AN1001

IC Temperature Sensor Accuracy Compensation with a PICmicro® Microcontroller

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INTRODUCTION

Microchip Technology Inc. provides a number of analog and serial-output Integrated Circuit (IC) temperature sensors. The typical accuracy of these sensors at room temperature is within one degree Celsius (±1°C). However, at hot or cold temperature extremes, the accuracy decreases non-linearly. Typically, the non-linearity has a parabolic shape. This application note derives an equation that describes the sensor's typical non-linear characteristics, which can be used to compensate for the sensor's accuracy error over the specified operating temperature range. A PICmicro® Microcontroller Unit (MCU) can be used to compute the equation and provide higher-accuracy temperature reading. This aplication note is based on the analog output MCP9700/MCP9701 and serial output MCP9800 temperature sensors.

SOLUTION APPROACH

The silicon characterization data is used to determine the non-linear sensor characteristics. From this data, an equation is derived that describes the typical performance of a sensor. Once all corresponding coefficients for the equations are determined, the coefficients will be used to compensate for the typical sensor's non-linearity.

The error distribution is provided using an average and ±1 standard deviation ($\pm \sigma$) before and after compensation. A total of 100 devices were used for the MCP9700/01, while 160 devices were used for the MCP9800.

Figure 1 shows the typical sensor accuracy before and after compensation. It illustrates that the compensation provides an accurate and linear temperature reading over the sensor operating temperature range.

A PICmicro MCU is used to compute the equation and compensate the sensor output to provide a linear temperature reading.

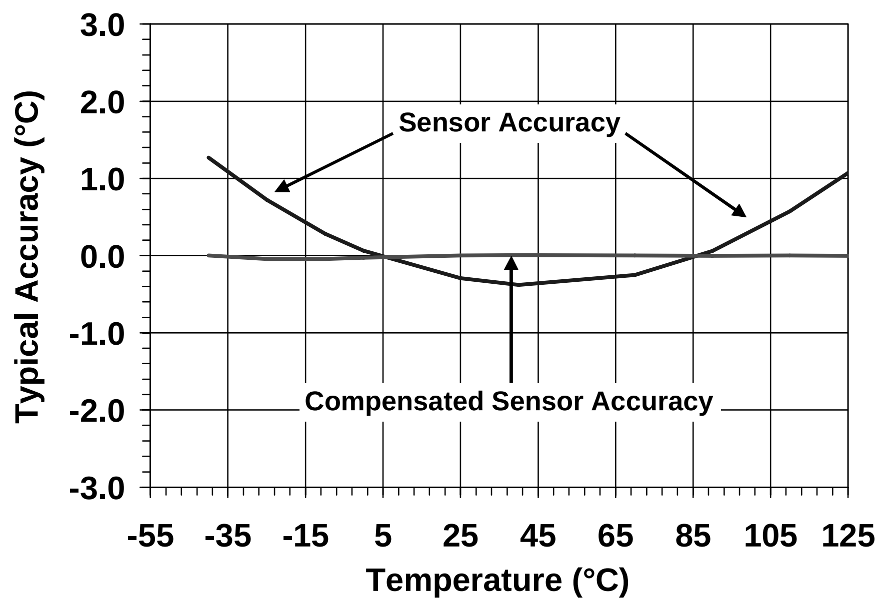

FIGURE 1: *Typical Sensor Accuracy Before and After Compensation.*

SENSOR ACCURACY

The typical sensor accuracy over the operating temperature range has an accuracy error curve. At hot and cold temperatures, the magnitude of error increases exponentially, resulting in a parabolic-shaped error curve. The following figures show the average and ±1°C standard deviation of sensor accuracy curve for the MCP9800, MCP9700 and MCP9701 sensors.

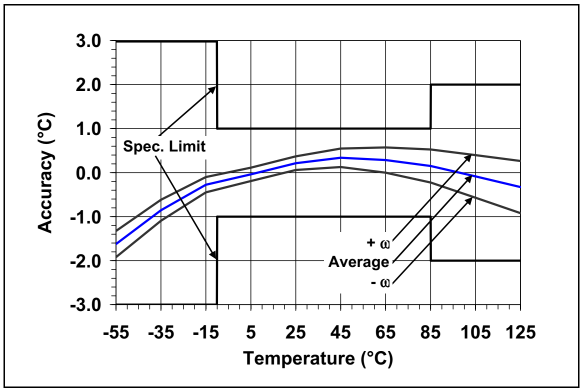

FIGURE 2: *MCP9800 Accuracy (160 parts).*

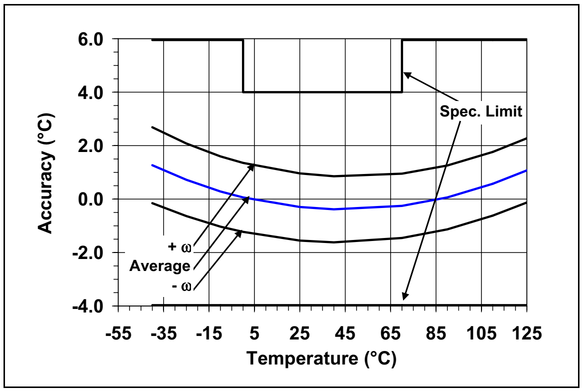

FIGURE 3: *MCP9700 Accuracy (100 parts).*

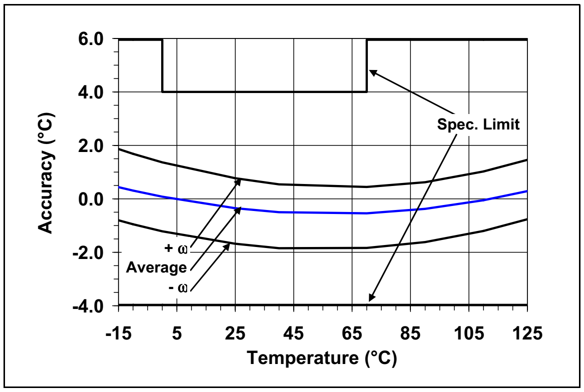

FIGURE 4: *MCP9701 Accuracy (100 parts).*

The accuracy specification limits published in the corresponding data sheets are also plotted in Figure 2, 3 and 4. Note that, due to the sensor non-linearity at temperature extremes, the accuracy specification limits are widened. This reduced accuracy at temperature extremes can be compensated to improve sensor accuracy over the operating temperature range.

SENSOR THEORY

Temperature sensors use a fully turned-on PNP transistor to sense the ambient temperature. The voltage drop across the Base-Emitter junction has the characteristics of a diode. This junction drop is temperature dependent, which is used to measure the ambient temperature. Equation 1 shows a simplified equation that describes the diode forward voltage.

EQUATION 1: DIODE FORWARD VOLTAGE

$$V_F = \frac{kT_A}{q} ln\left(\frac{I_F}{I_S}\right), \ I_F \gg I_S$$

Where:

k = Boltzmann's Constant (1.3807 x 10^{-23} J/K)

q = Electron Charge (1.602 x 10^{-19} coulombs)

T_A = Ambient Temperature

I_F = Forward Current

I_S = Saturation Current

I_S is a constant variable defined by the transistor size. A constant forward current (I_F) is used to bias the diode, which makes the temperature T_A the only changing variable in the equation. However, I_S varies significantly over process and temperature. This variation makes it impossible to reliably measure the ambient temperature using a single transistor.

In order to minimize I_S dependency, a two-diode solution is used. If both diodes are biased with constant forward currents of I_{F1} and I_{F2}, and the currents have a ratio of N (I_{F2}/I_{F1} = N), the difference between the forward voltages (ΔV_F) has no dependency on the saturation currents of the two diodes.

Equation 2 shows the derivation. ΔV_F is also called Voltage Proportional to Absolute Temperature (V_{PTAT}).

EQUATION 2: V_{PTAT}

$$\Delta V_F = V_{F1} - V_{F2}$$

$$\Delta V_F = \frac{kT_A}{q} \bullet ln\left[\frac{\frac{I_{F1}}{I_S}}{\frac{N \bullet I_{F1}}{I_S}}\right]$$

$$\Delta V_F = \frac{kT_A}{q} \bullet ln(N)$$

$$\Delta V_F = V_{PTAT}$$

Where:

V_F = Forward Voltages

I_F = Forward Currents

V_{PTAT} = Voltage Proportional to Absolute Temperature

V_{PTAT} provides a linear voltage change with a slope of (86 µV/°C)*ln(N)$|_{N = 10}$ = 200 µV/°C. This voltage is either amplified for analog output sensors or is interfaced to an Analog-to-Digital Converter (ADC) for digital sensors.

The accuracy of V_{PTAT} over the specified temperature range depends on the matching of both I_F and I_S of the two sensors [1]. Any mismatch in these variables creates inaccuracy in the temperature measurement. This mismatch contributes to the temperature error or non-linearity. The non-linearity can be described using a 2nd order polynomial equation.

FITTING POLYNOMIALS TO THE ERRORS

The accuracy characterization data will be used to derive a 2nd order equation that describes the sensor error. The equation will be used to improve the typical sensor accuracy by compensating for the sensor error.

Linear Fit Derivation

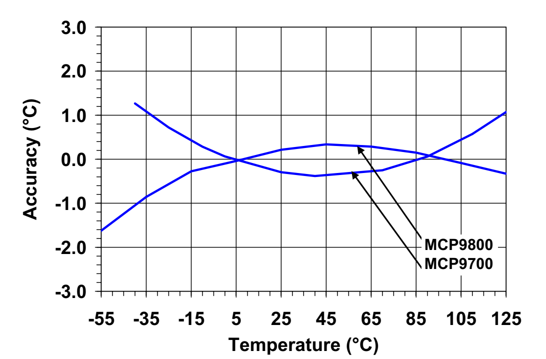

FIGURE 5: *Typical Accuracy Plot.*

Figure 5 shows a typical accuracy curve, indicating that the accuracy error magnitudes at hot and cold temperatures are not the same. There is a 1st order error slope, or temperature error coefficient (EC_1), from -55°C to +125°C. This error coefficient can be calculated using an end-point-fit method:

EQUATION 3: ERROR SLOPE

$$\Delta T_A = T_{hot} - T_{cold}$$

$$EC_1 = \frac{\Delta T_A}{\Delta Error}$$

Where:

T_{hot} = Highest Operating Temperature

T_{cold} = Lowest Operating Temperature

$Error_{T\_hot}$ = Error at Highest Oper. Temp

$Error_{T\_cold}$ = Error at Lowest Oper. Temp

EC_1 = 1st Order Error Coefficient

Once the error slope is calculated, the corresponding offset is determined at cold. This is done by adjusting for the error at cold temperature, as shown in Equation 4.

EQUATION 4: 1ST ORDER ERROR

$$Error_{T\_1} = EC_1(T_A - T_{cold}) + Error_{T\_cold}$$

Where:

$Error_{T\_1}$ = 1st order temperature error

Quadratic Fit Derivation

In order to capture the parabolic-shaped accuracy error between the temperature extremes (Figure 5), a 2nd order term, as well as the corresponding coefficient, needs to be computed.

The 2nd order temperature error coefficient EC_2, shown in Equation 5, can be solved by specifying a temperature T_A where the calculated 2nd order error $Error_{T\_2}$ is equal to the known error at T_A. For example, if T_A is +25°C and $Error_{T\_2}$ is equal to the temperature error at +25°C, then Equation 5 can be rearranged to solve for EC_2, as shown in Equation 6.

EQUATION 5: 2ND ORDER ERROR

$$Error_{T\_2} = EC_2(T_{hot} - T_A) \cdot (T_A - T_{cold}) + Error_{T\_1}$$

Where:

$Error_{T\_2}$ = 2nd order temperature error

EC_2 = 2nd order error coefficient

EQUATION 6: 2ND ORDER ERROR COEFFICIENT

$$EC_2 = \frac{(Error_{T\_2} - Error_{T\_1})}{(T_{hot} - T_A) \cdot (T_A - T_{cold})}$$

Equation 5 shows that when T_A is equal to T_{hot} or T_{cold}, the 2nd order term is forced to zero, with no error added to the 1st order error term. This is because the error at the T_{hot} and T_{cold} temperature extremes is included in the 1st order error ($Error_{T\_1}$). Equation 7 shows the complete 2nd order polynomial equation that will be used to compensate the sensors error.

EQUATION 7: 2ND ORDER POLYNOMIAL EQUATION

$$Error_{T\_2} = EC_2(T_{hot} - T_A) \cdot (T_A - T_{cold}) + EC_1(T_A - T_{cold}) + Error_{T\_cold}$$

Typical Results

Equation 8, Equation 9 and Equation 10 show the 2nd order error equation of the tested parts for the MCP9800, MCP9700 and MCP9701, respectively. Since these devices have functional differences, the operating temperature range and temperature error coefficients differ.

EQUATION 8: MCP9800 2ND ORDER EQUATION

$$Error_{T\_2} = EC_2(125°C - T_A) \cdot (T_A - -55°C) + EC_1(T_A - -55°C) + Error_{-55}$$

Where:

EC_2 = 150×10^{-6} °C/°C^2
EC_1 = 7×10^{-3} °C/°C
$Error_{-55}$ = -1.5°C

EQUATION 9: MCP9700 2ND ORDER EQUATION

$$Error_{T\_2} = EC_2(125°C - T_A) \cdot (T_A - -40°C) + EC_1(T_A - -40°C) + Error_{-40}$$

Where:

EC_2 = 244×10^{-6}°C/°C^2
EC_1 = 2×10^{-12}°C/°C ≈ 0 °C/°C
$Error_{-40}$ = -2°C

EQUATION 10: MCP9701 2ND ORDER EQUATION

$$Error_{T\_2} = EC_2(125°C - T_A) \cdot (T_A - -15°C) + EC_1(T_A - -15°C) + Error_{-15}$$

Where:

EC_2 = 200×10^{-6} °C/°C^2
EC_1 = 1×10^{-3} °C/°C
$Error_{-15}$ = -1.5°C

The above equations describe the typical device temperature error characteristics.

ACCURACY COMPENSATION

Higher error accuracy in a temperature monitoring application can be achieved by using the above equations to compensate for the sensor error, as shown in Equation 11.

EQUATION 11: TEMPERATURE COMPENSATION

$$T_{compensated} = T_{sensor} - Error_{T\_2}\big|_{T_A = T_{sensor}}$$

Where:

T_{sensor} = Sensor Output

$T_{compensated}$ = Compensated Sensor Output

For example, if the MCP9800 temperature output T_{sensor} = +65°C, the compensated temperature $T_{compensated}$:

$$T_{compensated} = 65°C - Error_{T\_2}\big|_{T_A = 65°C}$$

$$= 65°C + EC_2(125°C - 65°C)(65°C - -55°C)$$

$$+EC_1(T_A - -55°C) + Error_{-55}$$

$$T_{compensated} = 64.6°C$$

The Figures 6, 7 and 8 show average sensor accuracy accuracy with the 2nd order error compensation for all tested devices. The figures indicate that, on average, the sensor accuracy over the operating temperature can be improved to ± 0.2°C for the MCP9800, ± 0.05°C for the MCP9700 and MCP9701.

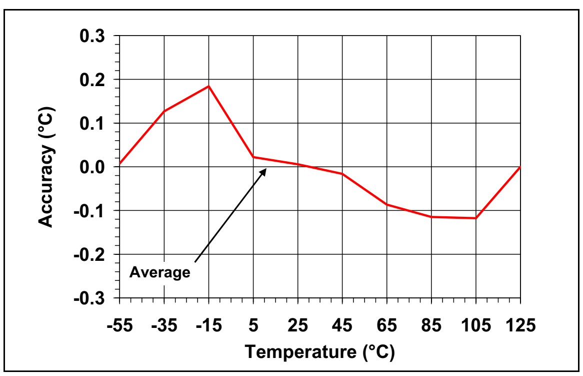

FIGURE 6: MCP9800 Average Accuracy After Compensation (160 parts).

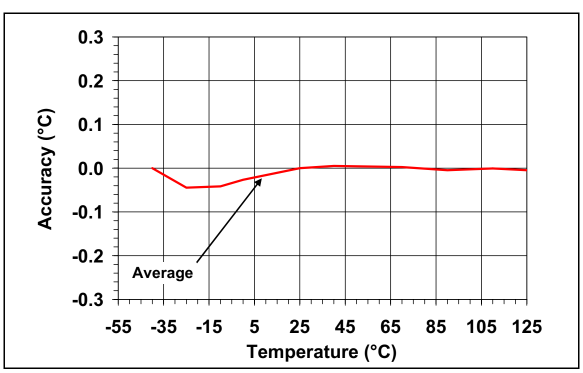

FIGURE 7: MCP9700 Average Accuracy After Compensation (100 parts).

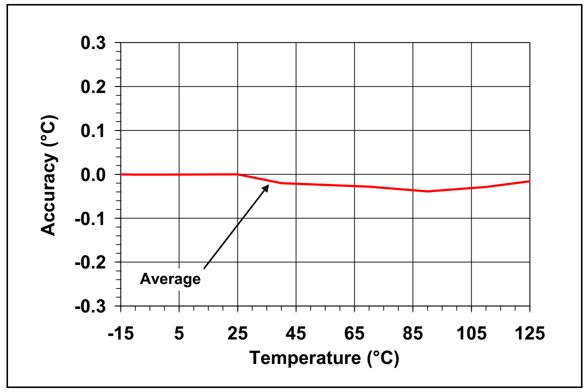

FIGURE 8: MCP9701 Average Accuracy After Compensation (100 parts).

Figures 9, 10 and 11 show an average and ±1 standard deviation of sensor accuracy for the tested parts with the 2nd order error compensation.

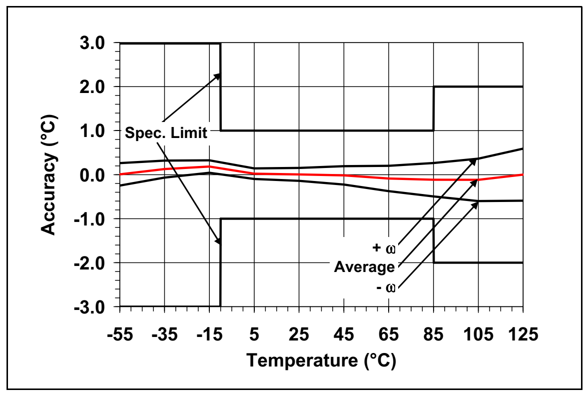

FIGURE 9: MCP9800 Accuracy After Compensation (160 parts).

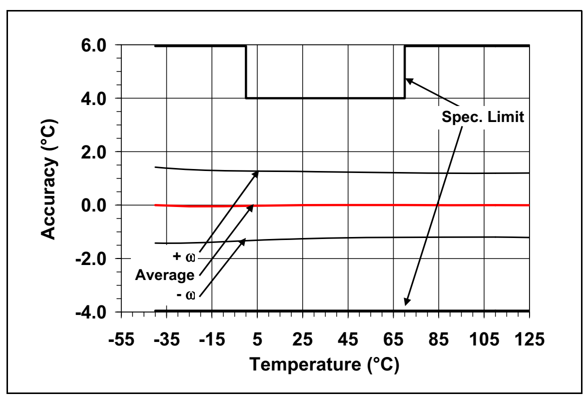

FIGURE 10: MCP9700 Accuracy After Compensation (100 parts).

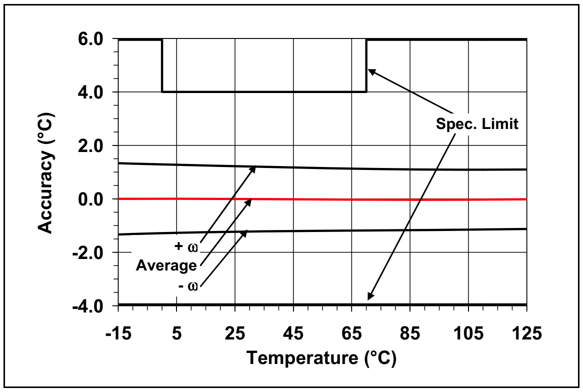

FIGURE 11: MCP9701 Accuracy After Compensation (100 parts).

When comparing Figures 9, 10 and 11's compensated accuracy with Figures 2, 3 and 4's uncompensated accuracy, it can be seen that the accuracy error distribution is shifted towards 0°C accuracy, providing a linear temperature reading.

The 2nd Order Temperature Coefficient

In all of the above compensations, the 2nd order temperature coefficient variable EC_2 was evaluated at +25°C. For most applications, the compensation characteristics at this temperature are adequate. However, changing the temperature at which EC_2 is evaluated provides relatively higher accuracy at narrower temperature ranges. For example, Figure 12 shows the MCP9700 EC_2 evaluated at 0°C, 25°C and 90°C.

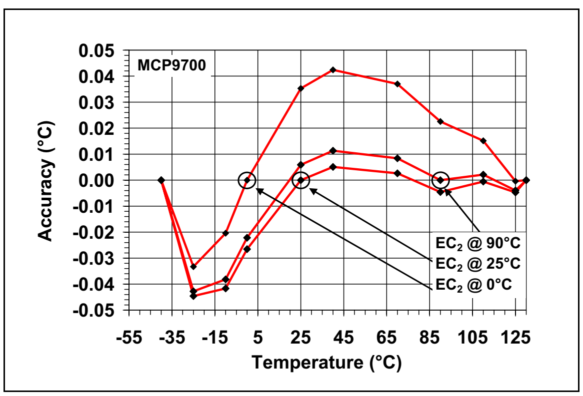

FIGURE 12: MCP9700 Average Accuracy with Varying EC_2.

When comparing EC2 at 0°C and +25°C, there is higher accuracy at cold rather than hot temperatures. However, for EC_2 evaluated at temperatures higher than +25°C, there is higher accuracy at hot rather than cold temperatures. The magnitude of accuracy error difference, however, among the various EC_2 values is not significant. Therefore, EC_2 evaluated at +25°C provides practical results.

CALIBRATION

Calibrating individual IC sensors at a single temperature provides superior accuracy for high-performance, embedded-system applications. Figure 13 shows that if the MCP9700 is calibrated at +25°C and the 2nd order error compensation is implemented, the typical sensor accuracy becomes ±0.5°C over the operating temperature range.

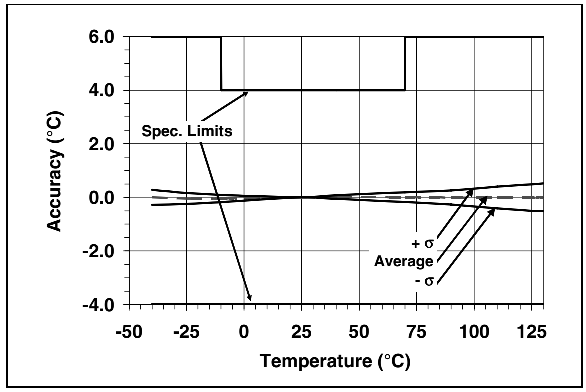

FIGURE 13: MCP9700 Calibrated Sensor Accuracy.

COMPENSATION USING PICmicro® MICROCONTROLLERS

A PICmicro MCU can be used to implement the 2nd order accuracy error compensation for embedded temperature-monitoring systems. This equation is relatively easy to implement in a 16-bit core MCU since built-in math functions are readily available. However, 12 and 14-bit cores require firmware implementation of some math functions, such as 16-bit add, subtract, multiply and divide. This application note includes firmware that can be used to compute and implement the compensation variables.

The file `an1001_firmware.zip` includes the MCP9700 and MCP9800 compensation firmware versions. These firmware versions are intended to be included in an existing embedded system firmware that uses a PICmicro MCU. All registers required to execute this routine are listed within the firmware. Once the temperature data from the device is retrieved using a serial interface or ADC input, the binary data needs to be loaded to the Bargb0 and Bargb1 registers. Detailed instructions are included in the firmware files.

Figure 14 shows the firmware flowchart.

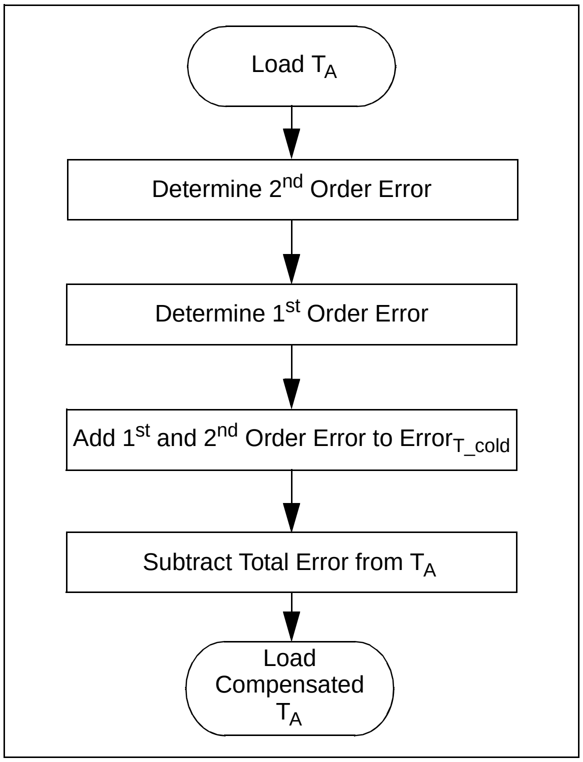

FIGURE 14: *Firmware Flowchart.*

TEST RESULTS

The MCP9800 and MCP9700 demo boards (MCP9800DM-PCTL and MCP9700DM-PCTL, respectively) were used to evaluate the compensation firmware. A constant temperature air-stream was applied directly to the temperature sensors. A thermocouple was used to accurately measure the air-stream temperature and compare the sensor outputs.

TABLE 1: MEASUREMENT ACCURACY — TEST RESULTS

Temperature	Temperature Error			
	MCP9700		MCP9800	
	W/O	W	W/O	W
-40°C	0.9	0.2	-1.0	0.1
-25°C	0.6	0.2	-0.4	0.2
0°C	0.4	0.4	0.2	0.1
+25°C	0.3	0.6	0.1	0.1
+40°C	0.4	0.7	0.1	0.2
+90°C	1.2	0.8	0.3	0.3
+110°C	1.8	0.7	0.6	0.3
+125°C	2.3	0.6	0.9	0.1

Note: The "W/O" columns designate accuracy without compensation, while the "W" columns designate accuracy with compensation.

The test result in Table 1 shows the accuracy improvement of using compensation firmware routines. At hot and cold temperatures, there is approximately 1°C to 2°C improvement, respectively.

CONCLUSION

The non-linear accuracy characteristics of a temperature sensor can be compensated for higher-accuracy embedded systems. The non-linear accuracy curve has a parabolic shape that can be described using a 2nd order polynomial equation. Once the equation is determined, it can be used to compensate the sensor output. On average, the accuracy improvement using compensation can be ±2°C (for all tested devices) over the operating temperature range. This compensation also improves the wide temperature accuracy specification limits at hot and cold temperature extremes. A PICmicro MCU can be used to compute the equation and compensate the sensor output using the attached firmware.

BIBLIOGRAPHY

[1] "High-Accuracy CMOS Smart Temperature Sensors", Bakker, A. and Huijsing, J. Kluwer Academic Publishing, Boston, 2000.

NOTES:

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