Introduction to MSP430 ADCs

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MSP430 Applications Engineer
Texas Instruments
Agenda

• Analog measurements with the MSP430
  ▪ Comparator, ADC10, ADC12, SD16, SD16_A
• Hands-on lab with ADC12
• Summary
Comparator A

- References usable internally and externally
- Low-pass filter selectable by software
- Input terminal multiplexer
- One interrupt vector with enable
Comparator-Based Slope ADC

- 10-bit+ accuracy
- Resistive sensors
- Low battery detect
- Very low cost
- App note SLAA038

\[
t_x = R_x \times C \times \ln \left( \frac{V_{CAREF}}{V_{CC}} \right)
\]

\[
R_{NTC} = 10k \times \frac{t_{NTC}}{t_{10k}}
\]
Example: Thermistor

- $R_{REF} = 10K$, $R_M = NTC$
- $V_{CAREF} = V_{CC} \times e^{-t/RC}$
- Relationship simplifies to single multiply & divide operations

$$R_{NTC} = 10k \times \frac{t_{NTC}}{t_{10k}}$$
Slope Resistance Considerations

- Measurement as accurate as $R_{REF}$
- $V_{CC}$ independent
- Resolution based on number of max counts possible
- Precharge of $C_M$ impacts accuracy
- Slope measurement time duration a function of RC
Integrating A/D Voltage Measurement

- $V_{IN}$ range is near full scale
- $P_{X,Y}$ toggling creates a 1-bit DAC at $V_{OUT}$
- Match $V_{OUT}$ to $V_{IN}$
- SLAA104

Used for voltage sensors, 10-bit+ resolution as accurate as $V_{CC}$

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Integrating A/D Considerations

• Resolution determined by times through S/W loop
• Inherently excellent noise immunity
• $V_{CC}$ must be known
• DAC pulse symmetry required
• Select RC values for $< +/- 1$ LSB $V_{OUT}$ ripple
• Reference: SLAA104
ADC10

- 200ksps+
- Autoscan
- Single Sequence Repeat-single Repeat-sequence
- Int/ext reference
- TA SOC triggers
- Data transfer controller
- 30us ref settling, No decoupling required
Why Is Autoscan + DTC Important?

70 cycles/Sample  Fully Automatic

// Software
Res[pRes++] = ADC10MEM;
ADC10CTL0 &= ~ENC;
if (pRes < NR_CONV)
{
    CurrINCH++;
    if (CurrINCH == 3)
        CurrINCH = 0;
    ADC10CTL1 &= ~INCH_3;
    ADC10CTL1 |= CurrINCH;
    ADC10CTL0 |= ENC+ADC10SC;
}

// Autoscan + DTC
_BIS_SR(CPUOFF);
ADC12

- 200ksps+
- Single Sequence Repeat-single Repeat-sequence
- Int/ext reference
- TA/TB SOC triggers
- Configuration memory/buffer
- DMA enabled
ADC12 Conversion Memory

- 16 memory buffer
- Each interrupt capable
- Each DMA enabled
Conversion Sequences

- Single or repeat
- Flexible channel selection
- Complete conversion timing control

<table>
<thead>
<tr>
<th>ADC12MEMa</th>
<th>0</th>
<th>SREFx</th>
<th>INCHx</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC12MEMb</td>
<td>0</td>
<td>SREFx</td>
<td>INCHx</td>
</tr>
<tr>
<td>ADC12MEMc</td>
<td>0</td>
<td>SREFx</td>
<td>INCHx</td>
</tr>
<tr>
<td>ADC12MEMd</td>
<td>1</td>
<td>SREFx</td>
<td>INCHx</td>
</tr>
</tbody>
</table>
Timer SOC Triggers - Accuracy

Automatic SOC trigger eliminates phase error
Timer SOC Triggers – Low-Power

// Interrupt
; MSP430 ISR to start conversion
BIS  #ADC12SC,&ADC12CTL0 ; Start conversion
RETI ; Return
;  

<table>
<thead>
<tr>
<th>CPU cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>16</td>
</tr>
</tbody>
</table>
ADC12 Reference Decoupling

- Power Supply
- Any used VRef

Any used reference must be decoupled with > 5uf
MSP430 SD16 Sigma-Delta Overview

• 16-bit sigma-delta architecture
• Independent converters
• 4096 samples per second
• Differential input
• Independent PGA
• Internal 1.2V reference
• Internal temperature sensor
• Converters can be grouped
• 2.7 – 3.6V
SD16 Features

- ‘F42x & ‘FE42x
- Multiple channels
- Single external input per channel
- Up to 256 OSR
- 1MHz $f_M$

SD16 Control Block

V_{REF} 

Temperature sensor 

Reference $f_M$

Divider

MCLK SMCLK ACLK TACLK

Ax.0 Ax.1 Ax.2 Ax.3 Ax.4 Ax.5 Ax.6 Ax.7

PGA 2nd Order ΣΔ Mod

Group/Start Conversion Logic

SD16PREx

SD16MEMx

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SD16_A Overview

- ‘F42x0 & ‘F20x3
- Single channel
- Multiple input pairs
- Input buffer
- AV<sub>cc</sub> measure
- 30kHz to 1.1MHz
- f<sub>M</sub> divider
- Up to 1024 OSR
SD16 A Input Design

• Four external input pairs
• Fully differential
• Internal channels:
  - Temperature
  - $AV_{CC}/11$
  - Offset shunt
• Selectable current vs. speed input buffer
• PGA: 1, 2, 4, 8, 16 & 32x

• SD16AEx bits for internal $A_{IN}$- connection to $AV_{SS}$

* Buffer not in ‘F20x3 devices
Input Select vs. Channel Select

• **SD16_A**: 1 channel, 4 external inputs per channel
  - MSP430F42x0 & MSP430F20x3

• **SD16**: 3 channels, 1 external input per channel
  - MSP430FE42x & MSP430F42x

• Channels are independent & can operate in parallel

• Inputs are multiplexed into each channel & must be selected/sampled sequentially
## SD16 Conversion Modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Channel, Single Conversion</td>
<td>A single channel is converted once.</td>
</tr>
<tr>
<td>Single Channel, Continuous Conversion</td>
<td>A single channel is converted continuously.</td>
</tr>
<tr>
<td>Group of Channels, Single Conversion (SD16 only)</td>
<td>A group of channels is converted once.</td>
</tr>
<tr>
<td>Group of Channels, Continuous conversion (SD16 only)</td>
<td>A group of channels is converted continuously.</td>
</tr>
</tbody>
</table>
Analog Input Range

- What is $V_{\text{REF}}$?
- What is the PGA setting?

$$V_{FSR} = \frac{V_{\text{ref}}}{2 \cdot \frac{GAIN}{PGA}}$$

- Applies to all inputs & modes

* $0V = Vss$ (SD16), $0V = \text{relative}$ (SD16A)
Input Step Response

- Key for mux switching
- Decimation filter must cycle out the delta
- SD16INTDLYx sets automatic settling time to 1\textsuperscript{st} conversion interrupt
- \( f_M = 1.048\text{MHz}; \) OSR = 256
  - \( f_{\text{SAMPLE}} = 4.096\text{ ksp} \)s ->
  - \( t_{\text{SETTLE(MAX)}} \sim 732\text{usec} \)
### Internal Reference

- **Internal 1.2V reference**
- **20ppm temperature coefficient**
- **$V_{REF}$ Options:**
  - External ref: $SD16REFON = 0$, $SD16VMIDON = 0$
  - Internal ref: $SD16REFON = 1$, $SD16VMIDON = 0$
  - Internal ref w/ buffered output: $SD16REFON = 1$, $SD16VMIDON = 1$

- **For temperature (A6): use internal reference**

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Internal Reference Settling Time

- $C_{VREF} = 470\text{nF}$
- Ref buffer = +100x faster reference settling
- Disable once settled
SD16 Data

- Normal mode reads 16-bit
- 24-bit access available
Agenda

• Analog measurements with the MSP430
  - Comparator, ADC10, ADC12, SD16, SD16_A

• Hands-on lab with ADC12

• Summary
ADC Lab – Goal

• Use ADC12 integrated temperature sensor
• Setup ADC12 to perform single conversion
• Loop continuously, converting to Degrees F and C in software
• Touch the MSP430 with finger to change temperature
ADC Lab - Considerations

- What must be set to make the ADC work?
- Sampling Time
- Input Clock
- Trigger
- Input Channel
- Mode
ADC Lab – Code

ADC12CTL0 = _________________________________;
// Setup ADC12, ref., sampling time
ADC12CTL1 = ___; // Use sampling timer
ADC12MCTL0 = _____________; // Select channel A10, Vref+
ADC12IE = 0x01; // Enable ADC12IFG.0
for (i = 0; i < 0x3600; i++); // Delay for reference start
ADC12CTL0 |= ENC; // Enable conversions
__enable_interrupt(); // Enable interrupts

while(1)
{
    ADC12CTL0 |= _______; // Start conversion
ADC Lab – Sampling Time

• Check DeviceDatasheet

<table>
<thead>
<tr>
<th>SENSOR(sample)</th>
<th>Sample time required if channel 10 is selected (see Note 3)</th>
<th>ADC12ON = 1, INCH = 0Ah, Error of conversion result ≤ 1 LSB</th>
<th>2.2 V</th>
<th>30</th>
<th>3 V</th>
<th>30</th>
<th>μs</th>
</tr>
</thead>
</table>

• Available clocks:
  - ACLK (32.768 kHz)
  - SMCLK (1 MHz)
  - ADC internal OSC:

<table>
<thead>
<tr>
<th>fADC12OSC (Internal ADC12 oscillator)</th>
<th>ADC12DIV=0, fADC12CLK=fADC12OSC</th>
<th>VCC = 2.2 V/3 V</th>
<th>3.7</th>
<th>5</th>
<th>6.3</th>
<th>MHz</th>
</tr>
</thead>
</table>

30us with a 6 MHz clock = 189 clocks
ADC Lab – Reference

- ADC12 has a built-in reference generator that is selectable to be 1.5V or 2.5V
- ADC12 can also accept an external reference on the Veref+/Veref- pins
- ADC12 can select Vcc as a reference
# ADC Lab Setting the bits

$$ADC12CTL0 = ADC12ON + REFON + REF2_5V + SHT0_7;$$

<table>
<thead>
<tr>
<th>SHT0x Bits</th>
<th>ADC12CLK cycles</th>
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<tbody>
<tr>
<td>0111</td>
<td>192</td>
</tr>
<tr>
<td>REF2_5V</td>
<td>Bit 6</td>
</tr>
<tr>
<td>0</td>
<td>1.5 V</td>
</tr>
<tr>
<td>1</td>
<td>2.5 V</td>
</tr>
<tr>
<td>REFON</td>
<td>Bit 5</td>
</tr>
<tr>
<td>0</td>
<td>Reference off</td>
</tr>
<tr>
<td>1</td>
<td>Reference on</td>
</tr>
<tr>
<td>ADC12ON</td>
<td>Bit 4</td>
</tr>
<tr>
<td>0</td>
<td>ADC12 off</td>
</tr>
<tr>
<td>1</td>
<td>ADC12 on</td>
</tr>
</tbody>
</table>

$$ADC12CTL1 = SHP;$$

SHP Bit 9 Sample-and-hold pulse-mode select. This bit selects the source of the sampling signal (SAMPCON) to be either the output of the sampling timer or the sample-input signal directly.

Sample-and-hold time. These bits define the number of ADC12CLK cycles in the sampling period for registers ADC12MEM0 to ADC12MEM7.

Reference generator voltage. REFON must also be set.

Reference generator on

ADC12 on
# ADC Lab - Defaults

- **ADC12CTL1**

<table>
<thead>
<tr>
<th>SHSx</th>
<th>Bits</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>11-10</td>
<td>00 ADC12SC bit</td>
</tr>
<tr>
<td></td>
<td></td>
<td>01 Timer_A.OUT1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 Timer_B.OUT0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11 Timer_B.OUT1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ADC12</th>
<th>SSELx</th>
<th>Bits</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>4-3</td>
<td>00</td>
<td>ADC12OSC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>01</td>
<td>ACLK</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>MCLK</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11</td>
<td>SMCLK</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CONSEQx</th>
<th>Bits</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2-1</td>
<td>00 Single-channel, single-conversion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>01 Sequence-of-channels</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 Repeat-single-channel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11 Repeat-sequence-of-channels</td>
</tr>
</tbody>
</table>
ADC Lab – Configuring the conversion

<table>
<thead>
<tr>
<th>SREFx</th>
<th>Bits</th>
<th>Select reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6-4</td>
<td>000 $V_{R_+} = AV_{CC}$ and $V_{R_-} = AV_{SS}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>001 $V_{R_+} = V_{REF_+}$ and $V_{R_-} = AV_{SS}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>010 $V_{R_+} = V_{REF_+}$ and $V_{R_-} = AV_{SS}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>011 $V_{R_+} = V_{REF_+}$ and $V_{R_-} = AV_{SS}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100 $V_{R_+} = AV_{CC}$ and $V_{R_-} = V_{REF_-}/V_{REF_-}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>101 $V_{R_+} = V_{REF_+}$ and $V_{R_-} = V_{REF_-}/V_{REF_-}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>110 $V_{R_+} = V_{REF_+}$ and $V_{R_-} = V_{REF_-}/V_{REF_-}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>111 $V_{R_+} = V_{REF_+}$ and $V_{R_-} = V_{REF_-}/V_{REF_-}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>INCHx</th>
<th>Bits</th>
<th>Input channel select</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3-0</td>
<td>0000 A0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0001 A1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0010 A2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0011 A3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0100 A4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0101 A5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0110 A6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0111 A7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000 $V_{REF_+}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1001 $V_{REF_-}/V_{REF_-}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1010 Temperature sensor</td>
</tr>
</tbody>
</table>

**ADC12MCTL0 = INCH_10 + SREF_1;**
ADC Lab – Final code

ADC12CTL0 = ADC12ON + REFON + REF2_5V + SHT0_7;
// Setup ADC12, ref., sampling time
ADC12CTL1 = SHP;     // Use sampling timer
ADC12MCTL0 = INCH_10 + SREF_1; // Select channel A10, Vref+
ADC12IE = 0x01;      // Enable ADC12IFG.0
for (i = 0; i < 0x3600; i++); // Delay for reference start
ADC12CTL0 |= ENC;    // Enable conversions
__enable_interrupt(); // Enable interrupts

while(1)
{
    ADC12CTL0 |= ADC12SC; // Start conversion
Agenda

• Analog measurements with the MSP430
  ▪ Comparator, ADC10, ADC12, SD16, SD16_A

• Hands-on lab with ADC12

• Summary
Selecting an MSP430 ADC

<table>
<thead>
<tr>
<th></th>
<th>channels</th>
<th>$f_{\text{SAMPLE}}$ (ksp/s)</th>
<th>min</th>
<th>max</th>
<th>res</th>
<th>$A_{\text{IN}}$</th>
<th>reference</th>
<th>triggering</th>
<th>gain</th>
<th>features</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC10</td>
<td>8</td>
<td>34</td>
<td>8</td>
<td>200+</td>
<td>10</td>
<td>57 Vss to Vref</td>
<td>1.4-3.6</td>
<td>1.5/2.5V</td>
<td>+/-1mA</td>
<td>SW/Timer/Cont</td>
</tr>
<tr>
<td>ADC12</td>
<td>12</td>
<td>34</td>
<td>12</td>
<td>200+</td>
<td>12</td>
<td>68 Vss to Vref</td>
<td>1.4-3.6</td>
<td>1.5/2.5V</td>
<td>+/-1mA</td>
<td>SW/Timer/Cont</td>
</tr>
<tr>
<td>SD16</td>
<td>3 ind</td>
<td>~4</td>
<td>16</td>
<td>85</td>
<td>16</td>
<td>+/-600mV</td>
<td>1.0-1.5</td>
<td>1.2V</td>
<td>+/-1mA</td>
<td>SW/Cont</td>
</tr>
<tr>
<td>SD16_A</td>
<td>4 mux'd</td>
<td>~0.03</td>
<td>16</td>
<td>85</td>
<td>16</td>
<td>+/-600mV</td>
<td>1.0-1.5</td>
<td>1.2V</td>
<td>+/-1mA</td>
<td>SW/Cont</td>
</tr>
</tbody>
</table>

- Voltage range to be measured?
- Max frequency for $A_{\text{IN}}$?
- How much resolution?
- Differential inputs?
- Reference range?
- Multiple channels?
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