Implementing a Temperature Compensated RTC

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Agenda

• Building a simple RTC with the MSP430
• What limits the accuracy of the simple RTC?
• What can we do to improve accuracy?
• An example of using correction techniques
A simple real time clock

- Simple MSP430 software RTCs are popular
- The 32kHz crystal osc is a suitable source of timing
- Several timers can generate 1 interrupt/second from the 32kHz oscillator
  - Timer A, Timer B, Basic Timer, Watchdog timer
- Each second, the CPU can wake very quickly (<6us) from LPM3, run at full speed to update time and date variables in RAM, and go back to sleep
- Typically an application would also do some housekeeping in the per second interrupt routine
  - Total system consumption can be <1.2uA
  - A 3022 coin cell battery can run many products for >10 years
- This is a classic MSP430 application
A simple real time clock - tradeoffs

• MSP430x4xx users usually use the basic timer
  ▪ Part of LCD controller support
  ▪ A very simple timer for just this type of application

• Users of other devices use Timer A/B or WDT
  ▪ The watchdog timer can be used, if watchdog functionality is not required

• Care is needed, if WDT is performing its watchdog function
  ▪ The longest watchdog timeout is 1s, but the interrupt period is also 1s
  ▪ Kicking the WDT at both the start and the end of the interrupt service can avoid false expiry of the WDT
Real time clocks – the problem

- Many appliances, such as water and electricity meters, operate over a wide temperature range
- Watch crystal frequencies vary significantly over this range
  - You don’t cook or freeze your wrist, so the good timekeeping of a watch is no indicator of performance
- Utilities are demanding precision real time clocks
  - This demands temperature compensation
- Precision real time clocks usually need to be ultra low power
  - They need to run for years from a small battery, for cost or size reasons
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Factors affecting clock accuracy

- **Manufacturing tolerance of the crystal**
  - Crystals better than 10ppm at room temp. can be expensive
  - 100ppm crystals are cheaper, if we can tolerate them

- **Incorrect loading of the crystal**
  - Crystals can be pulled off frequency by the loading applied to them (think VCXO)
  - A very poorly loaded crystal might be unstable, especially in the presence of high EMI

- **Handling can change the crystal**
  - Thermal shock during soldering can alter a crystal’s frequency

- **Temperature changes the crystal**
  - Over a wide temperature range, this is the biggest factor affecting clock accuracy

- **Crystals change with age**
  - Several ppm per year for typical 32kHz crystals
Real time clocks – the solution

• Every ADC used in the MSP430 family has an internal temperature sensor we can use for RTC compensation purposes
  ▪ Requires calibration as the product is tested
  ▪ Quick, simple calibration is adequate for most uses
  ▪ Devices without a true ADC might use Comp_A to form a slope ADC, and sense temperature with an external device

• Low precision crystals are cheaper than high precision, and may have just as good an aging characteristic
  ▪ Manufacturing tolerance error can be calibrated away as the product is tested
  ▪ Calibration can be fast, cheap and simple
  ▪ Calibration is best delayed as long as possible, so stresses relax
A typical crystal (Microtune)

<table>
<thead>
<tr>
<th>Package Size</th>
<th>DS26</th>
<th>DS15</th>
<th>DS10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal frequency</td>
<td>$F_L$</td>
<td>32.768 kHz</td>
<td>32.768 kHz</td>
</tr>
<tr>
<td>Load capacitance</td>
<td>$C_L$</td>
<td>8.2 pF</td>
<td>8.2 pF</td>
</tr>
<tr>
<td>Frequency tolerance</td>
<td>$\Delta F/F$</td>
<td>+/-20 ppm</td>
<td>+/-20 ppm</td>
</tr>
<tr>
<td></td>
<td>$\Delta F/F$</td>
<td>+/-30 ppm</td>
<td>+/-30 ppm</td>
</tr>
<tr>
<td></td>
<td>$\Delta F/F$</td>
<td>+/-100 ppm</td>
<td>+/-100 ppm</td>
</tr>
<tr>
<td>Series resistance typ./max.</td>
<td>$R_S$</td>
<td>30 / 42 kΩ</td>
<td>35 / 50 kΩ</td>
</tr>
<tr>
<td>Motional capacitance typ.</td>
<td>$C_1$</td>
<td>2.1 fF</td>
<td>2.1 fF</td>
</tr>
<tr>
<td>Static capacitance typ.</td>
<td>$C_0$</td>
<td>0.9 pF</td>
<td>0.9 pF</td>
</tr>
<tr>
<td>Drive level max.</td>
<td>$P$</td>
<td>1.0 μW</td>
<td>1.0 μW</td>
</tr>
<tr>
<td>Quality factor min.</td>
<td>$Q$</td>
<td>55'000</td>
<td>45'000</td>
</tr>
<tr>
<td>Insulation resistance min.</td>
<td>$R_i$</td>
<td>500 MΩ</td>
<td>500 MΩ</td>
</tr>
<tr>
<td>Aging first year max.</td>
<td>$\Delta F/F$</td>
<td>+/-3 ppm</td>
<td>+/-3 ppm</td>
</tr>
<tr>
<td>Turnover temperature</td>
<td>$T_0$</td>
<td>25 +/-5 °C</td>
<td>25 +/-5 °C</td>
</tr>
<tr>
<td>Frequency vs. temperature</td>
<td>$\Delta F/F_0$</td>
<td>$-0.035 \text{ ppm/}^\circ C (T - T_0)^2 +/-10%$</td>
<td>$-0.035 \text{ ppm/}^\circ C (T - T_0)^2 +/-10%$</td>
</tr>
</tbody>
</table>

Data sheet for a typical 32kHz crystal. Note:

- The crystal frequency peaks close to 25°C
- Frequency falls in a parabolic manner above and below 25°C
- The parabolic curve varies little between samples of crystal
- Aging is the same for low and high precision versions

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Crystal frequency with no correction

- Without correction, the crystal frequency changes parabolically with temperature.
- At high and low temperatures, realistic for severe climates and self-heating, the error is quite large.

Crystal spec:
Offset at 25°C = +/- 30 ppm,
Coefficient = \( \Delta T^2 \times -0.035 \) ppm.
Correcting for manufacturing tolerance

- With compensation for crystal manufacturing tolerance results are better at room temperature
- There is no improvement elsewhere

Crystal spec:
Offset at 25 C = +/- 30ppm,
Coefficient = $\Delta T^2 \times -0.035$ ppm
Fully correcting the crystal frequency

- With compensation for manufacturing tolerance and temperature a spread of errors something like the yellow band is achievable.

- Actual results will depend on layout and other factors.

Crystal spec:
Offset at 25 C = +/- 30ppm,
Coefficient = $\Delta T^2 \times -0.035$ ppm
Internal temperature sensors

- Each ADC in the MSP430 range – ADC10, ADC12, SD16 and SD16A has a temperature sensor with a near to straight line characteristic.
- The slope and the y-axis intercept point varies from sample to sample.
- Precise calibration requires measurement at two temperatures.
- Using a compromise value for the slope, and finding the y-axis intercept through a measurement at room temperature is good enough for most purposes.
External temperature sensors

• Some small MSP430 device have no true ADC, but they do have comparator A
  ▪ Can be used to make a low power slope ADC

• Used with an external temperature sensor, this could be the basis for a temperature compensated RTC design
A ULP temp corrected RTC

• We can compensate the clock with very little power increase over the simple RTC, if we:
  ▪ Run the ADC for a very short time, at well spaced intervals, and measure the temperature
  ▪ Calculate the current error in the crystal frequency, and integrate this over time, until we are one second fast or slow
  ▪ Make the time hop by one second, when the integration reaches its threshold

• Current consumption still extremely low
  ▪ A 3022 coin cell typically still runs products for 10 years

• Time hops can be mitigated if necessary
  ▪ Clock updates can be increased around the hop time, to allow them to be smoothed out
A low power temp corrected 1pps out

• Often, approvals, or other tests, require a 1pps output
• We can generate this very well on devices with the FLL clock module
• We use the fast CPU clock locked to the 32kHz clock
  ▪ A special feature of Timer A lets us time the output of the 1pps output to within one CPU clock cycle
  ▪ Most of the time the device can be in the LPM0 state
• Power consumption can still be quite low (~30uA)
  ▪ The additional consumption is usually not too important. The 1pps output does not need to be enabled at all times
What about devices without an FLL?

• **We have used the hardware module so far**
  - The simple factory calibration used it
  - The 1pps output used it
  - The corrected RTC only used the 32kHz crystal

• **We can calibrate the basic error by using an accurate external timer**

• **We can build a corrected RTC without the FLL**
Timer A generating an accurate 1pps

- Software must process an interrupt at each overflow
- Interrupt rate is low

\[
T = 65535 \times 0.9 + T_{adj}
\]

\[
9.065535 \times \Delta T_{adj} = \text{adj}
\]
Crystal frequency error estimation

- Crystal Offset
- Sensor parameters
- Sensor reading
- Temperature estimation
- Parabolic calculations

\[ \Delta T_{adj} \]

- Timer A one pulse per second Generator
- 1MHz SMCLK
- 1 second ticks
Factory calibration

• The basic error at the centre of the parabola can be measured quite simply at production time
  ▪ A precision 32kHz clock is connected to a Timer A input pin on the MSP430
  ▪ Timer A, a CPU clock frequency locked to the MCU’s 32kHz crystal, and a little software do the work
  ▪ We tell the meter the calibration room temperature, so the software can allow for the current position on the crystal’s parabola
  ▪ About 30 seconds of self calibration is all that is needed

• The MSP430’s internal temperature sensor can be calibrated at the same time

• Calibration parameters can be stored in the 430’s information memory
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Example: putting it all together in an energy meter application

- The real time clock is updated only once a second
- Correction by adding or subtracting a whole second is generally acceptable in a meter
- We could measure the temperature once a second in normal operation, without affecting energy measurement
- When the meter is in power off/RTC only mode we can measure the temperature once every few minutes, without high overall battery consumption
- We integrate error each second, at the current rate, until we are either:
  - a whole second ahead – we increment an extra second, or…
  - a whole second behind – we skip an increment of one second
Some Code & Demonstration

• We will look through key elements of some demonstration code, in C, to see in detail how it works
  ▪ This code implements both the ultra low power, and 1pps forms of compensated clock
  ▪ This code has been provided, and runs on the ATC board

• We will show it working in the 1pps mode
  ▪ Updates occur too infrequently in the ultra low power mode to provide a workable demonstration

• We will hand calibrate for the sample of MCU and crystal we have, and show the results we can achieve
Set things up, Interrupts do the rest

```c
void main(void)
{
    WDTCTL = WDTPW | WDTHOLD; /* Stop watchdog timer */
    init_fll(); /* Lock the FLL at 4MHz */
    init_lcd(); /* LCD to show the time */
    init_basic_timer(); /* Provides 1s kicks */
    set_rtc_sumcheck(); /* Init. the RTC */
    if (one_pps_active)
        init_pulse_stuffer(); /* Init. 1pps generation */
    init_adc(); /* Init. temp. sensing */
    _EINT();
    /* Sleep, and let interrupts do the work */
    if (one_pps_active)
        LPM0;
    else
        LPM3;
}
```
Estimating the crystal clock speed...

```c
void estimate_current_cycles_per_second(int16_t temperature)
{
    int32_t temp;

    /* A simple IIR filter smoothes noisy sensor readings */
    raw_temperature_from_adc +=
        temperature - (raw_temperature_from_adc >> 3);
    /* Find the temp., in Celsius, based on the sensor
       characteristics found at calibration time. */
    temp = raw_temperature_from_adc
        - temperature_sensor_intercept;
    temp *= temperature_sensor_slope;
    temp >>= 16;
    temperature_in_celsius = temp
}```
...Estimating crystal clock speed...

/* Now we need to calculate the ppm of clock error due to the current temperature. */
/* Subtract the centre point of the crystal curve. */
temp -= CRYSTAL_QUADRATIC_CENTRE_TEMPERATURE;
/* Do the parabolic curve calculation, to find the current ppm of error due to temperature. */
temp = temp*temp;
temp = (temp*CRYSTAL_QUADRATIC_COEFF) >> 16;
...Estimating crystal clock speed...

```c
switch (correction_components) {
    case RTC_CORRECTION_NONE:
        current_rtc_correction = 0;
        break;
    case RTC_CORRECTION_CRYSTAL_ERROR:
        current_rtc_correction = crystal_base_error;
        break;
    case RTC_CORRECTION_TEMPERATURE:
        current_rtc_correction = -temp;
        break;
    case RTC_CORRECTION_CRYSTAL_ERROR_AND_TEMPERATURE:
        current_rtc_correction = crystal_base_error - temp;
        break;
}

    current_estimated_cycles_per_second =
        CRYSTAL_BASE_CYCLES_PER_SECOND
        + current_rtc_correction;
```
void init_pulse_stuffer(void)
{
    TAR = 0;
    TACCR0 = 0;
    TACTL = TASSEL_2 | MC_2 | ID_2;
    P1SEL |= BIT0;
    P1DIR |= BIT0;
    TACCTL0 = OUTMOD0 | CCIE;
    /* Initialize the cycles per second with an approximation */
    current_estimated_cycles_per_second =
        CRYSTAL_BASE_CPS + crystal_base_error;
    cycles_left_this_second =
        current_estimated_cycles_per_second;
}
void update_pulse_stuffer(void) {
    uint16_t step;
    step = 65536U - 655U;
    cycles_left_this_second -= step;
    if (cycles_left_this_second <= 655) {
        step += cycles_left_this_second;
        TACCTL0 &= ~OUTMOD2;
        cycles_left_this_second = current_estimated_cycles_per_second;
    } else {
        TACCTL0 |= OUTMOD2;
    }
    TACCR0 += step;
}
int update_rtc(void)
{
    integrated_rtc_correction += current_rtc_correction;
    if (integrated_rtc_correction >= CRYSTAL_BASE_CPS)
    {
        integrated_rtc_correction -= CRYSTAL_BASE_CPS;
        /* We need to add an extra second to the RTC */
        bump_rtc();
    }
    else if (integrated_rtc_correction <= -CRYSTAL_BASE_CPS)
    {
        integrated_rtc_correction += CRYSTAL_BASE_CPS;
        /* We need to drop a second from the RTC */
        return;
    }
    bump_rtc();
}
A Real-Time Demonstration

• We will see the software’s 1pps mode in operation
• We will hand calibrate for the sample of MCU and crystal we have, using an accurate timer-counter
• We will show the results we can achieve with an accurate timer-counter, and..... a hairdryer!
• We cannot run this as a hands on lab session, as each person would need an accurate timer-counter......
• All the materials are provided, so you can try this for yourselves later
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