IC Temperature Sensor Accuracy Compensation with a PIC® Microcontroller

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INTRODUCTION

Microchip Technology Inc. provides a number of analog and serial output Integrated Circuit (IC) temperature sensors. Typically, these sensors are accurate at room temperature within one degree Celsius (±1°C). However, at hot or cold temperature extremes, the accuracy decreases nonlinearly. Normally, that nonlinearity has a parabolic shape.

This application note derives an equation to describe the typical nonlinear characteristics of a sensor, which is used to determine compensation for the sensor's accuracy error over a specified range of operating temperatures. A PIC® microcontroller unit (MCU) can compute the equation and provide a temperature reading with higher accuracy.

This application note is based on MCP9700 and MCP9701 analog-output temperature sensors and MCP9800 serial-output temperature sensors.

SOLUTION APPROACH

The silicon characterization data is used to determine the nonlinear sensor characteristics. From this data, an equation is derived that describes the typical performance of a sensor. When the corresponding coefficients for the equation are determined, the coefficients are used to compute the compensation for the typical sensor's nonlinearity.

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 as representative for the MCP9700 and MCP9701, while 160 devices was 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 PIC MCU is used to compute the equation and compensate the sensor output to provide a linear temperature reading.

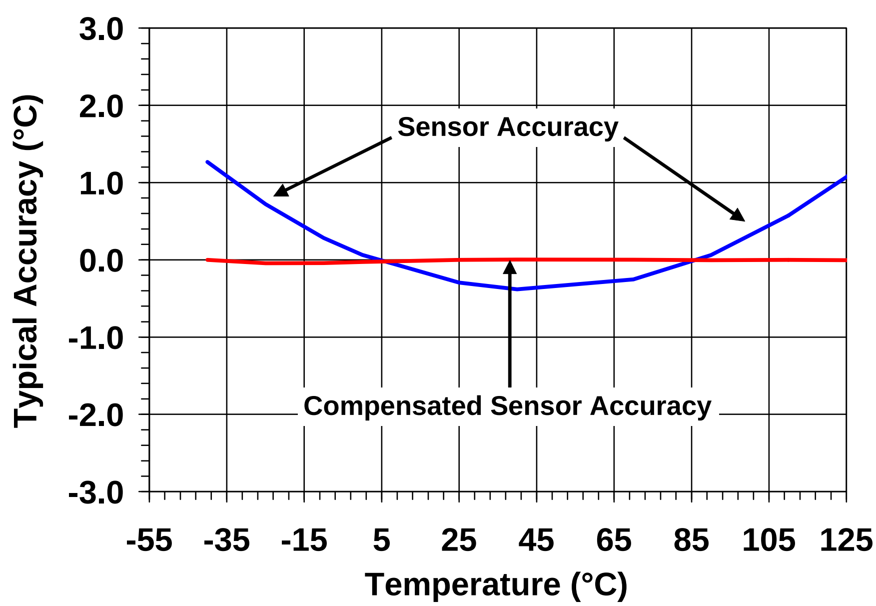

FIGURE 1: *Typical Sensor Accuracy Before and After Compensation.*

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 the sensor accuracy curve for the MCP9800, MCP9700 and MCP9701 sensors.

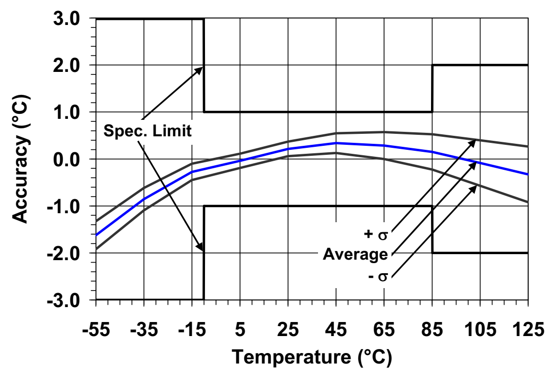

FIGURE 2: MCP9800 Accuracy (160 parts).

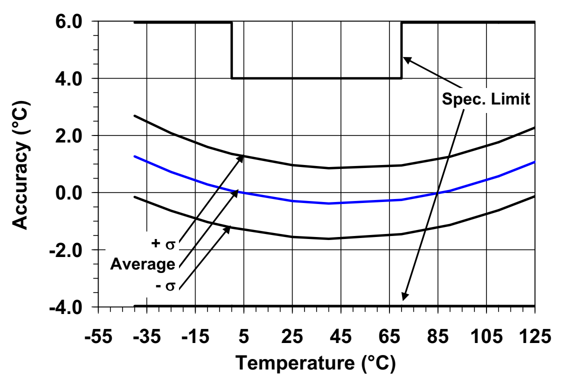

FIGURE 3: MCP9700 Accuracy (100 parts).

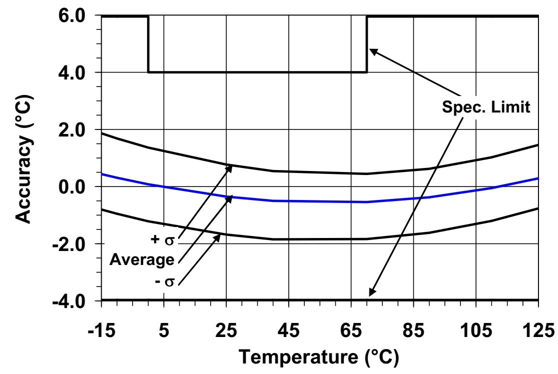

FIGURE 4: MCP9701 Accuracy (100 parts).

The accuracy specification limits for these sensors are published in the corresponding data sheets as plotted in Figure 2, Figure 3 and Figure 4. Note that due to the sensor nonlinearity at temperature extremes, the accuracy specification limits are widened. The reduced accuracy at temperature extremes can be compensated to improve sensor accuracy over the range of operating temperatures.

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. The 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. The variation makes it impossible to reliably measure the ambient temperature using a single transistor.

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, as shown in Equation 2. 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. The 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 forward current (I_F) and saturation current (I_S) of the two sensors (Bakker and Huijsing 2000). Any mismatch in these variables creates inaccuracy in the temperature measurement. The mismatch contributes to the temperature error or nonlinearity. The nonlinearity is described using a 2^{nd} order polynomial equation.

FITTING POLYNOMIALS TO THE ERRORS

The accuracy characterization data is used to derive a 2^{nd} order equation that describes the sensor error. The equation is used to improve the typical sensor accuracy by compensating for the sensor error.

Linear Fit Derivation

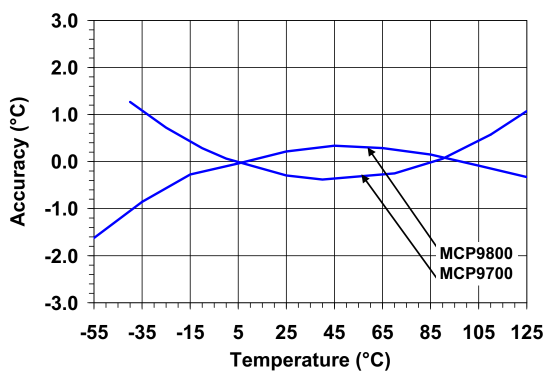

FIGURE 5: *Typical Accuracy Plot.*

Figure 5 shows a typical accuracy curve which indicates that the accuracy error magnitudes are not the same at hot and cold temperatures. There is a 1^{st} order error slope, or temperature error coefficient (EC_1), from -55° to +125°C. The error coefficient is 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	=	1^{st} Order Error Coefficient

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

EQUATION 4: 1^{ST} ORDER ERROR

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

Where:

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

Quadratic Fit Derivation

To capture the parabolic-shaped accuracy error between the temperature extremes (Figure 5), a 2^{nd} order term and the corresponding coefficient must be computed.

Equation 5 shows that the 2^{nd} order temperature error coefficient, EC_2, is solved by specifying a temperature T_A where the calculated 2^{nd} 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 is rearranged to solve for EC_2 as shown in Equation 6.

EQUATION 5: 2^{ND} ORDER ERROR

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

Where:

$Error_{T\_2}$	=	2^{nd} order temperature error
EC_2	=	2^{nd} order error coefficient

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

EQUATION 6: 2^{ND} ORDER ERROR COEFFICIENT

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

Equation 7 shows the complete 2nd order polynomial equation that is used to compensate the sensor error.

EQUATION 7: 2^{ND} 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 x 10^{-6} °C/°C^2
EC_1 = 7 x 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 x 10^{-6}°C/°C^2
EC_1 = 2 x 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 x 10^{-6} °C/°C^2
EC_1 = 1 x 10^{-3} °C/°C
$Error_{-15}$ = 1.5°C

The preceding equations describe the typical device temperature error characteristics.

ACCURACY COMPENSATION

To achieve higher accuracy in a temperature monitoring application, using Equation 8, Equation 9 and Equation 10 can 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 $T_{compensated}$ is 64.6°C as shown below.

$$T_{compensated} = 65°C - Error_{T\_2}\Big|_{T_A = 65°C}$$
$$= 65°C + EC_2(125°C - 65°C)(65°C - -55°C) + EC_1(T_A - -55°C) + Error_{-55}$$
$$T_{compensated} = 64.6°C$$

Figure 6, Figure 7 and Figure 8 show the average sensor 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, and ±0.05°C for the MCP9700 and MCP9701.

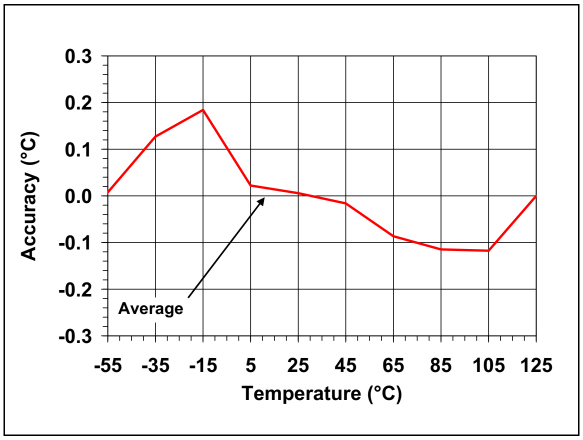

FIGURE 6: MCP9800 Average Accuracy After Compensation (160 parts).

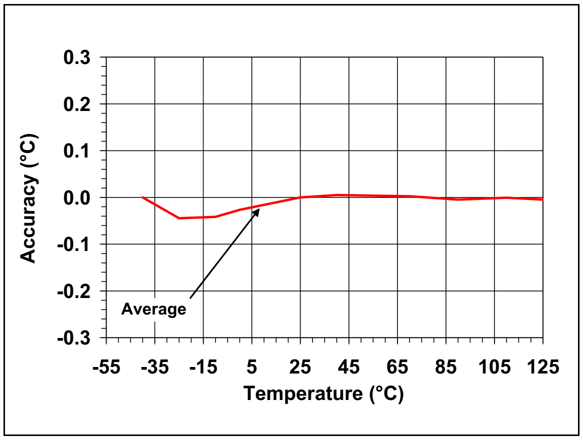

FIGURE 7: *MCP9700 Average Accuracy After Compensation (100 parts).*

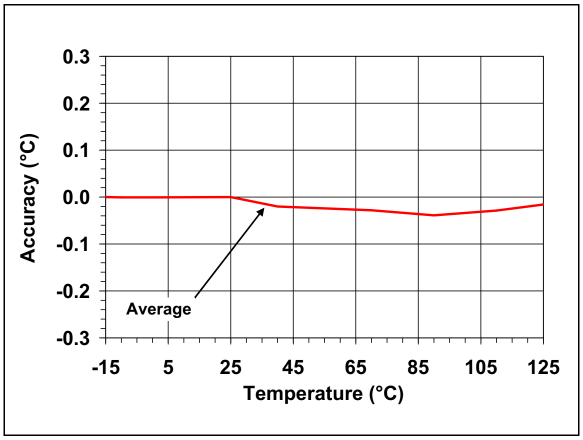

FIGURE 8: *MCP9701 Average Accuracy After Compensation (100 parts).*

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

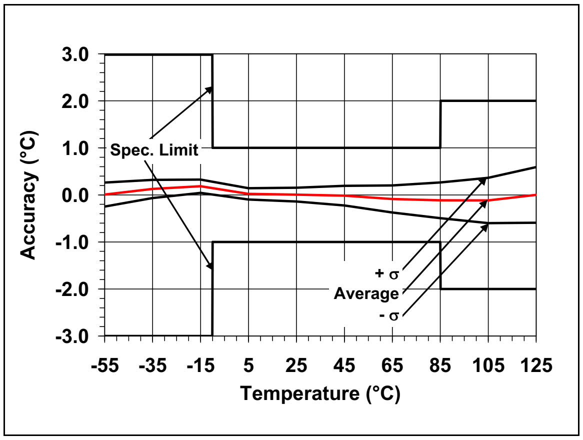

FIGURE 9: *MCP9800 Accuracy After Compensation (160 parts).*

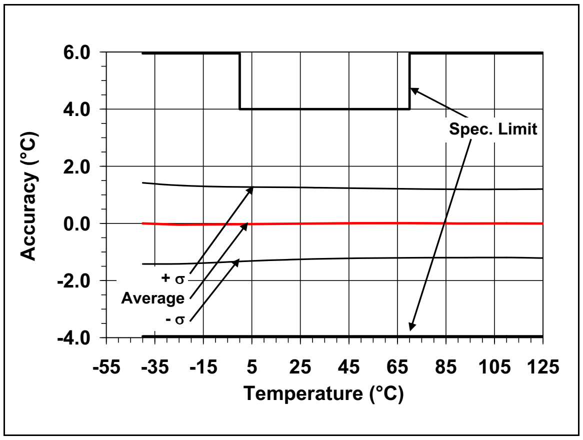

FIGURE 10: *MCP9700 Accuracy After Compensation (100 parts).*

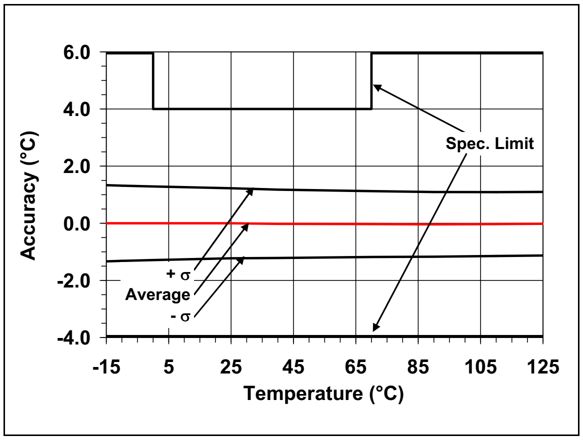

FIGURE 11: *MCP9701 Accuracy After Compensation (100 parts).*

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

The 2nd Order Temperature Coefficient

Among the 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°, 25° and 90°C.

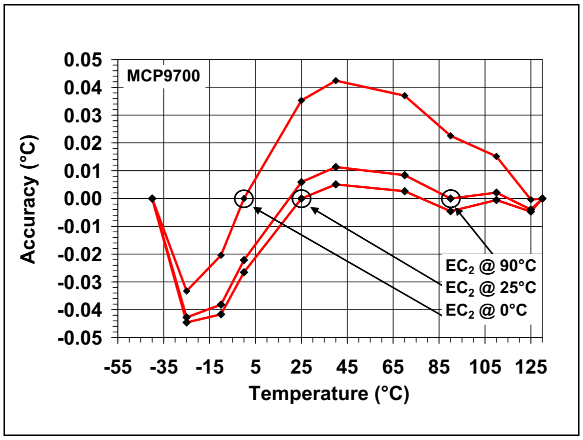

FIGURE 12: *MCP9700 Average Accuracy with Varying EC_2.*

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

CALIBRATION

Calibration of 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.

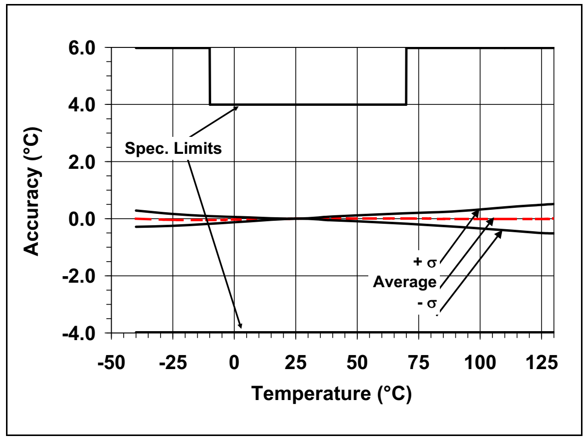

FIGURE 13: *MCP9700 Calibrated Sensor Accuracy.*

COMPENSATION USING PIC® MICROCONTROLLERS

A PIC MCU can implement the 2nd order accuracy error compensation for embedded temperature-monitoring systems. The 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 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 PIC 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 must be loaded to the Bargb0 and Bargb1 registers. Detailed instructions are included in the firmware files.

Figure 14 shows the firmware flowchart.

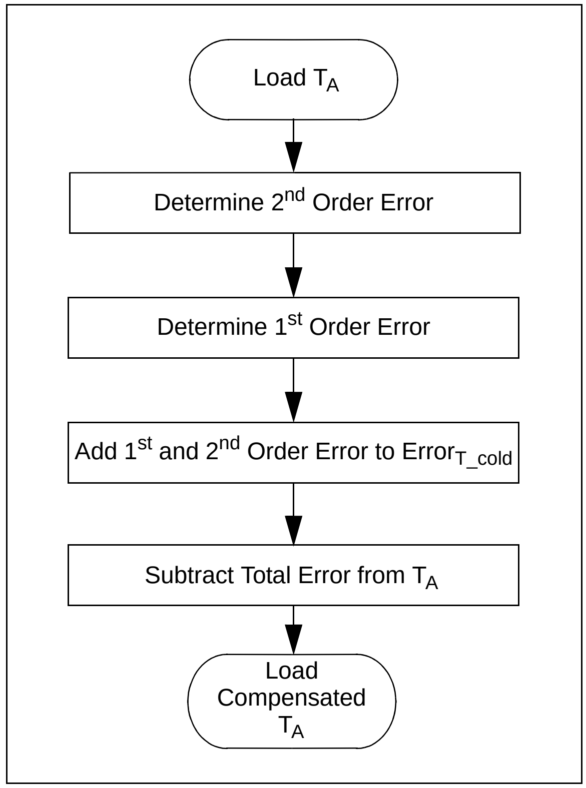

FIGURE 14: *Firmware Flowchart.*

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” and “W” columns indicate accuracy without and with compensation.

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

CONCLUSION

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

WORK CITED

Bakker, A., and J. Huijsing. 2000. *High-Accuracy CMOS Smart Temperature Sensors*. Boston: Kluwer Academic Publishing.

NOTES:

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