AN1413

Temperature Compensation of a Tuning Fork Crystal Based on MCP79410

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INTRODUCTION

An increasing number of applications that involve time measurement are requiring a Real-Time Clock device. The MCP79410 is a feature-rich RTCC that incorporates EEPROM, SRAM, unique ID and time-stamp.

This application note describes how to compensate the parabolic thermal drift of some crystals in RTCC-based projects, using the Calibration register.

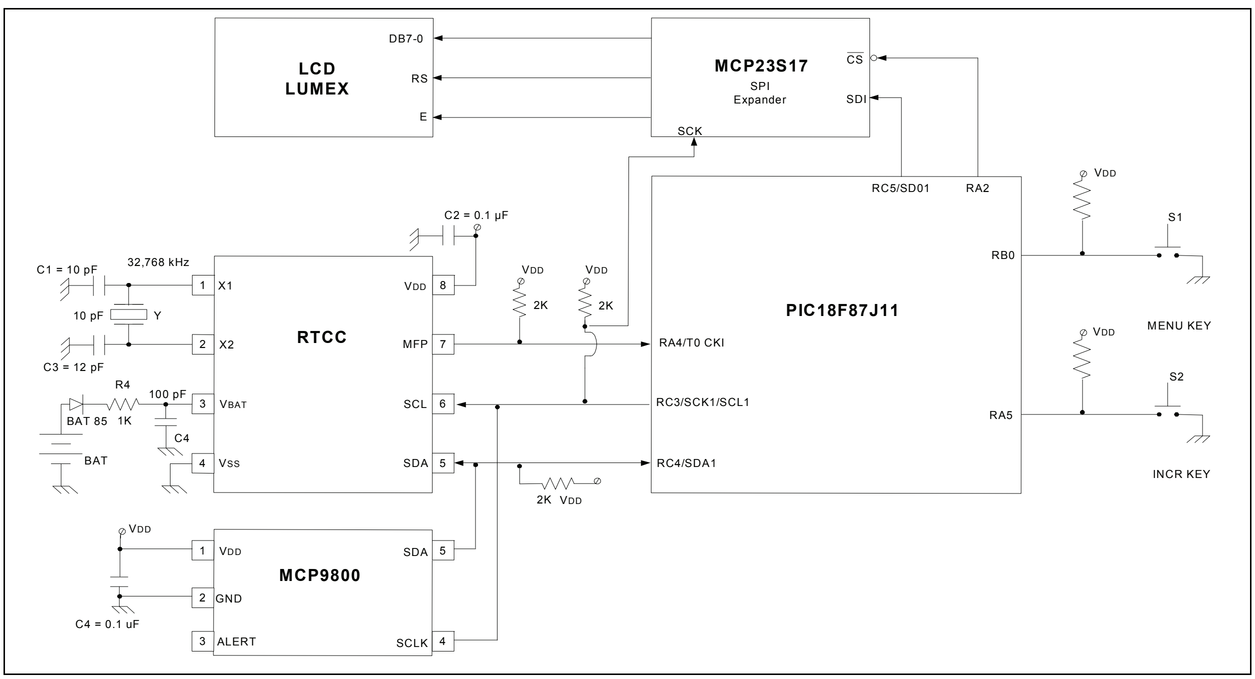
FEATURES OF THE RTCC

- I^2C™ Bus Interface
- RTCC with Time/Date: Year, Month, Date, Day of Week, Hours, Minutes, Seconds
- Support for Leap Year
- Low-Power CMOS Technology
- Input for External Battery Back-up
- 64 backed-up Bytes of SRAM
- On-Board 32.768 kHz Crystal Oscillator for the RTCC
- On-Chip Digital Trimming/Calibration of the Oscillator
- Operates down to 1.8V
- Back-up Voltage down to 1.3V
- Operating Temperature Range:
  - Industrial (I): -40°C to +85°C
- Multi-Function Pin:
  - Open-drain configuration
  - Programmable clock frequency out
- Interrupt Capability (based on the two sets of Alarm Registers (ALM0 and ALM1)
- Time Saver Function
- Time-Stamp Registers for holding the Time/Date of Crossing:
  - from VDD to VBAT
  - from VBAT to VDD

SCHEMATIC

The schematic includes a PIC18 Explorer demo board and the I^2C RTCC PICtail™ AC164140 as shown in Figure 1. (The PICtail daughter board includes the MCP9800 temperature sensor).

FIGURE 1: SCHEMATIC



The resources used on the demo board are:

- LCD
- Two push buttons
- AC164140 – PICtail daughter board including MCP9800

To access the LCD through a minimum of pins, the SPI on the MSSP1 module was used, in conjunction with a 16-bit I/O expander with SPI interface (MCP23S17).

The two on-board push buttons S1 and S2 are connected to RB0, RA5 GPIOs. The I^2C RTCC is part of the PICtail daughter board and is directly connected to the MSSP1 module of the MCU. All connections between the I^2C RTCC and the MCU (SDA, SCL, MFP) are open-drain and use pull-up resistors. On the RTCC PICtail daughter board are three other components:

- a 32.768 Hz crystal driving the internal clock of the RTCC
- a 3-Volt battery sustaining the RTCC when VDD is not present on the demo board.
- An I^2C temperature sensor (MCP9800), which is connected to the same I^2C bus.

FUNCTIONAL DESCRIPTION

MCP79410 is an I^2C slave device, working on the related bidirectional 2-wire bus. SDA is a bidirectional pin used to transfer addresses and data in and out of the device. It is an open-drain pin, therefore, the SDA bus requires a pull-up resistor to VCC (typically 10 kΩ for 100 kHz, 2 kΩ for 400 kHz). For normal data transfers, SDA is allowed to change only during SCL low. Changes during SCL high are reserved for indicating the Start and Stop conditions. SCL input is used to synchronize the data transfer from and to the device. The related internal structures have the following device address/control bytes (the RTCC is included in the SRAM bank):

- RTCC + SRAM: 0xDE for writes, 0xDF for reads
- EEPROM: 0xAE for writes, 0xAF for reads

The chip can support speeds up to:

- 400 kHz 2.5 to 5V
- 100 kHz 1.8 to 2.5V

The MCP9800 temperature sensor has the following I^2C addresses/control bytes:

- 0x90 for writes
- 0x91 for reads

DETAILS ABOUT IMPLEMENTATION

The application is designed around the PIC18 Explorer demo board, running on a PIC18F87J11 MCU. The code is written using the C18 compiler.

The firmware shows how to compensate a parabolic thermal drift of some crystals, using the Calibration register, included in the RTCC structure, at address 08h.

The operation of this register is described in the MCP7941X data sheet (DS22266):

"The Calibration register allows a number of RTCC counts to be added or subtracted each minute. This allows for calibration to reduce the PPM error due to oscillator shift. This register is volatile.

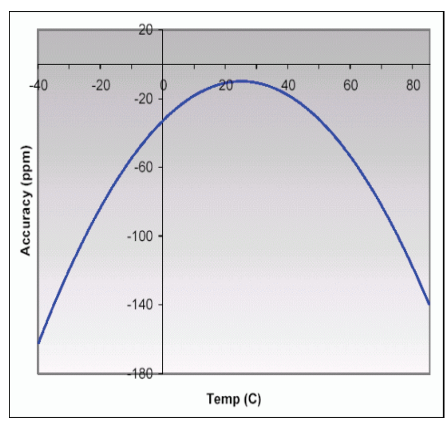
The Most Significant bit (MSb) in the register is the sign bit. If this bit is set to '`1`' then the bits 6:0 will be subtracted, if clear, '`0`', then this will be added. A value of `x0000000` will result in no calibration. The calibration is linear, with one bit representing two RTC clocks."

At this point, a good source of information is application note AN1365, "*Recommended Usage of Microchip Serial RTCC Devices*."

Without the correct crystal, the RTCC will not operate as to specification. There are two basic types of crystals that are suitable for use with the RTCC.

Tuning fork crystal – these are the most common type of crystal and are traditionally used with RTCC devices due to availability and low cost. The typical temperature curve for tuning fork crystals is shown below.

FIGURE 2: PARABOLIC CURVE FOR TUNING FORK CRYSTALS



The accuracy of the crystal is acceptable around the 25°C temperature. Moving away from this point the PPM changes drastically. It is recommended that the internal calibration be used to improve the accuracy at other temperatures.

The following crystals have been tested and found to work with the MCP7941X family. The table below is given as design guidance and a starting point for crystal and capacitor selection.

Manufacturer	Part Number	Crystal Capacitance	CX1 Value	CX2 Value
Micro Crystal	CM7V-T1A	7pF	10pF	12pF
Citizen	CM200S-32.768KDZB-UT	6pF	10pF	8 pF
Note: Please work with your crystal vendor.				

Similar observations about the temperature effect on crystals can be found on the Wikipedia® web site.

“A crystal’s frequency characteristic depends on the shape or ‘cut’ of the crystal. A tuning fork crystal is usually cut such that its frequency over temperature is a parabolic curve centered around 25°C. This means that a tuning fork crystal oscillator will resonate close to its target frequency at room temperature, but will slow down when the temperature either increases or decreases from room temperature. A common parabolic coefficient for a 32 kHz tuning fork crystal is 0.04 ppm/°C^2”

Relation 1A

$f = f0 \times [1 - 0.04 < ppm/C^2 > \times (T-T0)^2]$

The particular coefficient should be replaced in a more general manner:

Relation 1B

$f = f0 \times [1 - Tc \times (T-T0)^2]$

$Tc = [\ 0.030 \ldots 0.050\ ] < ppm/°C^2 >$

Or, in another form:

Relation 2A

$df = -Tc \times [(T-T0)^2]$

Relation 2B

$df = -TC \times [(T-T0)^2] / 1000$

$TC = 1000 * Tc$

Relation 2C

$df = - [(T-T0)^2] / KT$

f	=	frequency of the crystal
f0	=	frequency at the room temperature
T	=	ambient temperature
T0	=	turnover point (room temperature)
dT	=	deviation of temperature
df	=	frequency deviation
Tc, TC, KT	=	thermal coefficients

The formula used in **Relation 2B** will be used in firmware.

The same Wikipedia link describes further:

“In a real application, this means that a clock built using a regular 32 kHz tuning fork crystal will keep good time at room temperature, lose two minutes per year at 10 degrees Celsius above (or below) room temperature and lose 8 minutes per year at 20 degrees Celsius above (or below) room temperature due to the quartz crystal.

T0 = 25°C and thermal coefficient = 0.04ppm/°C^2 are usual values.”

The code offers through #define directives the ability to choose the most correct value for both variables: turnover point and thermal coefficient.

$T0 \sim 25°C$

$Tc = [0.030 - 0.050] < ppm/°C^2 >$

$TC = [\ 30 - 50\ ] < ppm/°C^2 >$

$KT = [\ 20 \ldots 30\ ] <°C^2/ppm>$

Since 1bit of the Calibration register adds 2CKs/minute, it means that 1 bit will be: 2/(60*32,768) = 2/1,966,080 ~ 1ppm.

The deviation of the frequency is also expressed in <ppm>, so the two relations must be equalized. Therefore, the calibration value must be calib = calib + 0x80 (keep in mind that the Calibration register must increase the frequency accordingly to subtract pulses along a minute, so it must have negative values):

Relation 3A

$calib = -Tc \times (dT^2)$

Relation 3B

$calib = -[TC \times (dT^2)] / 1000$

For accuracy and ease of use, **Relation 3B** will be used in the firmware.

Relation 3C

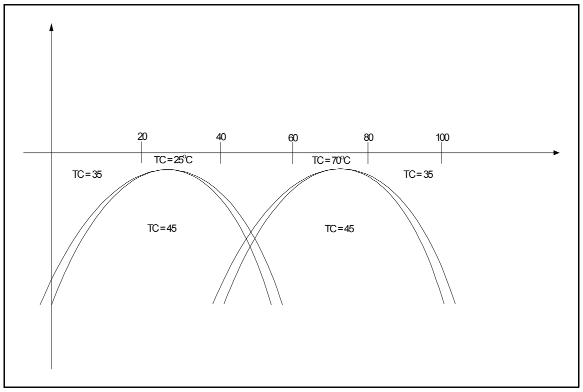
$calib = -(dT^2) / KT$

MATH RELATIONS AND THE PRECISION OF THE METHOD

As described in **Relation 2**, the math rule (frequency deviation versus temperature) describes for some crystals (tuning fork crystals) a parabolic curve, in which the main coefficient of the parabola is negative. This means that the frequency has a maximum in the turnover point (room temperature) and decreases for any other temperature value.

A description of this dependency is depicted in Figure 3, in which we can see few parabolas related to several values for the turnover point and the thermal coefficient.

FIGURE 3: PARABOLIC CURVE



Since this parabola has a negative coefficient, the Calibration register must be set with a negative value (bit7 = 1, the last 6 bits are significant) in order to finally obtain the frequency versus temperature flat curve.

More information about the compensation mechanism of the Calibration register can be found in the MCP7941X data sheet (DS22266).

The Calibration register must have negative values in order to compensate the decrease of frequency of the crystal. Accordingly,

calib < 127 therefore,

$dT < (127*25)^{1/2} \sim 56^{o}C \ (KT = 25^{o}C^{2}/ppm)$

Therefore, the ambient temperature must be in the range: [-30...+80] °C

QUANTIZATION ERRORS

Approximation of numbers on small machines creates quantization errors. 8-bit machines are especially affected.

Et represents the total error and is the sum of several possible errors.

Et = E1 + E2 + E3 +....

E1 = quantization of the thermal coefficient (KT)

E2 = truncation or rounding of the calibration value

E3 = error due to the imprecision of the MCP9800 temperature sensor

APPROXIMATION OF THE THERMAL COEFFICIENT (KT)

The first version of the code used, KT = 1/Tc, where Tc is given by manufacturers in the formula:

dF = -Tc x dT^2

Tc is expressed in <ppm> and is in the range [0.03... 0.05] <ppm/°C^2>

Consequently, formula (3) becomes:

calibration = -dT^2/KT

where KT = [20 ... 30] <°C^2/ppm>(3c)

KT is calculated manually and only once by the user, starting from the constant Tc = [0.03 ... 0.005] <ppm/°C^2>.

A source of errors is represented by the truncation at ‘unsigned char’ of the thermal coefficient (KT).

Tc = 0.039, therefore KT = 1/Tc = 25.6. (25 or 26)

A typical error can be seen in Equation 1:

EQUATION 1:

$$d\_cal = \frac{dT \times dT}{KT1} - \frac{dT \times dT}{KT2} = dT \times dT \times \left[\frac{1}{KT1} - \frac{1}{KT2}\right]$$

or

$$d\_cal = dT^2 \times \left[\frac{1}{25} - \frac{1}{25.5}\right] = dT^2 \times \frac{0.5}{625} = \frac{dT^2}{1250}$$

This means that for a 50°C temperature deviation, the error could reach 2ppm.

(50^2/1250 = 2500/1250 = 2 ppm)

In order to better this deviation, another math algorithm could be used. The Tc constant will be used instead of KT and dT is an unsigned long:

EQUATION 2:

$$dF = -Tc \times dT^2$$

$$calib = -Tc \times dT^2$$

$$Tc = [0.030 \ldots 0.050] \text{ ppm/}^oC^2$$

$$calib = -\frac{(-TC \times dT^2)}{1000}$$

$$TC = [30 \ldots 50]$$

where TC= 1000 x Tc

Since this method avoids the quantization of KT, we will obtain a better precision by using Tc. The two examples below use both methods.

TC = 39 dT = 20

Method 1 (using TC)

calib1 = 39 x 400/1000 = 15.6 ~ 16

Method 2 (using KT) KT= 1/0.039 = 25.6 ~ 26

calib2 = 400/26 = 15.38 ~ 15

TC = 39 dT = 50

Method 1 (using TC)

calib1 = 39 x 2500/1000 = 97.50 ~ 98

Method 2 (using KT) KT= 26

calib2 = 2500/26 = 96.15 ~ 96

CALIBRATION VALUE – TRUNCATION VERSUS ROUNDING

Truncation implies a constant negative offset of ~0.5 ppm while rounding offers a flat curve of the error on the whole range of temperatures (+/- 0.5 ppm).

Accordingly, the rounding method was used in the firmware.

ERRORS DUE TO THE MCP9800 TEMPERATURE SENSOR

The last possible error is represented by the temperature sensor.

As stated in the related data sheet, the error for each temperature range is listed below:

25°C	=	+/-0.5°C
[-10...+085]	=	+/-1.0°C
[-10...+125]	=	+/-2.0°C
dT	=	Deviation of the ambient temperature
eT	=	Temperature error of the I^2C™ sensor

The error of the calibration value `d_cal` is shown in Equation 3:

EQUATION 3:

$$d\_cal = \left(\frac{TC}{1000}\right) \times [(dT + eT)^2 - dT^2]$$
$$= \left(\frac{TC}{1000}\right) \times [eT^2 + 2 \times dT \times eT]$$
$$= \left(\frac{40}{1000}\right) \times [1 + 100] \sim 4ppm$$

Where TC = 40 ppm/°C^2
dT = 50°C
eT = 1°C

The value of the temperature sensor's error is higher than the error due to the quantization of KT.

APPLICATION'S DESCRIPTION

Three versions of the project can be found on Microchip's web site:

- the simulation project (`SIMUL_B03`)
- the real processing project (`REAL_B03`)
- the tester of the calibration mechanism (`SIMUL_MFP_B03`)

The simulation replaces the reads from the temperature sensor (`unsigned int MCP9800_rdtemp()`) through a simple setting of the `unsigned int ADC_temp` basic variable. Based on this value, the `temp_compensation()` function will calculate the values for the final variables, such as:

- `unsigned char temp = temperature`
- `unsigned char sgntemp = sign of the temperature`
- `unsigned char calib = value to be written in the calibration register`

The main function of the simulation project will increment or decrement the value of `ADC_temp`, depending on which push button was pressed, S1 or S2. Accordingly, the whole table (calibration versus temperature) will be covered, as below:

- °C to +80°C
- 0°C to -30°C

The real processing project reads the MCP9800 temperature sensor through the related read function `unsigned int MCP9800_rdtemp(void)`.

Furthermore, the compensation function `void temp_compensation(void)` will calculate the final values for the temperature, sign of temperature, deviation of the temperature (dT) and the value for the Calibration register. Since the correction value must be negative, the write in the Calibration register is `rtcc_wr (calib+0x80,ADDR_CAL)`.

The tester of the calibration mechanism measures and displays also the duration of 1 minute (µsec). The related table calculates the number of 32 kHz pulses along 1 minute.

All three projects can handle the compensation function through truncation or rounding of the calibration value. More comments on this subject can be found in the paragraph below.

FIRMWARE DESCRIPTION

The new functions introduced by the application are:

- `void temp_compensation(void)` – may be included in any RTCC project to compensate a parabolic thermal drift of a tuning fork crystal. Starting from the basic variable '`unsigned int ADC_temp`' it calculates the final values for: temperature, degree sign of temperature, dT and calibration. It is based on two methods, truncation or rounding.
- `unsigned int MCP9800_rdtemp(void)` – reads the ambient temperature on a I^2C bus. The format of the temperature sensor is the complement of 2 on 9,10,11,12 bits.
- `void ini_MCP9800(void)` – initialization of the temperature sensor
- `void per_mfp (void)` – specific for the calibration's tester `(simul_mfp_B03)`. The function measures (based on TMR0) the duration of one minute (value expressed in microseconds).

The most important of these functions is the temperature compensation function. The Firmware Code can be found in Appendix A.

As stated in the math relations paragraph, there are slight differences between the two basic methods of calculation for the calibration value, truncation and rounding.

Truncation will offer a permanent negative offset (1bit = 1 ppm), with an average value (in the whole temperature range) of -0.5 ppm.

Rounding will give an offset of +/- 0.5 ppm with an average value (in the whole temperature range) of ~ 0 ppm. Based only on this statement, it seems that rounding is better than truncation.

The experimental results obtained by the simulation project are condensed in the calibration versus temperature tables.

Slightly different values for the calibration are obtained through the two methods discussed earlier, truncation and rounding.

Drivers

Drivers are divided into 3 classes:

- LCD drivers
- RTCC's registers access drivers
- Temperature compensation functions

LCD Drivers

The application is implemented on a specific hardware, the PIC18 Explorer demo board. On this board it was important to reduce the number of GPIO pins used to access the LCD. Accessing the LCD is performed on a SPI bus (included in the MSSP1 module) through an auxiliary chip, the MCP23S17 SPI expander. The related drivers are:

- `wrcmnd_lcd (unsigned char cmnd_lcd)` (write command to LCD)
- `wrdata_lcd (unsigned char data_lcd)` (write data byte/character to LCD)
- `wrstr_lcd (const rom unsigned char *str_lcd)` (write to LCD a string stored in the flash).

Drivers to Access RTCC's Registers

Since MCP79410 is an I^2C RTCC, it will use the I^2C bus of the MCU (the MSSP1 module). Accordingly, the related drivers will be divided into two categories: basic I^2C drivers and RTCC drivers. They use as a control method the SPP1IF bit (flag) in the PIR1 register (interrupt flag of the MSSP1 module), read through polling and not through interrupts. The method represents an alternative to the classical "`i2c.h`" library, included in the C18 compiler.

FIGURE 4: FLOWCHART FOR A TYPICAL WRITE OPERATION (FOR A RANDOM BYTE ACCESS)

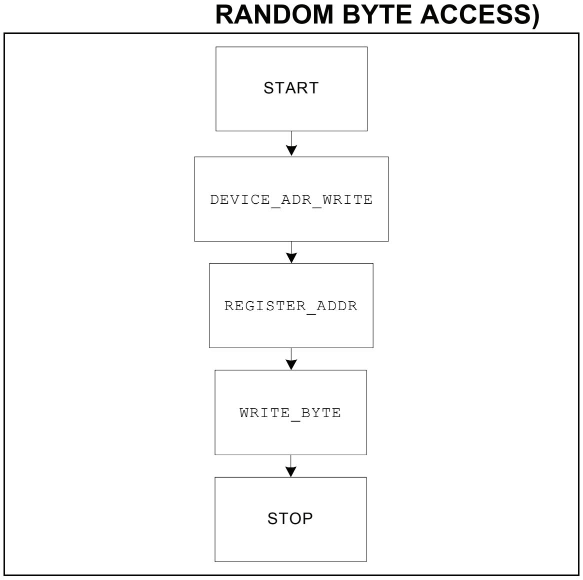
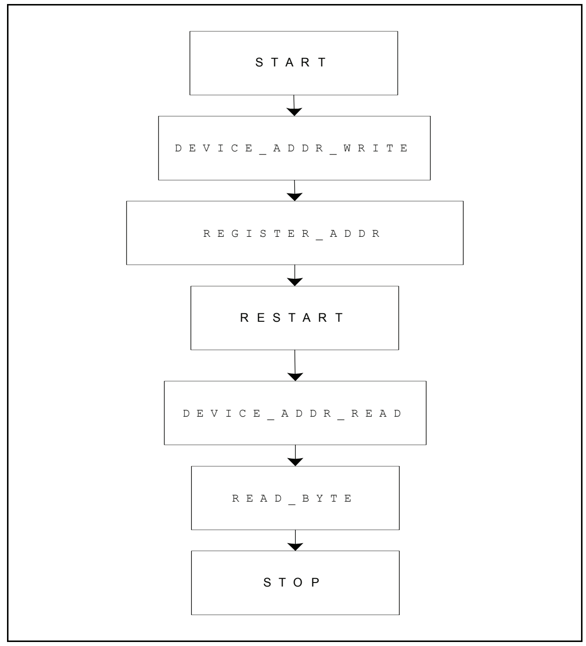


FIGURE 5: FLOWCHART FOR A TYPICAL READ OPERATION



ACESSING THE RTCC'S REGISTERS

There are two basic functions for accessing the RTCC: one for writes and one for reads. They can be defined as: `void rtcc_wr (unsigned char time_var, unsigned char rtcc_reg), unsigned char rtcc_rd (unsigned char rtcc_reg)`. Each of these two functions include error messages displayed on LEDs, which could signal when an operation is not acknowledged by the slave (RTCC).

EXAMPLE 1: FLOWCHART FOR WRITES TO THE RTCC

```
i2c_start()           ; //    start I2C communication: SDA goes down while SCL remains high
i2c_wr(ADDR_RTCC_WRITE); //    send the RTCC's address for write = 0xde
i2c_wr(rtcc_reg)      ; //    send the register's address
i2c_wr(time_var)      ; //    send data byte to the RTCC
i2c_stop()            ; //    stop I2C communication: SDA goes high while SCL remains high
```

EXAMPLE 2: FLOWCHART FOR READS FROM THE RTCC

```
i2c_start()           ; //    start I2C communication: SDA goes down while SCL remains high
i2c_wr(ADDR_RTCC_WRITE); //    send the RTCC's address for write = 0xde
i2c_wr(rtcc_reg)      ; //    send the register's address
i2c_restart()         ; //    switch to reads
i2c_wr(ADDR_RTCC_READ) ; //    send the RTCC's address for read = 0xdf
i2c_rd()              ; //    read the byte from the RTCC (register's content)
i2c_nack()            ; //    NoACK from MCU to the RTCC (no more bytes to read)
i2c_stop()            ; //    stop I2C communication: SDA goes high while SCL remains high
```


TESTS AND SIMULATIONS

During the development, the correctness of the math relations was tested through the simulation project. In the Temperature column there are pairs of temperatures. The frequency describes a parabola and, accordingly, the frequencies are symmetric around the turnover point. The turnover point (temp0) is usually 25°C. The results can be found in Table 1 and Table 2.

TABLE 1: CALIBRATION VERSUS TEMPERATURE – THE TRUNCATION METHOD

Temperature (°C)	Compensation -(ppm)		
25/25	0	0	0
26/24	0	0.03	0
27/23	0	0.16	0
28/22	0	0.35	0
29/21	0	0.62	0
30/20	0	0.98	0
31/19	1	1.40	1
32/18	1	1.91	1
33/17	2	2.49	2
34/16	3	3.16	3
35/15	3	3.90	3
36/14	4	4.72	4
37/13	5	5.62	5
38/12	6	6.59	6
39/11	7	7.64	7
40/10	8	8.78	8
41/09	9	9.98	9
42/08	11	11.27	11
43/07	12	12.64	12
44/06	14	14.08	14
45/05	45	15.60	15
46/04	17	17.12	17
47/03	18	18.88	18
48/02	20	20.63	20
49/01	22	22.46	22
50/00	24	24.38	24
51/-01	26	26.36	26
52/-02	28	28.43	28
53/-03	30	30.58	30
54/-04	32	32.80	32
55/-05	35	35.10	35
56/-06	37	37.48	37
57/-07	39	39.94	39
58/-08	42	42.47	42
59/-09	45	45.08	45
60/-10	47	47.78	47
61/-11	50	50.54	50
62/-12	535	53.39	53
63/-13	56	56.32	56
64-14	59	59.32	59
65/-15	62	62.40	62
66/-16	65	65.56	65
67/-17	68	68.80	68
68/-18	72	72.11	72
69/-19	75	75.50	75
70/-20	78	78.98	78
71/-21	82	82.52	82
72/-22	86	86.15	86
73/-23	89	89.86	89
74/-24	93	93.64	93
75/-25	97	97.50	97
76/-26	101	101.44	101
77/-27	105	105.46	105
78/-28	109	109.56	109
80/-30	117	117.98	117
81/-31	122	122.30	122
82/-32	126	126.71	126

TABLE 1: CALIBRATION VERSUS TEMPERATURE – THE TRUNCATION METHOD

TABLE 2: CALIBRATION VERSUS TEMPERATURE – THE ROUNDING METHOD

Temperature (°C)	Compensation -(ppm)		
25/25	0	0	0
26/24	0	0.03	0
27/23	0	0.16	0
28/22	0	0.35	0
29/21	1	0.62	1
30/20	1	0.98	1
31/19	1	1.40	1
32/18	2	1.91	2
33/17	2	2.49	2
34/16	3	3.16	3
35/15	4	3.90	4
36/14	5	4.72	5
37/13	6	5.62	6
38/12	7	6.59	7
39/11	8	7.64	8
40/10	9	8.78	9
41/09	10	9.98	10
42/08	11	11.27	11
43/07	13	12.64	13
44/06	14	14.08	14
45/05	16	15.60	16
46/04	17	17.12	17
47/03	19	18.88	19
48/02	21	20.63	21
49/01	22	22.46	22
50/00	24	24.38	24
51/-01	26	26.36	26
52/-02	28	28.43	28
53/-03	31	30.58	31
54/-04	33	32.80	33
55/-05	35	35.10	35
56/-06	37	37.48	37
57/-07	40	39.94	40
58/-08	42	42.47	42
59/-09	45	45.08	45
60/-10	48	47.78	48
61/-11	51	50.54	51
62/-12	53	53.39	53
63/-13	56	56.32	56
64-14	59	59.32	59
65/-15	62	62.40	62

TABLE 2: CALIBRATION VERSUS TEMPERATURE – THE ROUNDING METHOD

Temperature (°C)	Compensation -(ppm)		
66/-16	66	65.56	66
67/-17	69	68.80	69
68/-18	72	72.11	72
69/-19	76	75.50	76
70/-20	79	78.98	79
71/-21	83	82.52	83
72/-22	86	86.15	86
73/-23	90	89.86	90
74/-24	94	93.64	94
75/-25	98	97.50	98
76/-26	101	101.44	101
77/-27	105	105.46	105
78/-28	110	109.56	110
79/-29	114	113.72	114
80/-30	118	117.98	118
81/-31	122	122.30	122
82/-32	127	126.71	127

SETUP OF THE APPLICATION

First of all, choose from the data sheet of the crystal's manufacturer the correct values for the turnover point and the parabolic coefficient. Some of the values should be tested for the following range of temperatures:

- <0°C
- [°C - turnover point (25°C)]
- >turnover point (25°C)

These actions will test the MCP9800 temperature sensor. A final test should include measurements of the clock frequency (MFP) delivered by the RTCC in order to observe the correct operation of the calibration mechanism, using the `SIMUL_MFP_B03` simulation project. As mentioned in the data sheet, the calibration module adds or subtracts two pulses (in order to obtain a 1ppm precision) of the main frequency of the crystal (32768 Hz), with every bit of the Calibration register. The calibration module performs it only once per minute. The related test results can be found in Table 3. The column titled 1MIN T32K shows how many pulses are in one minute.

TABLE 3: TEST RESULTS

TEMP	calib (-)	1MIN (µsec)	1MIN T32K	TEMP	calib (-)	1MIN (µsec)	1MIN T32K	DIFF_1MIN (25°C) T32K
0	24	59,992,369	1,966,963	50	24	59,992,376	1,966,963	48 = 2 x 24
1	22	59,992,492	1,966,967	49	22	59,992,495	1,966,967	44 = 2 x 22
2	21	59,992,554	1,966,969	48	21	59,992,559	1,966,969	42 = 2 X 21
3	19	59,992,677	1,966,973	47	19	59,992,681	1,966,973	38 = 2 x 19
4	17	59,992,800	1,966,977	46	17	59,992,803	1,966,977	34 = 2 x 17
5	16	59,992,862	1,966,979	45	16	59,992,863	1,966,979	32 = 2 x 16
6	14	59,992,984	1,966,983	44	14	59,992,985	1,966,983	28 = 2 x 14
7	13	59,993,046	1,966,985	43	13	59,993,047	1,966,985	26 = 2 x 13
8	11	59,993,169	1,966,989	42	11	59,993,170	1,966,989	22 = 2 x 11
9	10	59,993,230	1,966,991	41	10	59,993,232	1,966,991	20 = 2 x 10
10	9	59,993,291	1,966,993	40	9	59,993,294	1,966,993	18 = 2 x 09
11	8	59,993,352	1,966,995	39	8	59,993,352	1,966,995	16 = 2 x 08
12	7	59,993,415	1,966,997	38	7	59,993,413	1,966,997	14 = 2 x 07
13	6	59,993,475	1,966,999	37	6	59,993,474	1,966,999	12 = 2 x 06
14	5	59,993,534	1,967,001	36	5	59,993,535	1,967,001	10 = 2 x 05
15	4	59,993,595	1,967,003	35	4	59,993,597	1,967,003	08 = 2 x 04
16	3	59,993,655	1,967,005	34	3	59,993,657	1,967,005	06 = 2 x 03
17	2	59,993,717	1,967,007	33	2	59,993,715	1,967,007	04 = 2 x 02
18	2	59,993,716	1,967,007	32	2	59,993,715	1,967,007	04 = 2 x 02
19	1	59,993,775	1,967,009	31	1	59,993,775	1,967,009	02 = 2 x 01
20	1	59,993,775	1,967,009	30	1	59,993,775	1,967,009	02 = 2 x 01
21	1	59,993,775	1,967,009	29	1	59,993,775	1,967,009	02 = 2 x 01
22	0	59,993,840	1,967,011	28	0	59,993,840	1,967,011	00 = 2 x 00
23	0	59,993,840	1,967,011	27	0	59,993,841	1,967,011	00 = 2 x 00
24	0	59,993,840	1,967,011	26	0	59,993,840	1,967,011	00 = 2 x 00
25	0	59,993,839	1,967,011	25	0	59,993,839	1,967,011	00 = 2 x 00
-1	26	59,992,253	1,966,959	51	26	59,992,253	1,966,959	52 = 2 x 26
-2	28	59,992,132	1,966,955	52	28	59,992,131	1,966,955	56 = 2 x 28
-3	31	59,991,948	1,966,949	53	31	59,991,947	1,966,949	62 = 2 x 31
-4	33	59,991,826	1,966,945	54	33	59,991,825	1,966,945	66 = 2 x 33
-5	35	59,991,705	1,966,941	55	35	59,991,703	1,966,941	70 = 2 x 35

TABLE 3: TEST RESULTS (CONTINUED)

TEMP	calib (-)	1MIN (µsec)	1MIN T32K	TEMP	calib (-)	1MIN (µsec)	1MIN T32K	DIFF_1MIN (25°C) T32K
-6	37	59,991,583	1,966,937	56	37	59,991,581	1,966,937	74 = 2 x 37
-7	40	59,991,400	1,966,931	57	40	59,991,399	1,966,931	80 = 2 x 40
-8	42	59,991,278	1,966,927	58	42	59,991,277	1,966,927	84 = 2 x 42
-9	45	59,991,094	1,966,921	59	45	59,991,094	1,966,921	90 = 2 x 45
-10	48	59,990,912	1,966,915	60	48	59,990,912	1,966,915	96 = 2 x 48
-11	51	59,990,729	1,966,909	61	51	59,990,729	1,966,909	102 = 2 x 51
-12	53	59,990,606	1,966,905	62	53	59,990,607	1,966,905	106 = 2 x 53
-13	56	59,990,424	1,966,899	63	56	59,990,424	1,966,899	112 = 2 x 56
-14	59	59,990,241	1,966,893	64	59	59,990,240	1,966,893	118 = 2 x 59
-15	62	59,990,057	1,966,887	65	62	59,990,057	1,966,887	124 = 2 x 62
-16	66	59,989,815	1,966,879	66	66	59,989,813	1,966,879	132 = 2 x 66
-17	69	59,989,631	1,966,873	67	69	59,989,629	1,966,873	138 = 2 x 69
-18	72	59,989,449	1,966,867	68	72	59,989,446	1,966,867	144 = 2 x 72
-19	76	59,989,204	1,966,859	69	76	59,989,203	1,966,859	152 = 2 x 76
-20	79	59,989,022	1,966,853	70	79	59,989,020	1,966,853	158 = 2 x 79
-21	83	59,988,777	1,966,845	71	83	59,988,774	1,966,845	166 = 2 x 83
-22	86	59,988,593	1,966,839	72	86	59,988,592	1,966,839	172 = 2 x 86
-23	90	59,988,350	1,966,831	73	90	59,988,347	1,966,831	180 = 2 x 90
-24	94	59,988,105	1,966,823	74	94	59,988,102	1,966,823	188 = 2 x 94
-25	98	59,987,862	1,966,815	75	98	59,987,859	1,966,815	196 = 2 x 98
-26	101	59,987,679	1,966,809	76	101	59,987,676	1,966,809	202 = 2 x 101
-27	105	59,987,435	1,966,801	77	105	59,987,430	1,966,801	210 = 2 x 105
-28	110	59,987,130	1,966,791	78	110	59,987,125	1,966,791	220 = 2 x 110
-29	114	59,986,886	1,966,783	79	114	59,986,881	1,966,783	228 = 2 x 114
-30	118	59,986,642	1,966,775	80	118	59,986,637	1,966,775	236 = 2 x 118
-31	122	59,986,397	1,966,767	81	122	59,986,393	1,966,767	244 = 2 x 122
-32	127	59,986,091	1,966,757	82	127	59,986,088	1,966,757	254 = 2 x 127

CONCLUSION

This application note presents how to compensate the parabolic thermal drift of tuning fork crystals using the Calibration register of Microchip's I^2C RTCC, MC7941X. Three versions of the application are presented: simulation drive, real drive and test drive (test of the calibration mechanism through a period meter). The project is performed on a PIC18 Explorer demo board, using the on-board resources: LCD (accessed through the SPI bus) and push buttons. The AC164140 PICtail daughter board (including an I^2C RTCC and an I^2C temperature sensor) is used. The code (drivers and main function) is written in C, using the C18 compiler. The target microcontroller is PIC18F87J11.

APPENDIX A: REVISION HISTORY

Revision A (11/2011)

Original Release.

APPENDIX B: FIRMWARE CODE

```
    void temp_compensation(void) {      //  SETS THE INTERNAL FREQUENCY ACCORDING THE TEMP,
                                        //  THROUGH THE CALIBRATION REGISTER
                                        //  this is the most important function of the code.
                                        //  it obtains the 4 main values : the ambient
                                        //  temperature 'temp', it's sign , the difference
                                        //  |dT|=|temp-temp0| and the calibration value
                                        //  the 'calib' will be always negative, in order to
                                        //  increase the frequency around the turn over point
                                        //  |temp| and sign will be printed on the LCD,
                                        //  |dT| will help to compensate the temp drift, through
                                        //  the calibration register.
   unsigned int ADC_res               ; //  reserve variable to store ADC_temp
// ADC_temp  = MCP9800_rdtemp()       ; //  obtain the 16bit temperature from the sensor
   ADC_res = ADC_temp                 ; //  store the ADC result
   if((ADC_temp&0x8000)==0x0000)        //  if temp = plus,
   { sgntemp = 0x00 ; }                 //  build the extended sign
   else { sgntemp = 0x01 ;              //  if temp = minus : build the extended sign,
          ADC_temp = (~ADC_temp)+1 ; }  //  2 is complement of the ADC value
   temp = (ADC_temp>>7)&0xff          ; //  build the 8bits temperature variable
   if(!sgntemp) {                       //  if a positive temperature
    if(temp >= temp0)
    { dT = temp - temp0           ;  }
    else { dT = temp0 - temp   ;  }  }  //  build | temp - temp0 |
    else { dT = temp0 + temp   ;  }     //  if a negative temperature, dT = temp0+temp
                                        //  once dT is calculated, the final formula
   calib = (TC*(dT*dT))/1000          ; //  unsigned char calibration value
   if(((TC*(dT*dT))%1000)>=500)
         { calib++  ; }                 //  rounding instead truncation
   rtcc_wr(calib+0x80,ADDR_CAL)       ; //  write in the calibration register the
                                        //  compensation value = -(TC/1000)*dT^2(always '-')
   ADC_temp = ADC_res                 ; //  restore the ADC value for further use :
                                      } //  LCD functions & WHILE LOOP
```

Note:	The function above belongs to the simulation projects, which replace the reads from the temperature sensor by virtual temperature samples. The real drive of the function will use real samples of temperature, taken from the MCP9800. (The real drive of the function can be found in the real drive project).

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