1uW Embedded Computing
*Using Off-the Shelf Components for Energy Harvesting Applications*

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Full Disclosure

• A processor guy
• 25+ years TI applications and marketing experience
• Work described today is based on MSP430F20xx target MCU
• Work described is for extreme ultra-low power applications that can be applied to any MCU and to provide ideas for thought …
Agenda

- Embedded Ultra-low-power basics
- What is 1uW?
- Firmware impact
- Clock frequency and gating
- Voltage scaling
- Power gating sensors
- A complete system
- Traps
- Summary

Goal: A 1uW computing system using low-cost, off-the-shelf components
ULP Embedded Systems Basics

$P = P_{dyn} + P_{stat}$

$= CV^2f + VI_{leak}$

1. Both frequency and voltage can be controlled
   - Lowering frequency has a linear effect
   - Lowering voltage has a squares the effect
   - Static and leakage currents are largely constant

2. Power manage peripherals

3. Effective code is a must
1uW Power Curve

1uW target = 2V x 0.5uA

Target MCU operating range = 1.8V – 3.6V
Flashing LED

- Often a marketing must-have for electronic system-functioning-properly indicator
- ~5mA pulse for 1ms
- 1/second
  - 0.1% duty cycle
  - 5uA adder on average
- 1/5 second
  - 0.02% duty cycle
  - 1uA (2uW) adder

2uW is unacceptable in our application!!!
// Setup timer output unit
CCTL1 = OUTMOD0_1;
_BIS_SR(CPUOFF);

#pragma vector=WDT_VECTOR
_interrupt watchdog_timer (void){
    P1OUT ^= 0x01;    // Toggle
}

while (1){
    P1OUT ^= 0x01;    // Toggle
    __delay_cycles(10000);    // Delay
}
Ultra-low Power Activity Profile

Reduce Standby Current

Reduce Active Time

Average

Average approaches standby
MSP430F20xx

Tiny workhouse since 2005
0.35u single-supply domain, nothing special
eZ430-F2013

- Popular $20 Development tool
- LED already on target used as indicator
- NTC Sensor + Resistor divider sensor added
  MCU GPIO used to create VCC and GND for sensor
- MSP430F2013 replaced with MSP430F2012
### Active Mode Options

<table>
<thead>
<tr>
<th>TEMP</th>
<th>VCC</th>
<th>TYP</th>
<th>UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1MHz</td>
<td>n/a</td>
<td>2.2V</td>
<td>220</td>
</tr>
<tr>
<td>1MHz</td>
<td>n/a</td>
<td>3V</td>
<td>300</td>
</tr>
<tr>
<td>1MHz</td>
<td>n/a</td>
<td>2.2V</td>
<td>190</td>
</tr>
<tr>
<td>1MHz</td>
<td>n/a</td>
<td>3V</td>
<td>260</td>
</tr>
<tr>
<td>4kHz</td>
<td>n/a</td>
<td>2.2V</td>
<td>1.3</td>
</tr>
<tr>
<td>4kHz</td>
<td>n/a</td>
<td>3V</td>
<td>1.6</td>
</tr>
</tbody>
</table>

**MSP430F20x from datasheet**

- **VLO/8**
  - n/a
  - 2.0V
  - 0.4
  - uA

**Fault from bench test**

- 25% reduction 3V to 2.2V ... 13% Flash to RAM
- With VLO/8 @2V standby = 0.8uW ~ 1.2KPS
- Current is for entire chip ... clock, memory, BOR ...

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Standby Mode Options

MSP430F20x from datasheet

<table>
<thead>
<tr>
<th>TEMP</th>
<th>VCC</th>
<th>TYP</th>
<th>UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>25°C</td>
<td>2.2V</td>
<td>0.7</td>
<td>uA</td>
</tr>
<tr>
<td>85°C</td>
<td>1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25°C</td>
<td>3V</td>
<td>0.9</td>
<td>uA</td>
</tr>
<tr>
<td>85°C</td>
<td>1.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25°C</td>
<td>2.2V</td>
<td>0.5</td>
<td>uA</td>
</tr>
<tr>
<td>85°C</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25°C</td>
<td>3V</td>
<td>0.6</td>
<td>uA</td>
</tr>
<tr>
<td>85°C</td>
<td>1.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

VLO/8  22°C  2.0V  0.3uA  uA

from bench test

• Reduction from 3V to 2.2V … 32kHz to VLO
• With VLO/8 @2V standby = 0.6uW ~ 0.4uW remains!
• Current is for entire chip … clock, memory, BOR …
Interrupt

DCO

Immediate-stable high-speed clock for event response
1uW Computing

- Active CPU=1MHz, Flash 3V
- Active CPU=1MHz, RAM 2V
- Active CPU=1KHz, 2V
- Standby CPU=1MHz Burst, 2V

- 1,000,000 IPS
- 50%
- 1000x
- ~1 KPS

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Add ULP ADC Sensor Processing

// MSP430F2012
---
// LPM3 VLO = 0.3uA
// ADC10 1sps = 0.0005uA
// Mainloop = 0.1uA
---
// Total = 0.4uA
// @2v = 0.8uw

~Divide / 200,000

Data Sheet = 200ksp/s!
1uW Computing + Sensor Processing

- Active
  - CPU = 1MHz
  - Flash 3V: 1,000,000 IPS
  - RAM 2V: 1,000,000 IPS
- Active
  - CPU = 1KHz
  - 2V: ~1KIPS
- Standby
  - CPU = 1MHz Burst
  - 2V: 10SPS ~1KPS

1000x
while (1) {
    ADC10CTL0 |= ADC10SC; // Sampling start
    while (ADC10CTL1 & ADC10BUSY); // ADC10BUSY?
    if (ADC10MEM < 0x1FF)
        P1OUT &= ~0x01; // LED off
    else
        P1OUT |= 0x01;   // LED on
}
while (1) {
    _BIS_SR(LPM3_bits + GIE); // Enter LPM3
    P1OUT |= 0x02;            // PWR to R+NTC
    ADC10CTL0 |= ADC10SC;    // Sampling start
    while (ADC10CTL1 & ADC10BUSY); // ADC10BUSY?
    P1OUT &= ~0x02;          // noPWR to R+NTC
    if (ADC10MEM < 0x1FF) {
        P1OUT &= ~0x01;       // LED off
    } else {
        P1OUT |= 0x01;        // LED on
    }
}

#pragma vector=WDT_VECTOR
__interrupt void watchdog_timer (void) {
    _BIC_SR_IRQ(LPM3_bits); // Exit LPM3
}
## Demonstration

<table>
<thead>
<tr>
<th>Condition</th>
<th>Vdd</th>
<th>Idd Measured</th>
<th>Calculated Watts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active/Flash 1MHz @ 3V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active/Flash 1MH @ 2V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active/Flash VLO/8 @ 3V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active/Flash VLO/8 @ 2V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standby VLO/8 + 1SPS @ 2V</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fully Autonomous Sensor Sampling

- ADC is triggered from timer – latency free
- ADC conversion code automatically transferred
- CPU only woken after a pre-determined sample size
1uW Computing Today

- **Off-the-shelf ‘F20xx is capable of 1uW computing**
  - Performance of 1-2KIPS
  - Including Sensor sample 1-10SPS
  - ULP standby clock
  - Instant-on and very accurate high-speed clock
  - I/O, interrupt capability, BOR and all RAM retained

- **Traps**
  - Firmware
  - Temperature increases leakage significantly
  - Floating inputs
  - Multiple voltage domain satiation
  - Watch for un-deterministic clocking
  - Where to get a 2V supply in a real application?
Thank You