral, referred to as the capacitive touch sensing unit (CTSU), measures a finger interacting with the capacitive sensor starts by generating an electrostatic field. Here the peripheral takes ambient measurements via the CTSU by measuring the parasitic (stray) capacitance between conductors or between two pads. The CTSU monitors the human interaction and via some specialized circuitry produces digital counts. These digital counts vary depending upon the interactions with the environment; as a user interacts with the sensor, these counts will eventually exceed a threshold, which can be represented in software as a touch. An overview of this process is shown in Figure 1.

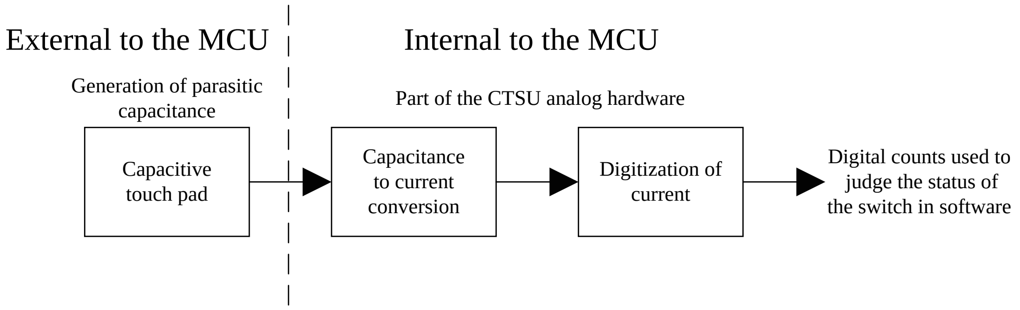

Figure 1: Block diagram describing the high-level overview of the different parts of a capacitive touch system.

An understanding of how the CTSU measures the interaction that the user has with the electrodes and what creates this the parasitic capacitance/electrostatic field are key to designing a robust system.

2. Generation of the Electrostatic Field

The electrostatic field that the MCU creates is represented as a capacitor that appears between the electrode or conductor, and any surrounding metal structure. The metal structure can include any of the following neighboring the electrode, attached to the TS port:

- Metal case
- Reference plane
- Other traces
- Another electrode

Since the coupling between the electrode and its environment does not change drastically over time, it can be represented as a constant capacitance C_p. When a finger interacts with the electrode and that stray capacitance, the result is a change in total capacitance by adding its own capacitance to it, given by C_f. With the addition of finger capacitance the total capacitance in the system becomes (1). This forms the basis for self-capacitive touch.

$$C_{total} = C_{finger} + C_{parasitic} \tag{1}$$

By measuring this increase in capacitance, the MCU is then able to discern the status of the button. This type of scenario describes the self-capacitance method of detecting a touch, as it measures the capacitance that the human body adds to capacitance already formed between itself (the electrode) and its surroundings, demonstrated in Figure 2.

The electrode shape is simple and relies on the system not having a lot of parasitic capacitance between the pad and its surroundings to increase its sensitivity.

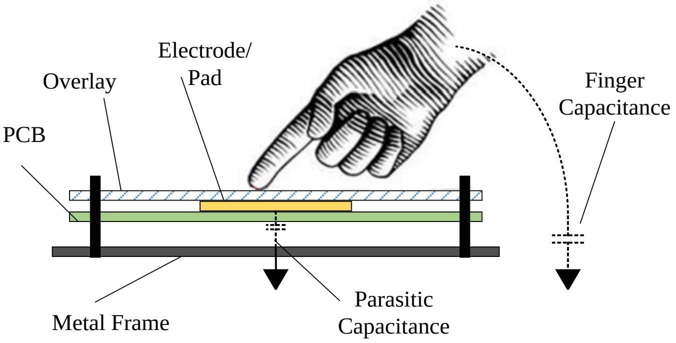

Figure 2: Diagram of a typical self-capacitive touch design.

In contrast to the self-capacitance method, the CTSU is able to drive a pair of TS channels connected to corresponding electrodes to create an electric field not only between the plates and the environment but also between the two plates themselves. The CTSU is then able to drive the plates in such a way as to remove the parasitic capacitance effect from the measurement while still detecting the interaction a human finger has as a decrease in capacitance in the system. Since the CTSU is measuring the finger's interaction with the field between the two plates this results in a more complicated electrode shape, which is represented as an interlocking pattern between a transmitting electrode and a receiving electrode as, shown in Figure 3.

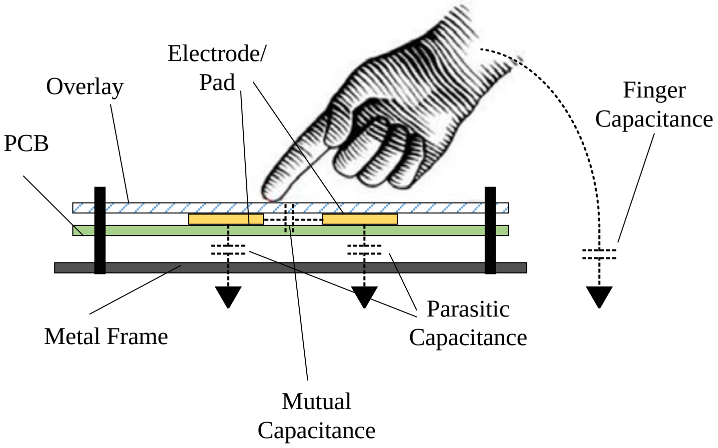

Figure 3: Diagram of a typical mutual-capacitive touch design.

With either method, before describing how the CTSU measures the pad's interaction with the environment it is important to understand how parasitic capacitance common to both methods of measurement is represented in the system.

2.1 Overview of parasitic capacitance

Before describing how parasitic capacitance is estimated, it is important to discuss what this type of capacitance is and how it is represented on a printed circuit board. Parasitic or stray capacitance is something that hardware engineers account for in their design of a return path for currents that occurs between two conductive structures- generally current carrying traces and copper planes under areas of the printed circuit board. Many printed circuit boards maximize this type of stray capacitance in specific areas of the board such that currents have as short a return path as possible to their source creating short loop areas. However, in a capacitive touch system the same techniques could result in a desensitization due to the way the CTSU operates.

As demonstrated in (1), the total capacitance of a pad that the CTSU measures is made up of both this parasitic capacitance and capacitance that the human body forms between the finger and ground. As described in later sections, the CTSU drives current to the pad to create the electrostatic field, which is subsequently measured. The human body capacitance that it must measure, however, is usually a percentage of the parasitic capacitance that forms between conductors.

This leads to two important characteristics a design must account for:

- The higher the percentage that the body capacitance is the more sensitive to touch the system will be. This usually results in a decrease in parasitic capacitance by not having a solid copper ground behind the pads or the non-parallel running of traces.
- Too much capacitance in the system will hinder the ability for the CTSU from estimating the total capacitance in the system as the driver will not be able to charge the total system capacitance.

Since body capacitance is outside the control of the designer, reducing the parasitic capacitance between the pad/trace and surrounding objects is accomplished by techniques such as not extending a solid plane under the pad, or by not running long parallel traces. Now that we understand the basics of how parasitic capacitance is formed and affected by a finger next is understanding the CTSU internal operation measures this interaction.

3. CTSU Capacitance Estimation

The CTSU measures the change in capacitance by converting the capacitance that the human body generates to a current via a switched capacitor filter. A switched capacitor filter is comprised of two switches, power, and a capacitor. To drive these components there is also a control signal that controls the sequence and frequency at which the two switches open and close. Together these components make up a switched capacitor filter network that charges and discharges the capacitances in the system. When a finger comes in contact with the sensor, and affects the capacitance the resulting current from this interaction is how the CTSU determines interaction with the electrode.

3.1 Measuring current via the Self-Capacitance Method

A diagram of these components forming a switched capacitor filter network is shown in Figure 4. This configuration where a singular TS channel is driving a pad describes the self-capacitance method.

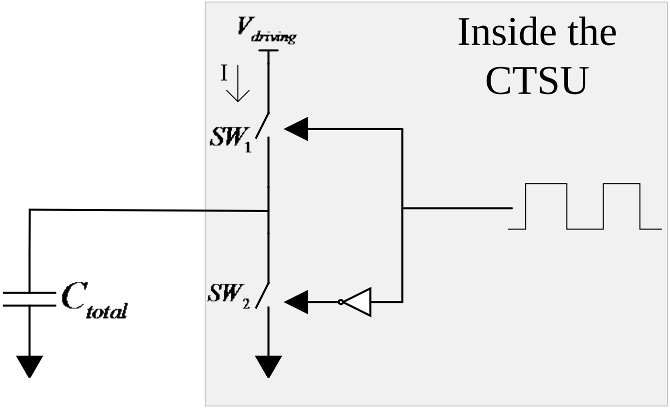

Figure 4: Example of the components making up a self-capacitive touch system

The switches, SW_1 and SW_2 are controlled such that when one is open the other is closed, allowing current to flow into a fully discharged capacitor. The capacitor, in this instance is not a physical capacitor but the total capacitance as described in section 2. The initial charge across the capacitor is zero before the first switch is closed and upon the closure of SW_1 the total capacitance is fully charged. During the next phase of operation after the capacitor is charged SW_1 opens as SW_2 closes simultaneously discharging the capacitor through the second switch. This discharge current does not appear across the supply ($V_{driving}$) as the first switch is open at this time, and current is only measured from the supply side. An example of the current flow as switches turn on and off is described in Figure 5.

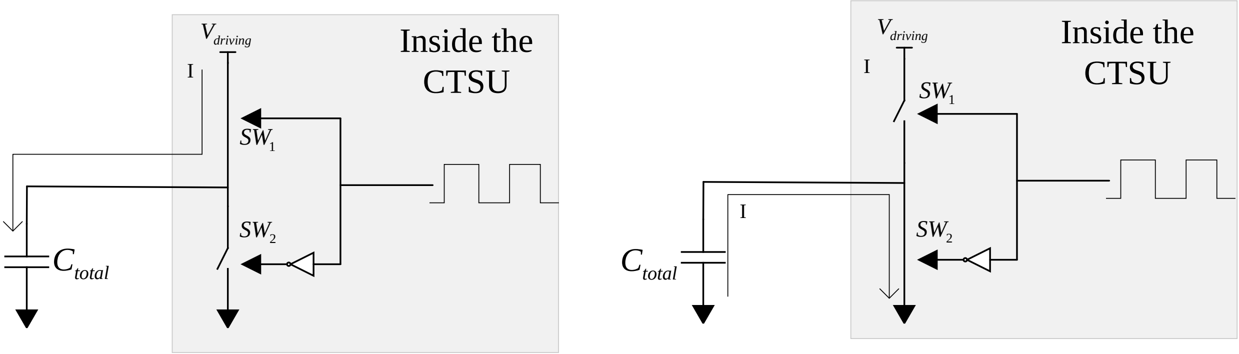

Figure 5: (Left) Current flow with the top switch closed, charging the capacitance, (Right) Bottom switch closed, discharging the capacitance.

The cycle repeats itself, charging and discharging the capacitor as described in Figure 6**.**

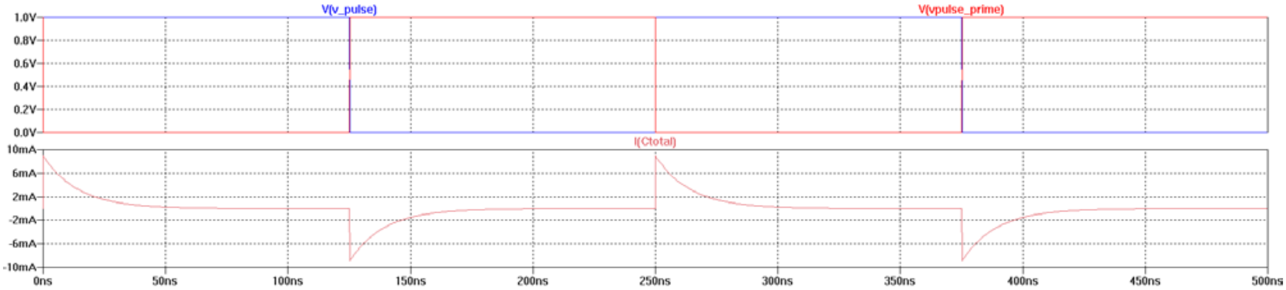

Figure 6: (Top) Pulses controlling the switches, (Bottom) Current flow through the capacitance.

From this operation, we can draw a basic operational relationship between the voltages, frequency and current that defines how to estimate current through capacitance. The CTSU then uses this current measurement to estimate the total capacitance in the system. For example, doing either of the following operations results in a linear increase in current measured by the peripheral:

- Increasing the total capacitance (i.e. a user interacting with the touch pad) while maintaining the same cycle of the two switches as shown in Figure 7.

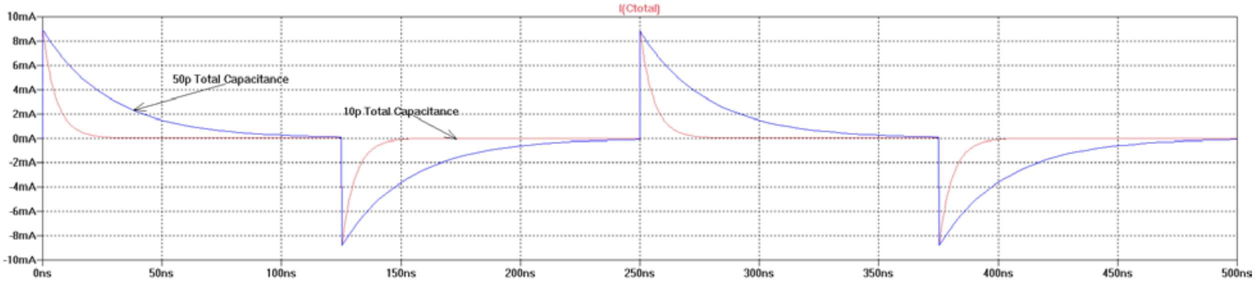

Figure 7: Describing the differences in discharge current over the same period with higher capacitance.

- Increasing the frequency at which the capacitance is charged and discharged as demonstrated in Figure 8: Demonstrating that higher frequency results in more charge/discharge cycles.

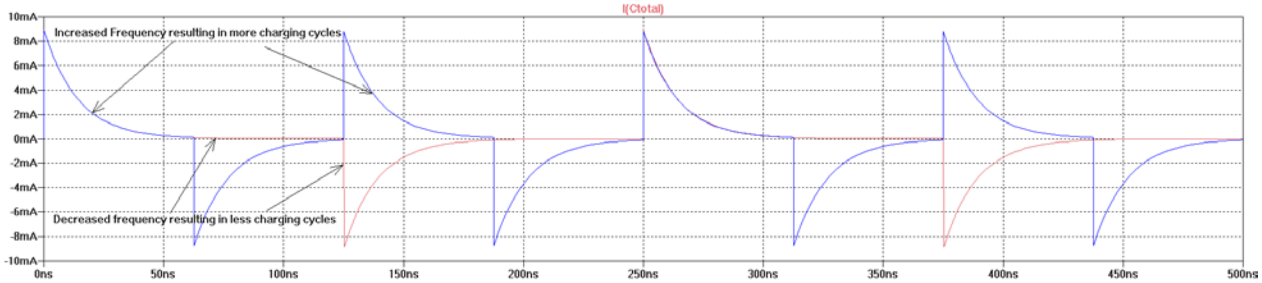

Figure 8: Demonstrating that higher frequency results in more charge/discharge cycles.

From this we are able to draw the following linear relationship (2) between the charging/discharging current, the capacitance, frequency, and driving voltage from the CTSU.

$$I_{measured} = v_d \, f_{switch} c_{total} \, \big|_{c_{total} = c_{finger} + c_{parastic}} \qquad (2)$$

3.2 Measuring current via the Mutual-Capacitance Method

In order to measure the mutual capacitance between the two neighboring pads (as shown in Figure 9) the CTSU must account for the parasitic capacitances between the individual RX and TX pads and any surrounding conductive structure. The CTSU switch setup is similar to the self-capacitance method, but instead of one pair of switches, there are now two and one pair is driven out of phase with respect to the other.

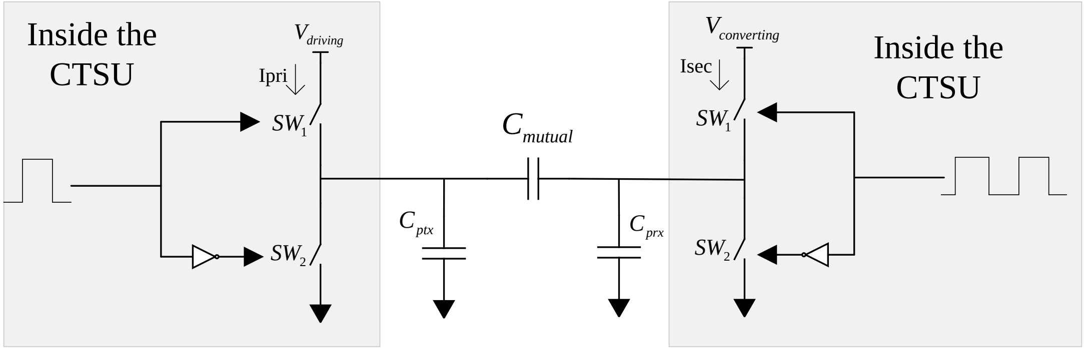

Figure 9: Diagram demonstrating the different parts of a mutual touch system being made up of two switches described in Figure 4.

This bidirectional current flow results in the creation of a field between the transmitting and receiving electrode attached to the pulse generator (Tx) and current detector (Rx). An overview of the current flow is shown in Figure 10.

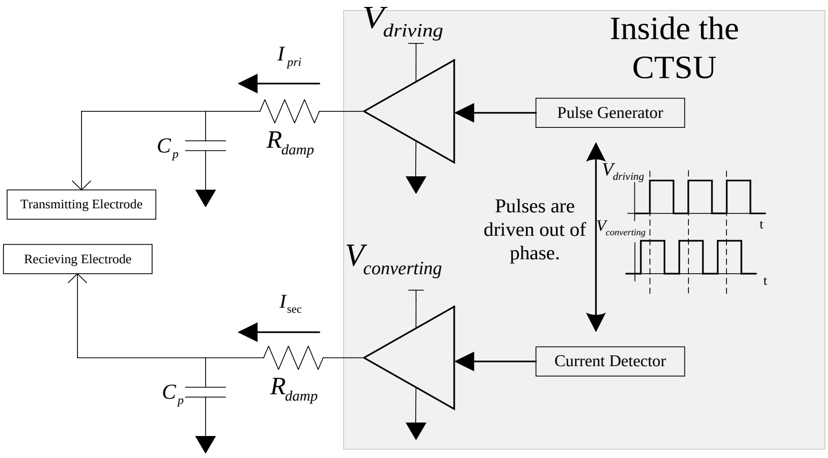

Figure 10: Diagram describing the current flow and voltage pulses

As the driving side of the electrode pulses, it charges both the parasitic capacitance associated with the two electrodes and mutual capacitance between the two electrodes. The primary current expressed as (3).

$$I_{pri} = f_{sw}C_pV_{driving} + f_{sw}C_{mutual}(V_{converting} - V_{driving}) \tag{3}$$

As the driving voltage goes to zero the converting voltage goes high and begins to drive a pulse from the opposite direction. The secondary current can be described similar to (4).

$$I_{\sec} = f_{sw}C_pV_{driving} + f_{sw}C_{mutual}(V_{converting} + V_{driving}) \tag{4}$$

However, since the currents being drive back and forth we can subtract the primary from the secondary current, resulting in (5).

$$I_{measured} = I_{\sec} - I_{pri} \tag{5}$$

By substituting both (3) and (4) into (5), we realize that because of the driving nature of the mutual method the parasitic capacitance is negated (6).

$$I_{measured} = \underbrace{f_{sw}\cancel{C}_pV_{driving}}_{\text{These terms cancel}} + f_{sw}C_{mutual}(V_{converting} + V_{driving}) - \underbrace{f_{sw}\cancel{C}_pV_{driving}}_{\text{These terms cancel}} - f_{sw}C_{mutual}(V_{converting} - V_{driving}) \tag{6}$$

In addition to negating the parasitic capacitance associated to each channel, the mutual capacitance term is now increased by a factor of two as demonstrated by the expression resolving to (7).

$$I_{measured} = f_{sw}C_{mutual}(2V_{driving}) \tag{7}$$

Comparing (7) to the resulting current from the self-capacitance method (2) it's clear that operating the CTSU using the mutual capacitance method comes with it two advantages due to the analysis of the current flow between the two channels:

- More robust to parasitic capacitance around the pads
- Twice the gain compared to the self-capacitive method of detection

With either method by keeping both the switching frequency and voltage constant, we are then able to estimate the capacitance via the charging and discharging current. The CTSU is able to vary the frequency to keep the relationship proportional during the tuning process, accounting for the variable nature of either the mutual pad design.

3.2.1 Simulation of the currents in Mutual Mode

To get a better understanding of the currents that correlate to the mutual capacitance between the two electrodes we can use SPICE, Figure 9 and Figure 10 to come up with an example simulation. We will represent the parasitic capacitances at $20pF$ and use a nominal damping resistor value of 560Ω on both the transmit and receive side of the switch. Lastly, in order to model the out of phase driving voltages, we will include a phase shift driving the switches such that the transmit side is both 90° ahead and behind the receiving or current detector pulse. The result of these two simulations is contained in Figure 11.

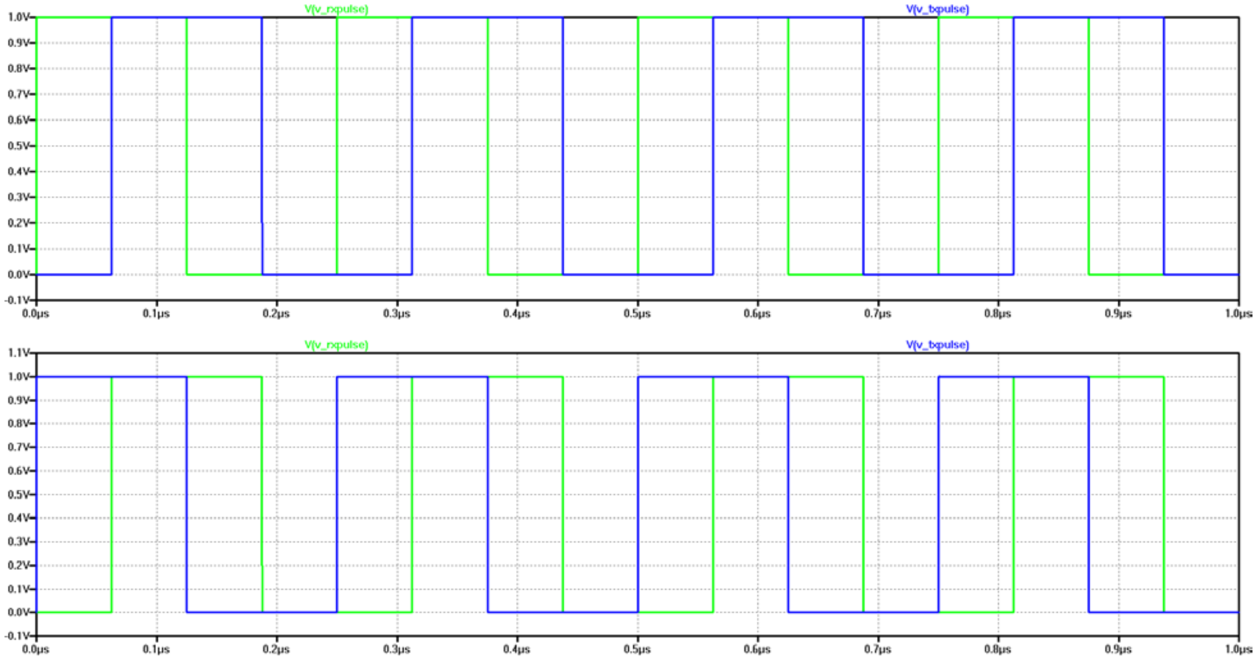

Figure 11: (Top) Driving pulses with the Tx pulse lagging the Rx pulse. (Bottom) Driving pulses with the TX pulse leading the Rx pulse.

More information on how the CTSU times the pulses is contained in the CTSU section of the hardware manual included in any Renesas hardware manual that contains within it, the CTSU as a peripheral. As we simulate the circuit with a 4 Mhz drive frequency, checking the current through the mutual capacitor (I_{cm}) we can visualize the currents in both directions through the capacitor, this is demonstrated in Figure 12 .

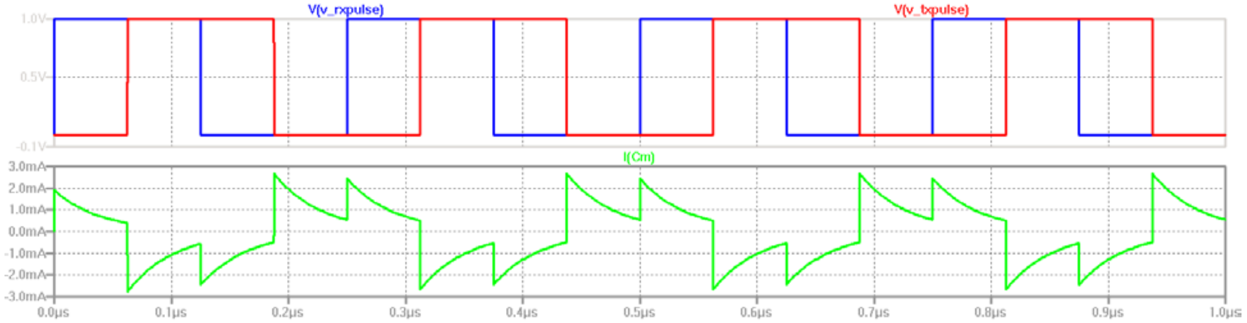

Figure 12: Currents through the mutual capacitance (bottom) overlaid with the driving voltages (top)

The convention for current in Figure 12, Figure 13, and Figure 14, is that from the receive side to the transmit side is positive. As demonstrated, each pulse rising edge from the receive side pushes current to the transmit side, conversely each rising edge from the transmit side pushes current in the other direction. The same relationship appears when the transmit side driver switches to leading the receive side as demonstrated in Figure 13. It is this pushing and pulling of current that creates the electrostatic field between the plates, we see represented as a mutual capacitance in Figure 9.

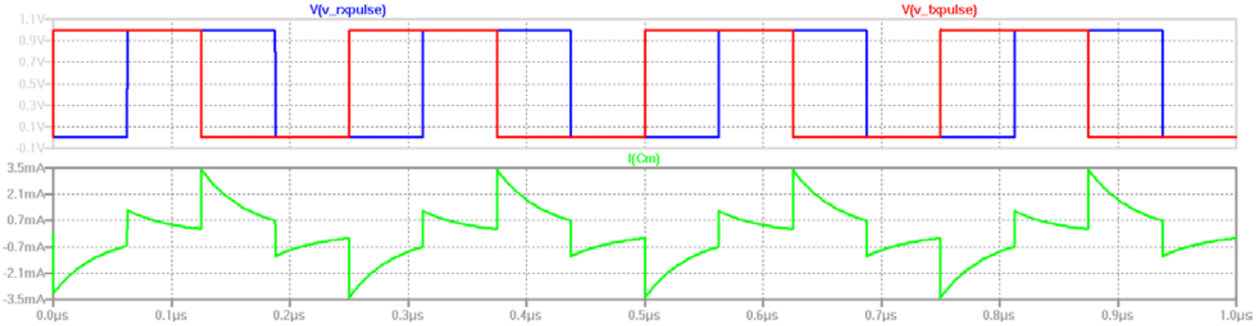

Figure 13: Currents through the mutual capacitance (bottom) overlaid with the driving voltages (top).

The CTSU subsequently measures this current, and from it estimates the capacitance. When a user comes in contact with the pad and lowers the overall capacitance the current lowers as well because of the established switched capacitor relationship (7). This interaction is demonstrated in Figure 14, where the green and blue trace demonstrates the mutual capacitance current before and after touch.

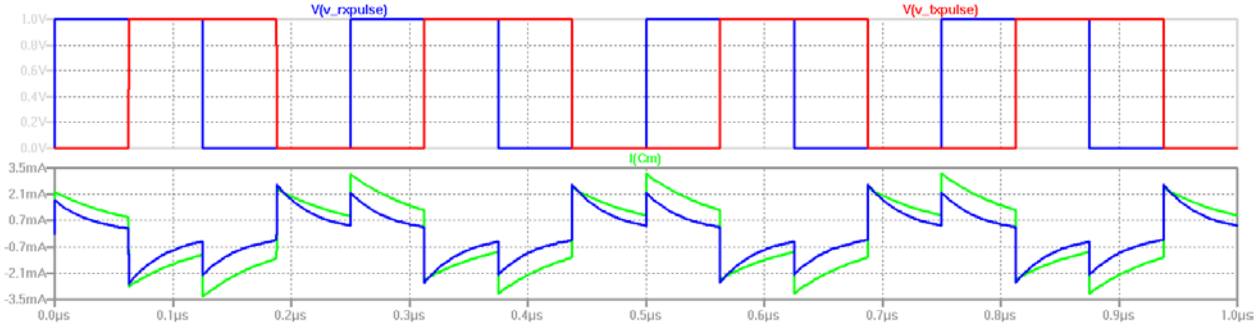

Figure 14: Mutual capacitance current before and after a touch (bottom) overlaid with driving voltages (top).

This resulting current drop is measured similar to the increase in current in the self-capacitance mode is then digitized to allow software to determine interaction with the board.

3.3 Turning the current to a digital measurement

After describing the relationship between current and capacitance in both the mutual and self-capacitance methods, and how the CTSU utilizes the board level parasitics to measure the field, attention is now given to how the digital counts that the CTSU produces from reading the current produced from the switched capacitor filter circuit.

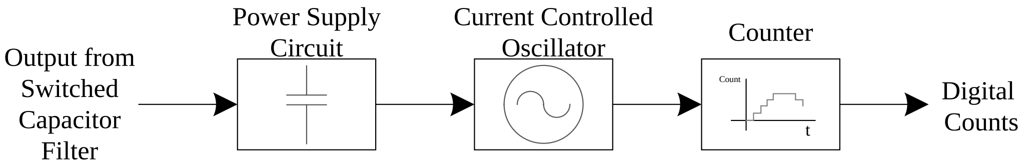

Figure 15: Overview of the current to counts conversion process

The overview of the process is shown in Figure 15, and is made up of the output from the switched capacitor filter, the power supply circuit, current oscillator and the counter. The conversion process starts with the power supply circuit taking the alternating output from the switch capacitor filter described in the previous section and low pass filters it with the connected TSCAP. This smoothed current feeds the current oscillator whose frequency is controlled in proportion to the measured current. This oscillation is then passed along to a counter that counts the number of oscillations producing a count. An overview of the results after each stage is shown in Figure 16 for self-capacitance mode, where the two rows of charts demonstrates how the current amplitude affects the digital counting process.

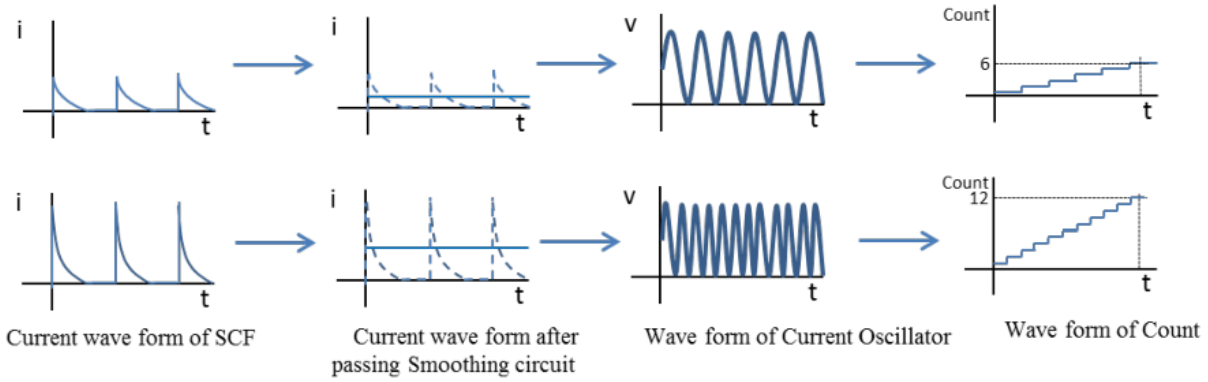

Figure 16: Waveforms describing the current and counts after each part of the conversion process with currents from self-capacitance mode.

This count value is then saved in a register for use by firmware to determine the touch-status of the button.

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Revision History

Rev.	Date	Description	
		Page	Summary
1.00	May 10, 2017	-	Initial Version Released

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