Ultra-low Power Precision Instrumentation
Priya Thanigai

Agenda

• ULP Precision Instrumentation and the MSP430

• Showcasing the F47xx SoC devices

• Application Examples in Precision Instrumentation
ULP Precision Instrumentation Defined

- “ULP” = “Ultra-low Power”
  - Portable
  - Handheld
  - Battery powered
- High Performance Analog Peripherals
  - Integrated analog for easy SoC development
  - Intelligent peripherals that use LP principles
- Display and User Interface
  - Display for output and measurement results
  - Essential for handheld instrumentation
- Communication Enabled
  - Data logging support
  - Capable of handling wired and wireless industry-standard communication protocols

MSP430 – Meeting the Requirements

- What makes the MSP430 low power?
  - Flexible architecture and low power modes
  - 0.1µA power down
  - 1µA standby
  - 250µA / MIPS
  - Instant-on stable high-speed clock
  - <50nA pin leakage
- Highly suited for precise instrumentation
  - Integrated analog - 10,12 or 16-bit ADCs, DACs, Op-Amps, Integrated Reference
  - Sensitive to LP needs - DTC, DMA enabled, Interrupt based
- Display support
  - LCD, LCD_A modules support up to 160 segments
  - Integrated charge pump
- Communication modules
  - Support for SPI, I2C, UART, LIN, IrDA
  - Integration with radio possible through UART/SPI
  - GPIO for keyboard/switch interface
Achieving Ultra-low Power with the MSP430

- Extended Ultra-low Power standby mode
- Minimum active duty cycle
- Interrupt driven performance on-demand

Multiple Oscillator Clock System

- High performance ‘on-demand’
- In <6µs the DCO is active and stable
- 3 clock sources: LFXT1, XT2CLK and DCOCLK (VLOCLK in 2xx devices)
- Crystal based clock – high precision
- Balance between performance and low power
Ultra-low Power Clock Control

CPU Off
DCO on
ACLK on
35µA

Active
DCO on
ACLK on
250µA

All
Clocks Off
0.1µA

Stand-by
DCO off
ACLK on
1µA

LPM0

LPM3
• RTC function
• LCD driver
• RAM/SFR retained

LPM4
• RAM/SFR retained

Interrupt Driven Programming

```
// Poll ADC12 conversion
for (;;) {
    while (!(ADC12IFG&0x0001));
    ADCResult = ADC12MEM0;
}
```

```
// ADC12 Interrupt
#pragma vector = ADC12_VECTOR
__interrupt void ADC12_ISR(void)
{
    ADCResult = ADC12MEM0;
}
```

100% CPU Load

- All peripherals, ports P1 and P2
- Extensive vectored interrupts – immediate servicing
- No loss of power due to polling
- More efficient: Less cycles → Lesser power

0.1% CPU Load

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Intelligent Analog in Instrumentation

- ADC
  - 10, 12, 16-bit resolution
- Op-Amp
  - Configurable modes for General Purpose, Buffer, Comparator, PGA, Differential Amp
  - Programmable for optimized gain and bandwidth
  - Multiple independent op-amps available
- HW MPY
  - 16 or 32-bit
  - Supports signed MPY, unsigned MPY, signed MAC and unsigned MAC operations
- DAC
  - 12-bit resolution
  - Synchronized update for multiple DACs

**ADC12**

- 200ksps+
- 4 modes
  - Single
  - Sequence
  - Repeat-single
  - Repeat-sequence
- DMA enabled
- TA/TB triggers for start of conversion
- Internal or external reference
- Configuration memory/buffer
- Integrated temperature sense
Enabling Low Power with DMA

; Interrupt
; MSP430 ISR for one output waveform
MOV &ADC12MEM0,0(R5) ; Get ADC value
INC R5 ; Inc pointer
AND #1Fh,R5 ; Modulo pointer
RETI ; Return

; Total

High Precision Timer Triggers

Automatic start-of-conversion triggers eliminate phase error
SD16/ SD16_A

- Single / multiple channels
- Single / Multiple input pairs
- Input buffer
- AVCC measure
- Ext/ Int reference
- Integrated temperature sense
- 30kHz to 1.1MHz
- Programmable gain amplifier
- fM divider
- Up to 1024 OSR

Converters Overview

- Voltage range to be measured?
- Max frequency for AIN?
- How much resolution?
- Differential inputs?
- Reference range?
- Multiple channels?
Communicating with the USCI

- Multiple serial communication modes
- Two independent blocks - USCI A&B
- Asynchronous communication modes
  - UART standard and multiprocessor protocols
  - UART with automatic Baud rate detection (LIN support)
  - IrDA (SIR - slow Infrared, up to 115kBaud)
  - LPMx wake up
- Synchronous communication modes
  - SPI (Master & Slave modes, 3 & 4 wire)
  - I²C (Master & Slave modes)
  - LPMx operation

Display using LCD Controller

- Drives static, 2-mux, 3-mux, 4-mux LCDs
- Configurable frame frequency
- Up to 160 segments
- Integrated charge pump on LCD_A
  - 15 configurable settings for charge pump voltage
  - Contrast control in software
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- Showcasing the F47xx SoC devices
- Application Examples in Precision Instrumentation

High Performance F47xx SoC Devices

- 60KB Flash / 2.5KB RAM
- 16MHz CPU
- 32x32 MPY
- Up to 4 SD16_A
- (2) USCI_A & B
- 2.2V Flash ISP
- 160 segments integrated LCD Driver with charge pump
- Integrated SVS
- All 72 I/O have integrated pull up/down resistors
MSP430F47xx Enhancements

- 16MIPS at 3.3V-3.6V
- 2.2V Flash ISP
- Pull-up/down Resistors
- Support for precision integer arithmetic
16 MIPS

- CPU and Flash optimized to work at 16 MHz
- Twice the processing performance
- XT2 supports up to 16 MHz

NEW!

32x32 Hardware Multiplier

- Supports 8/16/24/32-bit operands
- Zero CPU load
- DMA support
- Signed & unsigned multiply
- Signed & unsigned multiply accumulate
- Memory mapped registers for all operands and results
HW Multiplier Usage & Performance

```c
MPYS32L = 0x1234;          // Load lower 16 bits of operand 1
MPYS32H = 0x1234;          // Load upper 16 bits of operand 1
OP2L = 0x5678;            // Load lower 16 bits of operand 2
OP2H = 0x5678;            // Load upper 16 bits of operand 2
_BIS_SR(LPM4_bits);       // LPM4
// Result in RESLO & RESHI registers
```

<table>
<thead>
<tr>
<th>Operation</th>
<th>Result ready in MCLK cycles</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>OP1 x OP2</td>
<td>RES0 RES1 RES2 RES3 MPYC Bit</td>
<td></td>
</tr>
<tr>
<td>8/16 x 8/16</td>
<td>3 3 4 4 3</td>
<td>OP2 written</td>
</tr>
<tr>
<td>24/32 x 8/16</td>
<td>3 5 6 7 7</td>
<td>OP2 written</td>
</tr>
<tr>
<td>6/16 x 24/32</td>
<td>N/A 3 4 4 4</td>
<td>OP2H written</td>
</tr>
<tr>
<td>24/32 x 24/32</td>
<td>3 8 10 11 11</td>
<td>OP2L written</td>
</tr>
<tr>
<td>N/A</td>
<td>3 5 6 6 6</td>
<td>OP2H written</td>
</tr>
</tbody>
</table>

NEW!

F47xx SD16_A
- MSP430F47x3/4
- Differential inputs
- Single input pair
- Multiple converters
- 3 or 4 simultaneous conversions
- AVcc measure
- 30kHz to 1.1MHz
- Modulation frequency divider
- Up to 1024 OSR

NEW!

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NEW!

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SD16_A: Gain versus Dynamic Range

SD16_A: Oversampling Ratio

For an N-bit ADC Sine wave:
\[ \text{SNR} = N \times 6.02 + 1.76 \text{dB} \]

For an N-bit ADC Sine wave oversampling by k times:
\[ \text{SNR} = N \times 6.02 + 1.76 \text{dB} + 10 \times \log(k) \]

- Same total noise - spread over more frequencies
- Gentler transition band for anti-aliasing filter (AAF)
**SD16_A: SNR/SINAD over OSR**

\[ SINAD = 20 \log \frac{S}{N+D} \]

**OSR = 1024: Overall SINAD improvement of 25dB**

**SD16_A: Grouped Channels with Pre-Load**

- Control timing delay between grouped channels
- Configurable interrupt delay for settling
- Up to 4 conversions for settling time
- Reference settling <3 conversions
SD16_A: Tips & Tricks

- 16, 24-bit access available
  - OSR = 256
  - Digital filter output
  - SDHRMEMx (LSBAC=b)
  - SDHRMEMx (LSBAC=1)
- Offset calibration available using A7
- Internal temperature sensor using A6
- External capacitor of 100nF is recommended to reduce reference noise
- VMIDON = 1 \(\Rightarrow\) faster settling time
- Low power versus sampling frequency trade-offs

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USCI

- Independent USCI modules - A0/B0/A1/B1
- 4 simultaneous communication channels possible
- USCI_Ax modules
  - UART, SPI, Pulse shaping for IrDA communications, Automatic baud rate detection for LIN communications
- USCI_Bx modules
  - I²C, SPI
- LPMx wake-up

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**LCD_A**

- Ultra-low power
- Fully automatic
- 4/3/2/1 mux
- Up to 160-bit display
- Internal regulated voltage generator
- Internal or external bias generation
- Contrast control
- 1/2 bias for 3 or 4 mux
- Internal clock generation

**LCD_A: Voltage and Biasing Options**

- **Required for LCD Module**

  - \( V_{LCD} = AV_C \) Internal BIAS
    - R33
    - R23
    - R13
    - R03
  - \( V_{LCD} = AV_C \) External BIAS
    - R33
    - R23
    - R13
    - R03
  - \( V_{LCD} = CP \) Internal BIAS
    - R33
    - R23
    - R13
    - R03
  - \( V_{LCD} = CP \) External BIAS
    - R33
    - R23
    - R13
    - R03
**LCD_A: Current Consumption**

<table>
<thead>
<tr>
<th>V_{LCD} = A V_{CC}, 1/3 internal bias</th>
<th>~4.5 μA</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_{LCD} = A V_{CC}, 1/3 external bias</td>
<td>~2.3 μA</td>
</tr>
<tr>
<td>V_{LCD} = CP, 1/3 internal bias</td>
<td>~7.5 μA</td>
</tr>
<tr>
<td>V_{LCD} = CP, 1/3 external bias</td>
<td>~5 μA</td>
</tr>
</tbody>
</table>

- Vcc with external bias is lowest current option
- Using internal bias adds 1 to 2 μA
- Enabling CP adds 2 to 4 μA

**Available Devices**

<table>
<thead>
<tr>
<th>Part number</th>
<th>Flash</th>
<th>RAM</th>
<th># of SD16 A</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSP430F4783</td>
<td>48KB</td>
<td>2.0KB</td>
<td>3</td>
</tr>
<tr>
<td>MSP430F4784</td>
<td>48KB</td>
<td>2.0KB</td>
<td>4</td>
</tr>
<tr>
<td>MSP430F4793</td>
<td>60KB</td>
<td>2.5KB</td>
<td>3</td>
</tr>
<tr>
<td>MSP430F4794</td>
<td>60KB</td>
<td>2.5KB</td>
<td>4</td>
</tr>
</tbody>
</table>
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Applications in Precise Instrumentation

• Energy metering – Single phase and two-phase
• High precision handheld instrumentation – Thermostat, Gas monitor
• SoC solutions – Single chip weigh scale
E-Metering

- An energy meter is a device that measures the amount of electrical energy consumed

Key requirements in E-Metering:
- Highly precise, simultaneous V&I measurements
- Differential inputs eliminate the need for level shifting
- High dynamic range
  - Need to measure both light and heavy loads
- Capacity for intensive math computation
  - Active and reactive power calculated real-time
- Additional converter can be used in tamper detection

Demo MSP430F47x4 Single Phase E-meter
Demo: High-Precision Thermostat

- Implemented with F47×4
- Wide dynamic range
- 0.01°F precision
- Ultra-low power <6µA @ 3 sec sampling
- 16-bit resolution
- Low-cost NTC thermistor for high-precision measurement
- LCD_A (with charge pump) for display with contrast control

Thermostat: Software Flow

1. Initialize SD16, Basic Timer
2. Enter LPM3 with interrupts enabled
   - 3 sec Timer interrupt occurs
   - Wake up from LPM3 on Timer interrupt
   - Turn on reference for SD16
   - Enter LPM0 with interrupts enabled
   - SD16 data ready
3. Wake up from LPM0 on SD16 interrupt
   - Store sampled temperature
   - Update LCD
15-year Battery Life Thermostat

1µA Standby LPM3
3µA LCD
+ 2µA ADC Function

†Battery life calculated based on 1250mAH AAA supply

Single Chip, Low Power Weigh Scale

• Single-chip implementation with F42x
• Resistive full-bridge sensor
• 0-10kg, 1g resolution (.15µV)
• Ratiometric reference
• Offset and gain calibration included
• 2.7V – 3.0V operation
• 256 SD16 samples averaged – 18 bit result

Application report SLAA220
Summary

• The MSP430 family of devices meet the key requirements of ULP Precision Instrumentation
  • Intelligent integrated analog
  • Ultra-low power support in architecture
  • Communication support
  • Display capabilities
• The F47xx family presents a high performance upgrade
  • First family among 4xx devices with increased MIPS and reduced flash ISP voltage
  • Highly precise analog with 4 integrated SD16 modules
  • More computational horsepower with 32x32 HW MPY
• One device diverse applications!
Thank You.