Enabling Single Touch Capacitive Sensing with MSP430

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Agenda

• Overview of Single Touch Applications
• System-Level Careabouts
• MSP430 Implementations
• Keys, Sliders & Demos
• Summary
Applications of Touch Sensing

- Alternative to mechanical switches
  - Low cost
  - Longer life
- Flexible user interface
  - Simple buttons
  - Sliders
- Adaptable
- Useful in...
  - Consumer electronics
  - Appliances
  - Residential control
- ... and almost anywhere a switch is currently used
Touch Sensing Overview

• Different technologies
  ▪ Optical, Resistive, Capacitive, Strain,…

• All detect change in system

• Optical
  ▪ Expensive
  ▪ Complex system design

• Resistive
  ▪ Require sensor material that changes R when touched
  ▪ Relatively low cost, but is an additional element to the BOM

• Capacitive
  ▪ Can be implemented on PCB directly
  ▪ Flexible sensor size & shape
  ▪ Cost is a function of the PCB and any externals needed
Capacitive Methods

• Charge transfer technology
  ▪ Quantum Research Group patented solution
  ▪ Fixed function ICs that measure charge transfer from one sensor C to another
  ▪ Stimulus signal and measurement integrator

• Capacitive measurement via ADC
  ▪ Stimulus signal impacts capacitive sensor element, resulting voltage is measured by ADC
  ▪ ADI implementation using a 16-bit Sigma-Delta to perform C-to-Digital conversion

• Relaxation Oscillator
  ▪ Creates oscillator dependent on sensor C variation & measures frequency

• RC Charge/Discharge
  ▪ Using high frequency clock, times charge and/or discharge times for sensor element with varying C
MSP430 Capacitance Measurement

- Change in capacitance due to physical proximity of a finger or other conductive object

- Method 1:
  - Create oscillator dependent on capacitance of the sensing element
  - Measure freq change when sensor C is changed by touch

- Method 2:
  - Measure R-C charge/discharge where R is constant and the sensor element capacitance changes due to touch
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**Capacitive Fundamentals**

- **Base capacitance created by PCB mechanics**
- **Capacitance change due to changing parasitics**
  - Finger touch proximity (or conductive other source)
- **Minimize base capacitance**
  - Limit parasitics
  - Limit sensor size
- **Maximize impact of change**
  - Match sensor & finger areas for greatest delta-C
  - Minimize distance between sensor and finger
- **Sensitivity**

\[
C = \frac{\varepsilon_0 \varepsilon_r A}{d}
\]

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<th>Dielectric Constant ((\varepsilon_r))</th>
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<td>Air</td>
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Capacitive PCB Sensor

- Copper pour on PCB makes a good sensor element
- ~10-20mil spacing between sensor & adjacent elements
- Size pads to maximize finger overlap for max delta C
- Simple pads can also be good sliders
- For true sliders, sizing pads such that more than one is touched at a time helps determine position
PCB Thickness

- Material and thickness matters
  - Goal 1: Small base C
  - Goal 2: Stable base C

\[ C = \frac{\varepsilon_0 \varepsilon_r A}{d} \]

- As d decreases, the base capacitance increase
- For a given sensor size and insulator thickness, the delta C created by a touch is fairly constant
- This change is a smaller percentage of the base C as d goes down
- Thinner PCBs require more care in insulator selection and thickness
Layout & Grounding

• Minimize noise & signal coupling with solid ground pour on sensor side of PCB

• Hatch pour underneath sensors if possible
  ▪ Solid pour ok for noise, but increases base capacitance (larger A)
  ▪ No pour has no increase in base capacitance but no noise benefits
  ▪ A hatch of 50% is a good compromise
Sensors & Ground Influence

• Tradeoff between PCB ground pour under sensors and sensitivity

• No Pour
  ▪ Low base C
  ▪ Small delta C

• 25-75%
  ▪ Base C increases
  ▪ Larger delta C

• Solid Pour
  ▪ Large base C
  ▪ Harder to influence change = lower delta C
Insulators & Assembly

- An insulator is usually needed between PCB and user
- Insulator material must be non-conductive
- Thin is better
  - $C$ is inversely proportional to the distance between the conductors
- No air should be present between insulator and the sensors on the PCB
  - $C$ is proportional to the dielectric constant
- Use adhesives to secure sensor and insulator
  - Nonconductive adhesives, air-free
  - Those which tolerate temperature and humidity changes well are recommended
Insulator Spacing

• Achievable sensitivity is inversely proportional to insulator thickness

Sensitivity vs. Thickness
(Finger press, 8x8mm pad, 1.5mm FR4 PCB)
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RO System Overview

- Osc created using comparator with frequency a function of sensor capacitance
- Charge/discharge limits set by R’s (1/3 Vcc & 2/3 Vcc)
-Freq is 1/[1.386 x R_c x C_sensor]
- delta C => delta f
RO Frequency Measurement

- Slow interrupt defines window for measurement
- Faster RO periods are counted via Timer_A
- CPU clock speed used to eliminate ISR s/w capture latency error

$\text{ACLK} < \text{RO Freq} < \text{CPU MCLK}$
Measurement Relationships

- Usable counts increase with measurement time
- Using VLO/64 for ACLK & DCO_cal/32768 for SMCLK
  - \( (100K \ R \sim 625kHz \ f_{RO}) \)

\[
\begin{align*}
  f_{RO} &= \frac{1}{1.386 \times R \times C}, \quad t_{RO} = \frac{1}{f_{RO}} \\\n  t_{\text{window}} &= \frac{1}{f_{ACLK} / \text{DIV}_{ACLK} / \text{DIV}_{WDT}} \quad \text{or}\ldots \\\n  t_{\text{window}} &= \frac{1}{f_{DCO} / \text{DIV}_{SMCLK} / \text{DIV}_{WDT}} \\\n  \text{counts} &= \frac{t_{\text{window}}}{t_{RO}}
\end{align*}
\]

![Graph of RO Counts vs. C_Sensor](image)
Complete RO System

- Requires Comp_A+ (needs mux input for multiple sensors)
- One external R per sensor, three for reference feedback
- External connection to TACLK
- Power Vref ladder via port pin for ULP
RO Current Consumption

- Longer \( t_{\text{measure}} = \) more counts
- Also means higher average \( I_{cc} \)
  - DCO: \( \sim 85\mu A @ 1\text{MHz} \)
  - Comp_A+: \( \sim 45\mu A \)
  - CA Vref: \( V_{cc}/(1.5R) \) (for 100k R’s, \( \sim 20\mu A \))

- Define \( t_{\text{measure}} \) for adequate counts for application
  - Bigger delta C, smaller \( t_{\text{measure}} \) can be used
  - Design to fewest counts needed for lowest current

![Current & Measurement Time vs. Measurement Window (1% C_delta)](chart.png)
RO Tradeoffs

- Needs Comp_A+ input mux for multiple sensors
- Sensors used limited by usable CA+ mux inputs
- External R’s needed to setup CA+ reference
- External CAOUT to TACLK required
- Good noise immunity: freq vs. voltage
- Programmable measurement time
- No high speed clock needed
- Measurement time dependent influenced by Vcc & Temp (VLO & DCO)
RC System Overview

- RC discharge time measured using interrupt on GPIO
- P1.x/P2.x GPIOs used
- Port pin used to charge sensor cap and measure discharge time
  - GPIO = Output high (charge C)
  - GPIO = Input (discharge C)
  - GPIO INT on low threshold
- Timer_A used to measure discharge time of C_sensor
**RO Measurement Cycle**

**Charge Sensor**
Set Px.y to Output High

**Discharge Sensor**
Set Px.y to Input w/ H-L INT enabled

**Measure $t_{\text{discharge}}**
Start Timer_A & Enter LPM0

LPM0
Px.y INT?

**Measure $t_{\text{discharge}}**
Stop Timer_A & Read TAR
Switch Px.y to Output Low

Enter LPM3

Switch to Next Sensor
Measurement Relationships

- Usable counts increase with increased reference clock
- Using $\text{ACLK} = \text{VLO} \& \text{SMCLK} = \text{DCO\_cal}$
  - $5.1\text{Mohm R}$

$$V(t_{rc}) = Vcc \times e^{-\frac{t}{RC}} , V(t_{rc}) = Vcc \times [1 - e^{-\frac{t}{RC}}]$$

$$V_{IT-} = Vcc \times e^{-\frac{t_{\text{discharge}}}{RC}} , V_{IT+} = Vcc \times [1 - e^{-\frac{t_{\text{charge}}}{RC}}]$$

$$V_{IT-} = 0.4 \times Vcc , V_{IT+} = 0.6 \times Vcc$$

$$t_{\text{discharge}} = -RC \times \ln(0.4), t_{\text{charge}} = -RC \times \ln(1 - 0.6)$$

$$t_{CLK} = \frac{1}{f_{DCO} / DIV_{SMCLK}}$$

$$counts_{\text{discharge}} = \frac{t_{\text{discharge}}}{t_{CLK}}, counts_{\text{charge}} = \frac{t_{\text{charge}}}{t_{CLK}}$$

$$counts_{\text{avg}} = \frac{counts_{\text{discharge}} + counts_{\text{discharge}}}{2}$$
RC Optimizations

- Two sensor elements can share a single R
- Each sensor can be charged, then discharged for an average result: better noise rejection
**RC Current Consumption**

- \( t_{\text{measure}} \) is constant:
  - \( \sim 2t_{\text{RC\_charge}} \)
  - \( R = 5.1\text{Mohm} \)
  - Counts TACLK

- **Average Icc depends on**
  - \( \text{Tau} = RC \)
  - DCO current consumption

- **Set TACLK for adequate counts for application**
  - Bigger delta C, lower \( f_{\text{DCO}} \) can be used
  - Design to fewest counts needed for lowest current

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<th>SMCLK (counts)</th>
<th>1MHz (1)</th>
<th>8MHz (4)</th>
<th>12MHz (6)</th>
<th>16MHz (8)</th>
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<tr>
<td>( I_{\text{cc_avg}} ) (uA)</td>
<td>0.16</td>
<td>0.04</td>
<td>0.12</td>
<td>0.16</td>
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<tr>
<td>( t_{\text{meas}} ) (ms)</td>
<td>0.02</td>
<td>0.04</td>
<td>0.06</td>
<td>0.08</td>
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RC System Careabouts

- Requires interrupt enabled GPIO for measurement
- One pin per sensor, shared resistor per two sensors
- $R$ is Mohm’s (5.1M)
  - With pF $C$, large $R$ required for a measurable charge/discharge time
- Low pin leakage of MSP430 ideal for the methodology
- Noise rejection aided by charge/discharge average
- Measurement window is fixed by RC charge/discharge time: high freq reference clock needed to “count”
- Measurement counts dependent on Vcc & Temp (DCO)
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Touch Sensor Careabouts

• What is the application:
  ▪ A switch replacement?
  ▪ Position detection? (e.g. slider)

• Threshold: Establish a “usable” limit
  ▪ Can it be reached?
  ▪ Enough noise margin?
  ▪ Tolerant to manufacturing changes?

• Filtering: Noise coupling
  ▪ Given large R in RC method, noise can easily couple in
  ▪ Multi-result averaging: RC charge/discharge method
  ▪ RO method inherently immune due to multiple cycles per measurement

• Tracking: Baseline capacitance can shift
  ▪ Periodically adjust base capacitance count set-point
  ▪ Take care to exclude a “touched” sensor result from any tracking algorithm
Tracking C_base

- C_base measurement result can change over time
  - Humidity effects
  - Temperature
  - Component tolerances
  - Voltage drift

- Failure to track this change adequately can result in false key events or inability to detect events

- Algorithm basics:
  - Adjust for a decreasing C rapidly, e.g. on each measurement, since this is not a function of sensor excitation
  - Adjust for increasing C very slowly as this may be due to a finger hovering over a key, not just C_base drift
  - Exclude an increasing C adjustment when any keys are pressed as it may be caused by the user, not C_base drift
Example: C base Tracking

- Adjust base result quickly when cap decreases
  - Ex: re-average with current result

- Adjust base result slowly when cap increases
  - Ex: adjust by 1 with each measurement
  - Only adjust if no keys are pressed

- Set “Threshold” level low enough that the sum of all key deltas will be greater if any key is press
  - Alternatively, can adjust on per key basis

- Note: sign of delta calc changes for the two methods
  - RO: counts decrease when key excited
  - RC: counts increase when key excited

\[
\text{Delta}_{\text{total}} = 0 \\
i = 0
\]

\[
\text{Measure Sensors}
\]

\[
\text{Delta}_i = \text{base}_i - \text{meas}_i \\
\text{If Delta}_i < 0: \\
\{ \text{base}_i = (\text{base}_i + \text{meas}_i) / 2 \} \\
\text{Delta}_i = 0 \\
\text{Delta}_{\text{total}} += \text{delta}_i \\
i++
\]

\[
\text{i = max?}
\]

\[
\text{If Delta}_{\text{total}} < \text{Threshold:} \\
\{\text{base}_i = \text{base}_i - 1\}
\]
Data Filtering

• Measurement results often noisy due to a number of factors including voltage supply

• When enough counts can be measured, simply throwing away the LSBs may be good enough
  ▪ Works ok for simple key press detection

• A low pass filter of each key result will more adequately remove any unwanted noise and help stabilize the results, especially when measuring position on a slider

• Critical when counts are at a premium in the system due to constraints such as the PCB, insulator and power budget
Key Press Detection

• **Measurement Flow**
  - Step 1: Establish a base count measurement
  - Step 2: Set a key press count threshold
  - Step 3: Scan keys

• **Set detection threshold ~50% of maximum count delta expected from the given implementation**
Key Pad Current Consumption

**RO Method**
- Use smallest $t_{meas}$ (lowest SMCLK) for needed counts
  - $\Delta C$ 5% 1MHz, WDT = SMCLK/1/512
  - $\Delta C$ 2% 1MHz, WDT = SMCLK/4/512

**RC Method**
- Use lowest TACLK for needed counts
  - $\Delta C$ 5% 8MHz TACLK
  - $\Delta C$ 2% 16MHz TACLK

Sensor Switch Application- RO
Current & SPS vs. Sensor Count (~20 counts)

Sensor Switch Application- RC
Current & SPS vs. Sensor Count (~20 counts)
Demo: ULP Key Detection

• RC measurement flow

```c
// RC Method: Measurement Excerpt
...
P1OUT &= ~(BIT0+BIT1+BIT2+BIT3); // everything is low
P1OUT |= active_key; // Charge the sensor
_NOP();_NOP();_NOP(); // short time for hard pull high
P1IES |= active_key; // -ve edge trigger
P1IE |= active_key;
P1DIR &= ~active_key; // set the active key to input
timer_count = TAR; // Take a snapshot of the timer
LPM0;
meas_cnt[i]= timer_count;
... // Now repeat with charging cycle and average results
```

```c
// Port ISR
...
timer_count=TAR-timer_count; // Get charge/discharge time
...```

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Demo: ULP Key Detection

- RO measurement flow

```c
// RO Method: Measurement Excerpt
TACTL = TASSEL_0+MC_2;       // TACLK, cont mode
TACCTL1 = CM_3+CCIS_2+CAP;    // Pos&Neg Capture
CACTL1 |= CAON;               // Turn on comparator
for (i = 0; i<Num_Sen; i++)
{
    switch (i)
    {
        case 0:         // Sensor 1
            CAPD = CA_Ref+S_1;   // Disable I/O: CA1 ref, 1st sensor
            CACTL2 = CA_1+CA_2;// CA1 ref, CAx sensor
            break;
    ...
}
WDTCTL = WDT_meas_setting;    // Set duration of sensor measurement
TACTL |= TACLR;               // Clear Timer A TAR
LPM0;                         // Wait for WDT interrupt
meas_cnt[i] = TACCR1;         // Save result

// WDT ISR
...
TACCTL1 ^= CCIS0;             // Create SW capture of CCR1
...```
Slider Scanning

- **Measurement Flow**
  - Step 1: Establish a base count measurement
  - Step 2: Set a key press count threshold
  - Step 3: Scan keys
  - Step 4: Calculate position based on counts for each key

- Apply linear weighting algorithm
- Filter noise counts for jitter-free operation
Position

- Establish design to steps/sensor required
  - Sensor size
  - Insulator thickness
- Smoothly linearize steps across the slider

Set max delta expected
Set steps per key (steps<sub>KEY</sub>)
Step size = max delta / steps<sub>KEY</sub>
(slider steps = steps<sub>KEY</sub> * #keys)

Get key delta & limit to max value
position<sub>KEY</sub> = delta / step size

If KEY pressed: Slider position = position<sub>KEY</sub> + steps<sub>KEY</sub>*weight<sub>KEY</sub>
(0, 1, 2, 3...)

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Endpoint

- Handle end-point touch
  - Press beyond max
  - Movement beyond max
  - Movement from max

Key Threshold

Min position

Max position

Max

Delta

If end KEY pressed AND last position = max

If end-1 position \( \leq \) last end-1 position

position = max position
(finger moving beyond max)

If end KEY pressed AND last position = 0

If end-1 KEY not pressed

position = max position
(finger approaching from max)
4-key Slider Current Consumption

RO Method
• t_meas user programmable
  ▪ Larger window = more counts
  ▪ Define smallest window for needed counts, use lowest DCO for window

RC Method
• t_meas is fixed by RC
  ▪ Faster TACLK = more counts
  ▪ Don’t divide TACLK, set = to fastest DCO required for needed counts

Sensor Slider Application- RO
Count Delta & Current Consumption vs. SMCLK (~5SPS)

Sensor Slider Application- RC
Count Delta & Current Consumption vs. SMCLK (~5SPS)
Demo: ULP Slider Detection

// Sensor slider definitions
#define Num_Sen 4  // # of sensors
#define KEY_lvl 5  // min count for a "key press"
                    // Must be less than step_size
#define max_cnt 100 // Set below actual max delta expected
#define num_steps 16 // How many steps per key?
#define step_size (max_cnt/num_steps) // Step size for position

...if (delta_cnt[i] > max_cnt) // count exceeds preset upper delta
    delta_cnt[i] = max_cnt;  // limit to set point

key_pos[i] = delta_cnt[i]/step_size; // individual "position"

if (key_pos[i] > 0) // If the key is "pressed",
    position = key_pos[i] + num_steps*(i); // Pos=0-16, key weight

• Determine legitimate number of steps for a given application
• Linearize across all sensors for entire slider span
// Handle max end of slider
if (key_press[3] && position_old == Num_Sen*num_steps)
        position = Num_Sen*num_steps; // moving beyond the max
    }
    position = Num_Sen*num_steps; // approaching from max
**Multiplexed Sliders**

- **Multiplex sensors for better pin:sensor ratio**
  - Increases base capacitance
  - Measured delta C will be lower

- **Mux for unique pattern for each position**

- **Multiple sensors should be excited for proper location & direction detection**
ATC2006 Touchpad Interface

• 8 port pins used
• $2 \times 8 = 16$ sensors
• 0-7: P1.0-P1.5, P2.6, P2.7
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Summary

• Capacitive touch sensing can be an attractive option
  ▪ …for existing switch replacement
  ▪ .. and more: potentiometer replacement, multi-position switches

• MSP430 RO Method
  ▪ Works in Comp_A+ devices
  ▪ Number of independent sensors limited by CA+ mux
  ▪ Needs 1 external R per sensor + reference ladder
  ▪ Sensitivity limited by current consumption, flexible measurement time

• MSP430 RC Method
  ▪ Can be implemented on any MSP430
  ▪ Up to 16 independent sensors (16 interruptible GPIOs)
  ▪ Single external R per two sensors
  ▪ Sensitivity limited by on-chip max clock frequency, fixed measurement time
  ▪ Lowest power implementation
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