Enabling Capacitive Touch Sensing with MSP430

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Agenda

• Overview of Touch Sensing 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
  ▪ Multi-position 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

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

<table>
<thead>
<tr>
<th>Material</th>
<th>Dielectric Constant ((\varepsilon_r))</th>
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<tr>
<td>Vacuum</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

Delta C vs. Pour
(8x8mm sensor on 1.5mm FR4)
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
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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 $1/(1.386 \times R_c \times C_{\text{sensor}})$
- 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

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

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

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

RO Counts vs. C_Sensor

![Graph showing RO Counts vs. C_Sensor](image-url)
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 $I_{\text{cc}}$
  - DCO: ~85uA @ 1MHz
  - Comp_A+: ~45uA
  - CA Vref: $V_{\text{cc}}/(1.5R)$ (for 100k R’s, ~20uA)

- 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

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<th>$t_{\text{meas}}$ (ms)</th>
<th>$I_{\text{cc Avg}}$ (uA)</th>
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1MHz SMCLK/x (counts)

Current & Measurement Time vs. Measurement Window (1\% C_delta)
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** $t_{discharge}$
Start Timer_A & Enter LPM0

**LPM0**
Px.y INT?

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

**Enter LPM3**

Switch to Next Sensor

Charge to VCC

Discharge to VSS

0xFFFF

TAR

ΔTAR

ΔTAR

VCC

Threshold

VSS

$t_1$

$t_2$

Active LPM0

Active LPM3

Active LPM0

Active LPM3

Technology for Innovators™
Measurement Relationships

• Usable counts increase with increased reference clock

• Using $\text{ACLK} = \text{VLO} \& \text{SMCLK} = \text{DCO_cal}$
  - 5.1Mohm $R$

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

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

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

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

$$t_{CLK} = \frac{1}{f_{DCO} / \text{DIV}_{SMCLK}}$$

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

$$\text{counts}_{\text{avg}} = \frac{\text{counts}_{\text{discharge}} + \text{counts}_{\text{charge}}}{2}$$
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:
  $\sim 2 \times t_{\text{RC\_charge}}$
  - $R = 5.1\, \text{Mohm}$
  - Counts TACLK

- Average $I_{\text{cc}}$ depends on
  - $\tau = RC$
  - 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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Current & Measurement Time vs. Measurement Window (1% $C_{\text{delta}}$)

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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 \( 5.1 \text{M} \)
  - 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

\[
\text{Delta}_{i} = \text{base}_{i} - \text{meas}_{i}
\]
\[
\text{if } \text{Delta}_{i} < 0: \{ \text{base}_{i} = (\text{base}_{i} + \text{meas}_{i}) / 2 \}
\]
\[
\text{Delta}_{i} = 0
\]
\[
\text{Delta}_{\text{total}} += \text{delta}_{i}
\]
\[
i++
\]
\[
i = \text{max}？
\]
\[
\text{If Delta}_{\text{total}} < \text{Threshold:}
\]
\[
\text{\{base}_{i} = \text{base}_{i} - 1}\]
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

```
// 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
```

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

Get key delta & limit to max value
position_{KEY} = \text{delta} / \text{step size}

If KEY pressed: Slider position = position_{KEY} + steps \times weight_{KEY}
(0, 1, 2, 3...)

Set max delta expected
Set steps per key (steps_{KEY})
Step size = max delta / steps_{KEY}
(slider steps = steps_{KEY} \times \#\text{keys})
Endpoint

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

![](endpoint_diagram.png)

<table>
<thead>
<tr>
<th>Key</th>
<th>Threshold</th>
<th>Min position</th>
<th>Max position</th>
<th>Delta</th>
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<td>4</td>
<td></td>
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</table>
4-key Slider Current Consumption

RO Method
- \( t_{\text{meas}} \) user programmable
  - Larger window = more counts
  - Define smallest window for needed counts, use lowest DCO for window

RC Method
- \( t_{\text{meas}} \) 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

```c
// 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
Demo: ULP Slider Endpoint

// 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
- 2x8 = 16 sensors
- 0-7: P1.0-P1.5, P2.6, P2.7
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• 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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