

Thermistor Temperature Sensing with MCP6SX2 PGAs

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INTRODUCTION

This application note shows two designs that use a precise, negative temperature coefficient (NTC) thermistor for temperature measurement. The thermistor is placed in a resistive divider to linearize the temperature-to-voltage conversion. The voltage is processed in the analog domain by the MCP6SX2 (MCP6S22 or MCP6S92) Programmable Gain Amplifier (PGA) before conversion to the digital domain.

The first design is simpler and has a smaller temperature range. The second design changes the PGA's gain to achieve a greater temperature range. Both designs use a piece-wise linear interpolation table to correct the remaining non-linearity and convert voltage into degrees Celsius. The design trade-offs between these approaches will be discussed.

These circuits take advantage of the MCP6SX2's input multiplexer (MUX). The PGA is used to process multiple signals and/or temperatures and digitally sets the most appropriate gain for each input. This reduces overall design complexity and allows for temperature correction of other sensors.

THERMISTOR

The thermistor used in the application note is part number 2322 640 55103 from BC Components®; see Figure 1 and Figure 2. This part is selected for its accuracy and cost. The thermistor's temperature is T_{TH} , while the rest of the circuit is at ambient temperature T_A .

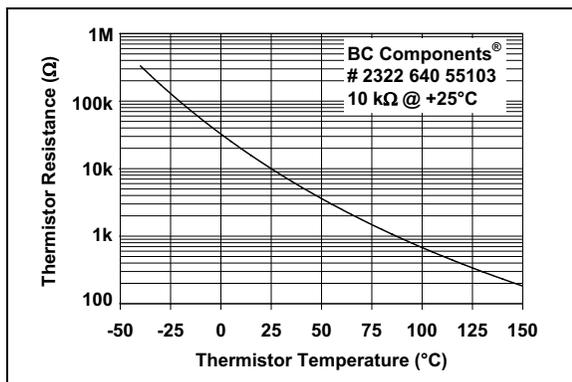


FIGURE 1: *Thermistor Response.*

Key specifications include [1, 2]:

- Resistance at +25°C: 10 kΩ ± 1%
- $B_{25/85}$ tolerance: ±0.75%
- Operating temperature range: -40°C to +125°C (to +150°C for short periods)
- Maximum power
 - 100 mW, $T_{TH} = 0^\circ\text{C}$ to +55°C
 - 100% de-rated at $T_{TH} = -40^\circ\text{C}$ and +85°C
- Thermal dissipation factor: 2.2 mW/°C
- Response time: 1.7 s (in oil)

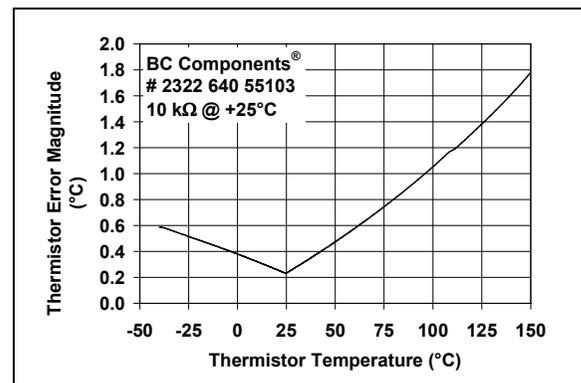


FIGURE 2: *Thermistor Accuracy.*

Thermistors with different price and accuracy trade-offs may also be used in this application. It is simple to modify the circuits to match the desired accuracy.

CIRCUIT

The circuit shown in Figure 3 is used for both designs described later. It is implemented on the MCP6SX2 PGA Thermistor PICtail™ Demo Board; see reference [12].

The resistor R_A makes the voltage vs. temperature response reasonably linear. R_B and C_B reduce the noise and act as an anti-aliasing filter for the ADC. The MCP6SX2 PGA (MCP6S22 [5] or MCP6S92 [6]) buffers the voltage V_{DIV} . The PGA can be digitally controlled to change its gain or channel (input).

The PIC16F684 [8] is on the Signal Analysis PICtail™ Daughter Board; see reference [11]. It has an internal 10-bit ADC that converts V_{OUT} to the digital domain. It can further process V_{OUT} (e.g., averaging) and convert it to temperature. It communicates with the PGA via the SPI serial bus.

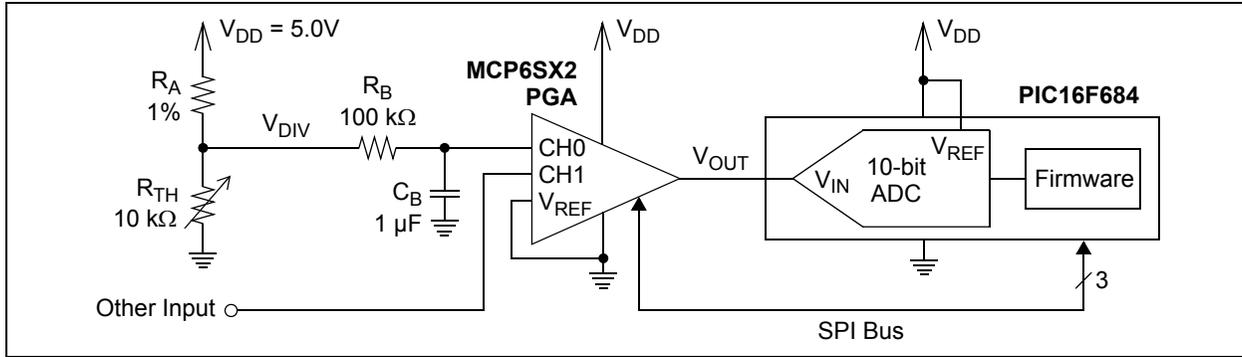


FIGURE 3: Thermistor PGA Circuit.

The ADC's voltage reference is powered from the same voltage as the voltage divider, giving a ratiometric circuit; errors in V_{DD} will be automatically corrected at the ADC.

FIRST DESIGN

This design emphasizes simplicity and uses a standard approach to designing the thermistor circuit. The traditional op amp is replaced with a PGA so that it can multiplex multiple inputs.

Analog Design

The first design keeps the PGA at a gain of +1 V/V for design simplicity. The resistor R_A is set to its nominal +25°C value (10.0 kΩ) for best performance at room temperature; this is a very common design choice. While this is a simpler design, its accuracy is relatively low, as will be seen. Notice that Figure 4 shows a much more linear response than Figure 1.

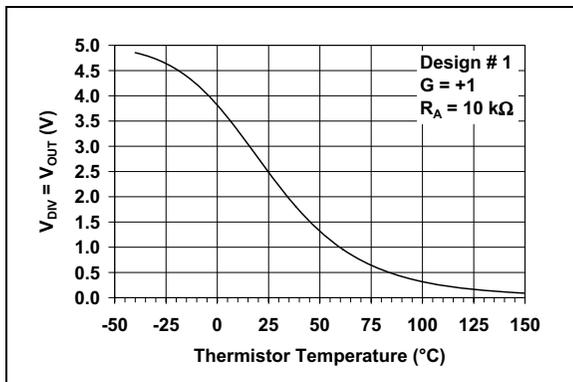


FIGURE 4: Voltage Divider and PGA Outputs.

Temperatures between +125°C and +150°C can be included in the design for overtemperature indication where accuracy is not as important.

The thermistor power dissipation causes a self-heating temperature error. Calculating the thermistor's power dissipation across temperature, and then dividing by the specified 2.2 mW/°C thermal dissipation factor, gives the self-heating temperature error shown in Figure 5. This is a small, consistent error. It is simple to adjust for this error using the piece-wise linear interpolation table in firmware.

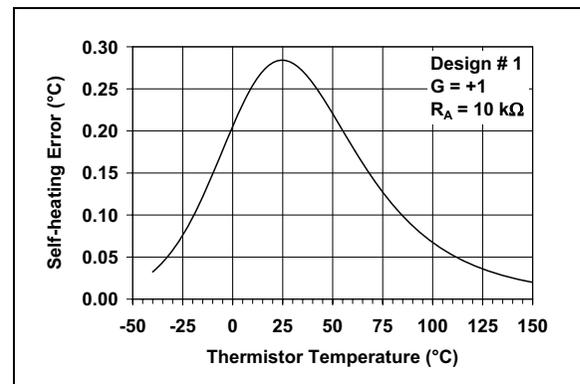


FIGURE 5: Thermistor Self-heating Error.

Analog Error Analysis

Figure 6 displays the ADC's temperature resolution, while Figure 7 shows the expected worst-case analog circuit errors. Both plots are based on these assumptions:

- ADC's DC Error $\leq \pm 3.5$ LSB
- PGA's gain error $\leq \pm 0.1\%$ ($G = +1$)
- PGA's input offset error $\leq \pm 1$ mV (including PSRR and temperature drift)
- Specified thermistor accuracy

This design achieves an ADC temperature resolution of 0.25°C over the -25°C to +73°C temperature range. The analog circuit accuracy is better than 1.2°C over the same range. Other temperature ranges will have different resolutions and accuracies.

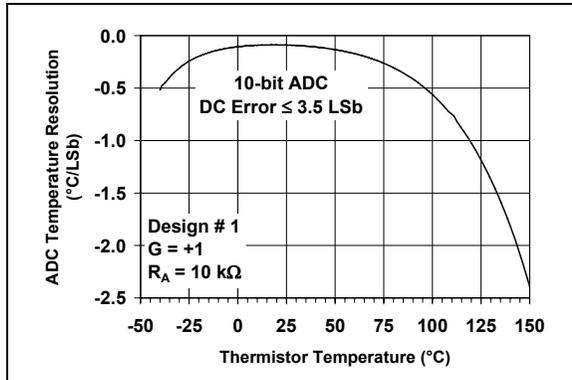


FIGURE 6: ADC's Temperature Resolution.

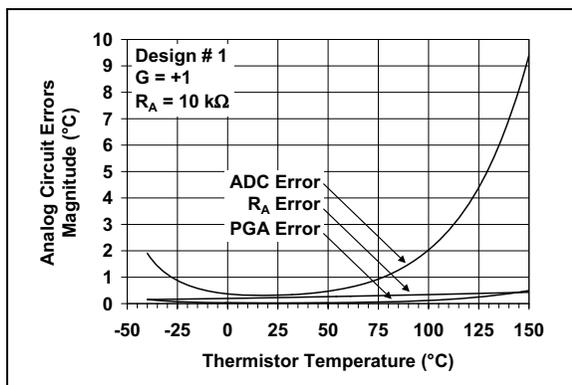


FIGURE 7: Analog Circuit Errors.

Digital Design

The PIC16F684 microcontroller [11, 12] handles several important tasks. It communicates with the PGA to set its input channel, can average the measured signal to reduce noise and converts the result into the temperature at the thermistor using a piece-wise linear interpolation table. The microcontroller can either have a SPI port built in or the SPI interface can be implemented in software on the microcontroller [7].

FLOWCHART

The flowchart in Figure 8 shows the program flow for the first design. The firmware is available in 00897 Source Code.zip file in the "00028 - MCP6SX2 PGA Thermistor PICtail Demo Board" directory. The firmware was written in relocatable assembly code. main.asm controls the overall program flow. The PGA routines are in pga.inc and pga.asm. The thermistor routines are located in Therm_PGA1.inc and Therm_PGA1.asm.

The Signal Analysis PC Program commands the PIC16F684 firmware to perform a real-time sample. The firmware reads the ADC value and passes it to the Piece-wise Linear Interpolation (PwLI) routine. The PwLI routine converts the 10-bit ADC value into a 16-bit fixed decimal point degrees Celsius value. The fixed

decimal point format reports degrees Celsius in tenths of a degree. Performing the piece-wise linear interpolation in tenths of a degree provides better resolution of degrees Celsius. Finally, the 16-bit degrees Celsius value is sent to the Signal Analysis PC Program for display on the real-time strip chart graph.

In the final design, the designer can elect to report in tenths of a degree or round up in whole degrees.

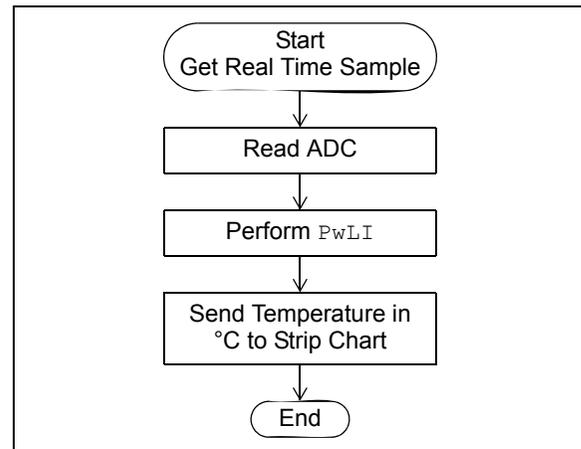


FIGURE 8: Flowchart for First Design.

PIECE-WISE LINEAR INTERPOLATION TABLE

A piece-wise linear interpolation table [9] is used to convert ADC codes to estimated temperature. The ADC's codes were divided into 64 segments, with 16 codes per segment. The codes in the table are at end points between segments. Table 1 shows the end points chosen for this design.

TABLE 1: INTERPOLATION TABLE END POINTS.

Gain (V/V)	ADC Code (LSb)	T _{TH} (°C)	R _{TH} (Ω)	V _{OUT} (V)
1	1008	-49.4	630 k	4.922
	16	156.1	159	0.078

Values of R_{TH} outside the thermistor's specified temperature range (-40°C to +150°C) are estimates only; they are not given by the manufacturer. The thermistor self-heating error correction has been included in Table 1.

The table's entries go outside of the -40°C to +150°C range to ensure proper functioning of the piece-wise linear interpolation table when the reading overflows. In this algorithm, the table values outside the valid range take on the nearest valid value. This means that when ADC code > 1008, the table returns a value of -49.3°C. When ADC code < 16, the table returns a value of 156.1°C.

Digital Error Analysis

Figure 9 shows the estimated interpolation error for the interpolation table. This design suffers from poor ADC resolution at temperature extremes. The accuracy of this piece-wise linear interpolation table is 0.05°C over the -25°C to $+73^{\circ}\text{C}$ temperature range. Over the -40°C to $+150^{\circ}\text{C}$ temperature range, the accuracy degrades to 1.0°C .

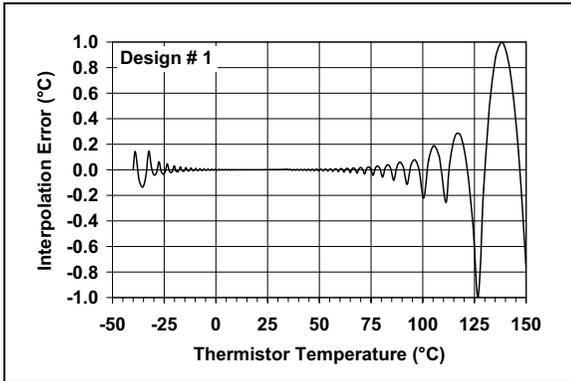


FIGURE 9: Piece-wise Linear Interpolation Error, Design # 1.

The digital roundoff error will be roughly proportional to the ADC temperature resolution curve's envelope (see Figure 6). If the roundoff error is much less than the ADC resolution, this error will have little impact.

The total digital error includes both the piece-wise linear interpolation error and the round-off error.

SECOND DESIGN

This design emphasizes accuracy and resolution. It uses the PGA's capability to change gain to overcome the limitations of the first design. The PGA can multiplex multiple inputs if needed.

Analog Design

The second design changes the PGA's gain from +1 to +8 to +32 V/V. The resistor R_A is set to $28.0\text{ k}\Omega$ so that the voltage vs. temperature response is reasonably linear at low temperatures; see Figure 10 (compare to Figure 4). The response is nearly flat at higher temperatures, so the PGA's gain will be increased to compensate. Though this is a more complex design, its resolution and accuracy are greater than the first design's.

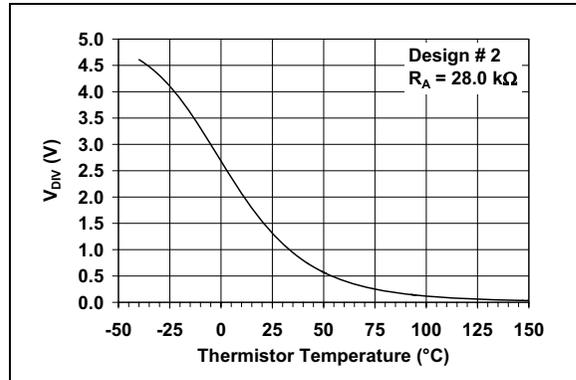


FIGURE 10: Voltage Divider Output.

Temperatures between $+125^{\circ}\text{C}$ and $+150^{\circ}\text{C}$ can be included in the design for overtemperature indication when accuracy is not as important.

The thermistor power dissipation causes a self-heating temperature error. Calculating the thermistor's power dissipation across temperature, and then dividing by the specified $2.2\text{ mW}/^{\circ}\text{C}$ thermal dissipation factor, gives the self-heating temperature error shown in Figure 11. This is a small, consistent error. It is simple to adjust for this error using the piece-wise linear interpolation table in firmware.

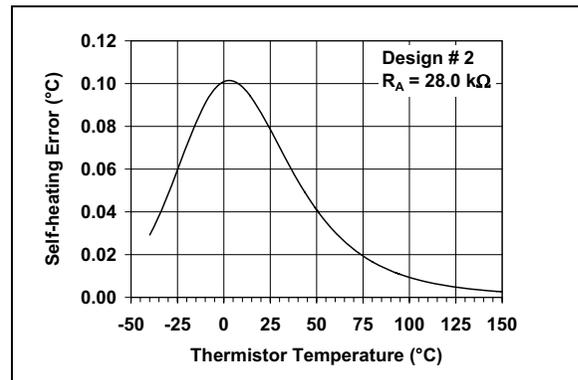


FIGURE 11: Thermistor Self-heating Error.

PGA Gain

The sensitivity that V_{DIV} shows to temperature (Figure 10) is poor at higher temperatures. It is intentionally designed this way so that the PGA can be set at higher gains as temperature increases (Figure 12).

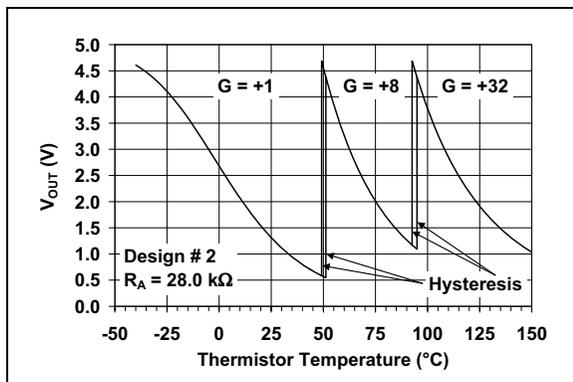


FIGURE 12: PGA Output Voltage.

The gain change points were chosen to make the ADC's resolution as good as possible (see Figure 13) at a reasonable cost. The number of gains was kept low to minimize the piece-wise linear interpolation table's size in firmware.

The maximum voltage allowed in each range is 300 mV from V_{DD} . This keeps the PGA in its specified output range and allows some headroom for noise. The minimum voltage allowed is well above 300 mV from ground, which keeps the PGA in its most linear region of operation.

Random noise can make the PGA's gain change frequently. Adding hysteresis to the gain-selection algorithm (in firmware) reduces this problem. The hysteresis needs to be large enough to compensate for the PGA's maximum gain error ($\pm 1\%$).

Figure 12 and Table 2 show a hysteresis of 1.7°C and 2.0°C at the lower temperature and higher temperature transitions, respectively. The gain-change points are separated by 6% of V_{DIV} , which is six times larger than the PGA's maximum gain error; this ensures proper functioning of the gain-change algorithm. The thermistor self-heating error has been corrected in Table 2.

TABLE 2: PGA GAIN-CHANGE POINTS WITH HYSTERESIS.

Gain (V/V)	Gain Change (V/V)	ADC Code (LSb)	V_{DIV} (V)	T_{TH} ($^\circ\text{C}$)
1	1 \rightarrow 8	< 113	0.552	50.9
8	8 \rightarrow 1	> 960	0.586	49.2
	8 \rightarrow 32	< 226	0.138	94.6
32	32 \rightarrow 8	> 960	0.146	92.6

Analog Error Analysis

Figure 13 displays the ADC's temperature resolution and Figure 14 shows the expected worst-case analog circuit errors. Both plots are based on these assumptions:

- ADC's DC Error $\leq \pm 3.5$ LSb
- PGA's gain error $\leq \pm 1\%$ ($\pm 0.1\%$ at $G = +1$)
- PGA's input offset error $\leq \pm 1$ mV (including PSRR and temperature drift)
- Specified thermistor accuracy

This design achieves an ADC temperature resolution of 0.27°C over the -40°C to $+150^\circ\text{C}$ temperature range. The analog circuit accuracy is better than 3.0°C over the same range. Other temperature ranges will have different resolutions and accuracies.

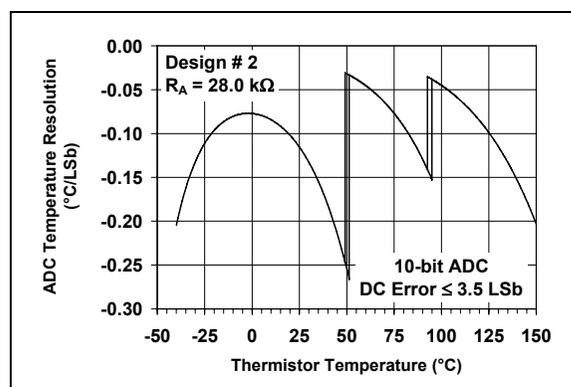


FIGURE 13: ADC's Temperature Resolution.

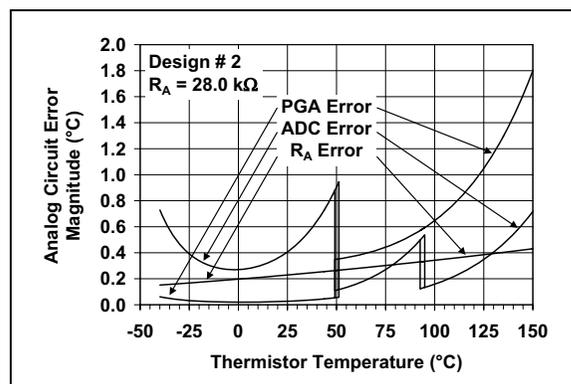


FIGURE 14: Analog Circuit Errors.

Digital Design

The PIC16F684 microcontroller [11, 12] handles several important tasks. It communicates with the PGA to set its gain and input channel, can provide averaging to reduce the noise and converts the result into the temperature at the thermistor using a piece-wise linear interpolation table. The microcontroller can have either a SPI port built in or the SPI interface can be implemented in software on the microcontroller [7].

AN897

FLOWCHARTS

The second design's flowchart is shown in Figure 15. It is very similar to the first design program, with the exception that it has added a PGA hysteresis routine. The firmware is available in the 00897 Source Code.zip file. The firmware was written in relocatable assembly code. The main.asm file controls the overall program flow. The PGA routines are in pga.inc and pga.asm. The thermistor routines are in Therm_PGA2.inc and Therm_PGA2.asm.

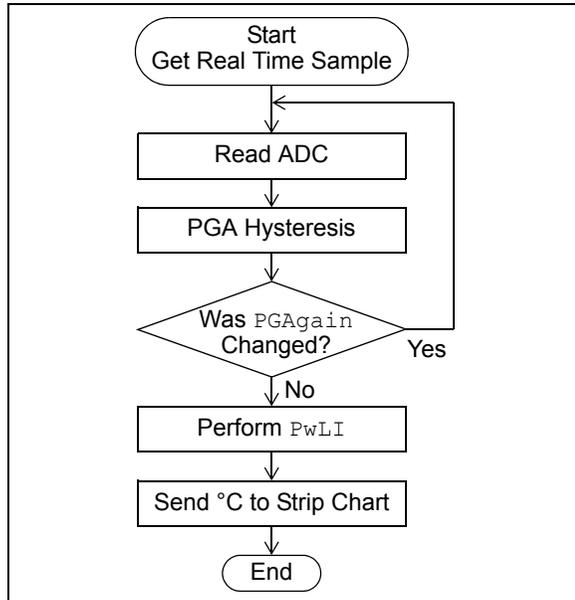


FIGURE 15: Flowchart for Second Design.

The Signal Analysis PC Program commands the PIC16F684 firmware to perform a real-time sample. The firmware reads the ADC value and passes it to the PGA hysteresis routine. Figure 16 shows the detail of the PGA hysteresis routine. The routine checks to see what PGA gain is set (the variable "PGAGain"). Based on PGAGain, the ADC value is tested for end-point (trip) values. If the ADC value is beyond the trip point value, PGAGain is set to the next higher or lower gain setting. Upon exiting the PGA hysteresis routine, the firmware checks if PGAGain was changed. If there was no change (Return 0), the program continues. If there was a change (Return 1), the firmware re-reads the ADC.

Once the PGA gain and ADC value are known, both values are passed to the piece-wise linear interpolation routine. Based on the PGA gain setting, the correct look-up table is referenced. The PwLI routine converts the 10-bit ADC value into a 16-bit fixed decimal point degrees Celsius value. The fixed decimal point format reports degrees Celsius in tenths of a degree. Performing the piece-wise linear interpolation in tenths of a degree provides better resolution of degrees Celsius. Finally, the 16-bit degrees Celsius value is sent to the Signal Analysis PC Program for display on the real-time strip chart graph.

In the final design, the designer can elect to receive reports in tenths of a degree or that they be rounded up into whole degrees.

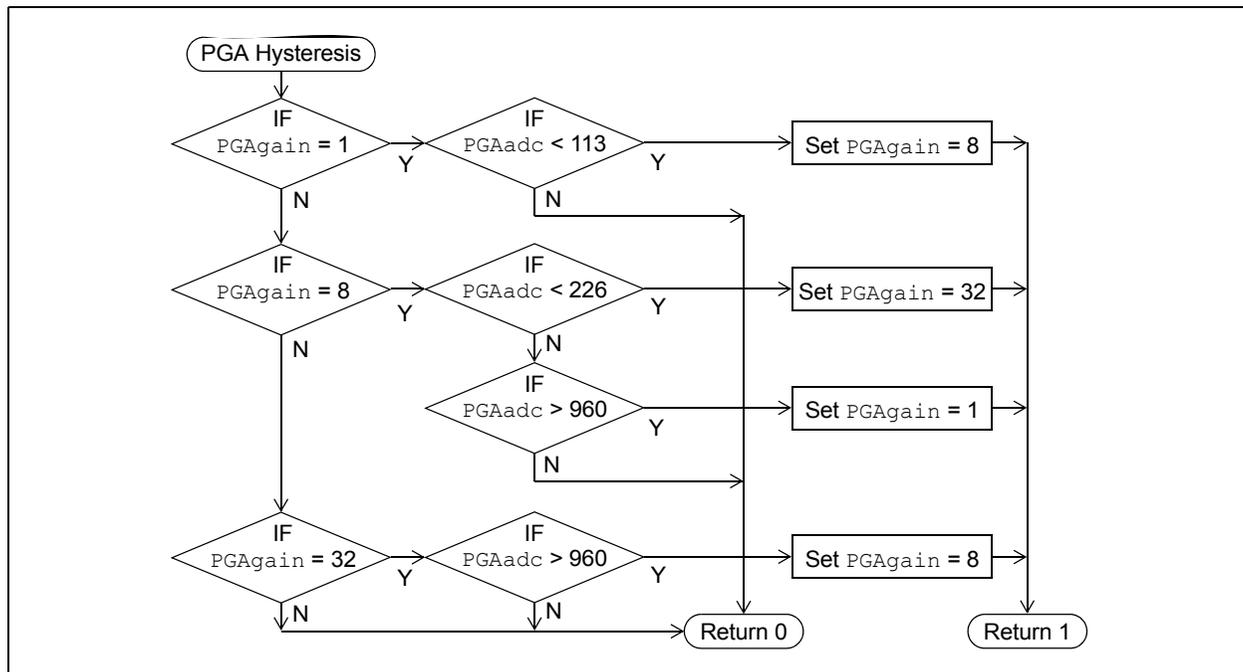


FIGURE 16: Flowchart for Second Design's PGA Hysteresis Subroutine.

PIECE-WISE LINEAR INTERPOLATION TABLE

Each of the three gains uses a piece-wise linear interpolation table [9] to convert ADC codes to estimated temperature. Within each table, the ADC's codes were divided into 64 segments, with 16 codes per segment. The tables only include those ADC codes at the end points between segments. Table 3 shows the extreme valid table entries for each of the three tables.

TABLE 3: INTERPOLATION TABLE END POINTS.

Gain (V/V)	ADC Code (LSb)	T _{TH} (°C)	R _{TH} (Ω)	V _{OUT} (V)
1	960	-43.5	420k	4.688
	112	51.2	3.44k	0.547
8	960	49.2	3.72k	4.688
	224	94.9	787	1.094
32	960	92.6	845	4.688
	208	150.9	179	1.016

Values of T_{TH} and R_{TH} outside the thermistor's specified temperature range (-40°C to +150°C) are estimates only; they are not provided by the manufacturer. The thermistor self-heating error correction has been included in Table 3.

The table's entries go outside of -40°C to +150°C to ensure proper functioning of the piece-wise linear interpolation table when the reading overflows. In this algorithm, the table values outside the valid range take on the nearest valid value. This means that when G = 1 and ADC code > 960, the table returns a value of -43.5°C. When G = 32 and ADC code < 208, the table returns a value of 150.9°C.

The other table entries beyond the end points in Table 3 (e.g., near gain-change points) are zero because the hysteresis algorithm will prevent them from being read. This approach has been used for readability.

Digital Error Analysis

Figure 17 shows the estimated interpolation error for the interpolation table. Changing the PGA's gain takes full advantage of the ADC's resolution. The accuracy of this piece-wise linear interpolation table is 0.034°C over the -40°C to +150°C temperature range. The improved ADC temperature resolution makes this design's piece-wise linear interpolation table behave much better than the first design's.

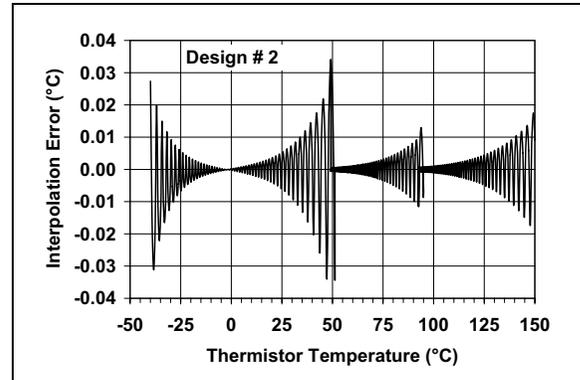


FIGURE 17: Piece-wise Linear Interpolation Error, Design # 2.

The digital roundoff error will be roughly proportional to the ADC temperature resolution curve's envelope (see Figure 13). When the roundoff error is much less than the ADC resolution, it will have little impact.

The total digital error includes both the piece-wise linear interpolation error and round-off error.

DESIGN COMPARISON

Figure 18 shows the thermistor's specified accuracy. It contributes the same error to both designs.

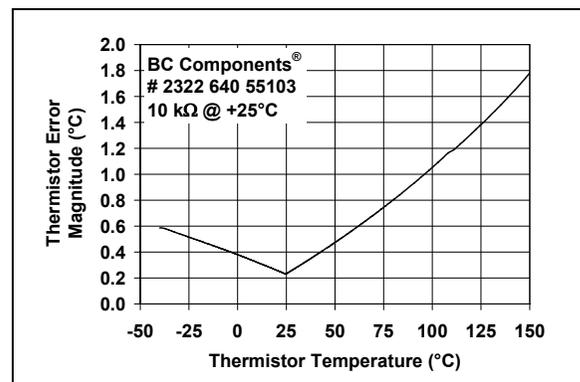


FIGURE 18: Thermistor Accuracy.

Figure 19 compares the ADC temperature resolution between the first and second design. The second design is better because changing the PGA's gain helps improve the ADC temperature resolution.

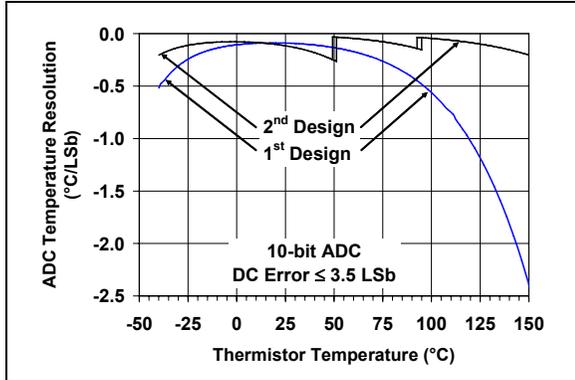


FIGURE 19: ADC Temperature Resolution.

Figure 20 compares the analog circuit errors between the designs. The second design's error is better at high temperatures because the ADC's temperature resolution is better. It is also better at low temperatures because R_A has been selected to linearize the temperature-to-voltage conversion there.

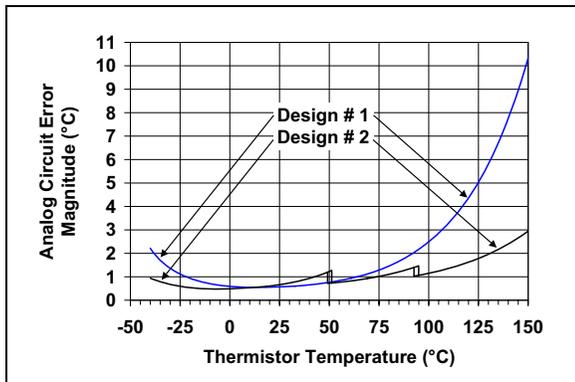


FIGURE 20: Analog Circuit Error Comparison.

The digital piece-wise linear interpolation errors are compared in Figure 21. The second design has much better performance because the linear interpolation table segments cover smaller changes in temperature.

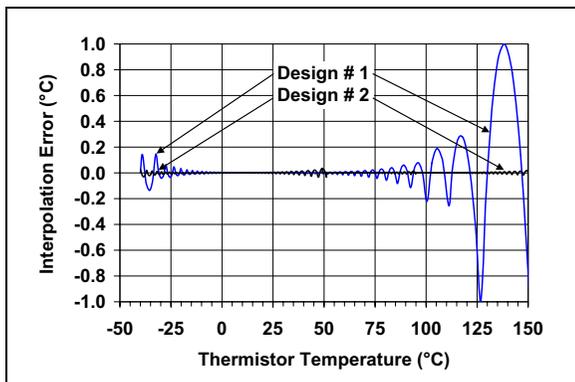


FIGURE 21: Digital Interpolation Error Comparison.

Figure 22 compares the total errors (thermistor plus circuit plus piece-wise linear interpolation) of the first and second designs. The digital roundoff error has been excluded for simplicity.

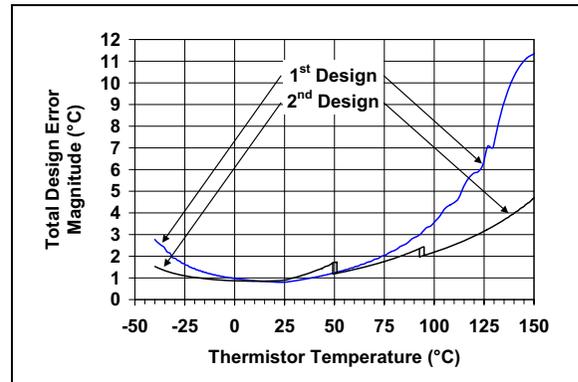


FIGURE 22: Total Error Comparison.

Other trade-offs between the two designs are summarized in Table 4.

TABLE 4: TRADE-OFFS.

Criteria	First Design	Second Design
Temperature Range	Medium	High
Temperature Accuracy	Low	High
Discontinuity at gain changes	—	$\pm 0.3^\circ\text{C}$
Firmware Size	Low	Medium

MEASURED RESULTS

Both designs were measured on the bench. The thermistor was emulated with the variable resistor R_{var} on the MCP6SX2 PGA Thermistor PICtail™ Demo Board shown [12]. The ADC outputs were converted to estimated thermistor temperatures based on the nominal resistor values. Figure 23 shows the first design's measured error, while Figure 24 shows the second design's measured error.

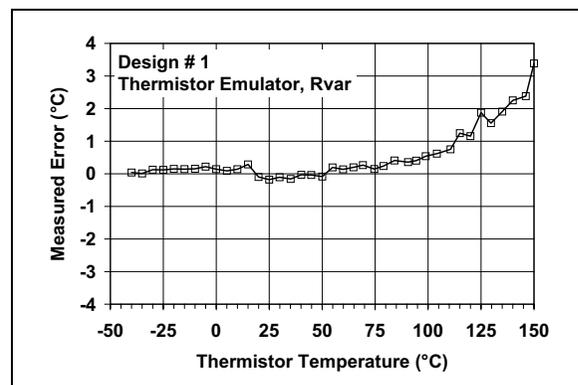


FIGURE 23: Measured Errors, Design # 1.

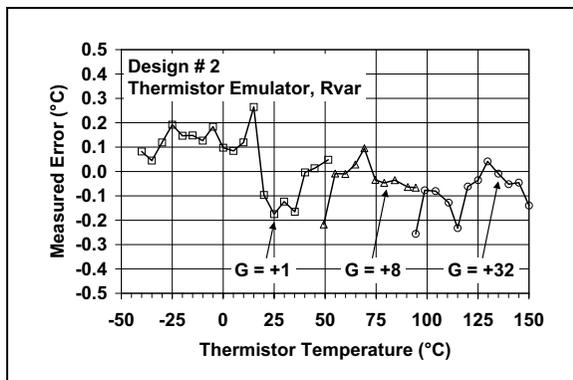


FIGURE 24: Measured Errors, Design # 2.

Note that it was necessary to add a resistor in series with R_{var} at high temperatures in order to have 5°C spacing between data points.

Both Figure 23 and Figure 24 agree with the design results; the second design has much better performance. The 1% resistors in R_{var} will give roughly the same error as the thermistor.

The thermistor was then used to measure room temperature using Design # 2. The result was ADC code 281 with a gain of +1, which corresponds to 23.7°C (74.7°F).

DESIGN ALTERNATIVES

The references in this application note include information on other design approaches. AN685 [3] covers more traditional application circuits using thermistors. AN867 [4] shows an alternative thermistor circuit using the PGA; it has greater flexibility, but increased design cost and complexity. AN990 [13] gives an overview of sensors.

The following sections discuss modifications to the designs in this application note.

Increased Accuracy

In order to achieve greater accuracy, the analog components need to be more precise. 12-bit ADCs, (e.g., the MCP3201) will increase the resolution. A 0.1% tolerance resistor for R_A will reduce the circuit error.

Calibrating the thermistor [1, 2] will cancel most of its variation over process. It may be beneficial to also calibrate the circuit. This will increase firmware complexity and execution time on the microcontroller unless the corrections are included in the linear interpolation table(s).

The piece-wise linear interpolation table may need more entries, especially for the first design. The calculations will require more precision, which results in slower processing time.

Other Gains

The second design can be done with other gains. Increasing the number of gains has the drawback of needing more piece-wise linear interpolation tables, increasing the firmware size.

Adding a gain(s) between +1 and +8 increases the ADC resolution. The decrease in gain accuracy (from 0.1% at $G = +1$ to 1% at $G \geq +2$) reduces the overall accuracy, especially at a gain of +2. The tradeoffs depend on the design specifics.

Adding a gain between +8 and +32 improves both the accuracy and the ADC resolution at higher temperatures. The choice of +16 is a good one.

Removing the gain of +32 may be attractive for designs that reach a reduced temperature range (e.g., +125°C). Changing the gain of +32 to +16, instead of removing it, is one compromise.

When the gains are related by a common multiplier, the hysteresis algorithm is simplified. When $G = 1, 2, 4, 8, 16,$ and 32 , the multiplier is 2. When $G = 1, 4$ and 16 , the multiplier is 4. The gain increases all occur at one ADC code, while the gain decreases all occur at another ADC code. Thus, the hysteresis algorithm only has to compare the ADC code to two code values and change the gain based on the result.

More Input Channels

When more than two inputs (including other temperature sensors) need to be multiplexed into the ADC, the 6-channel MCP6S26 and the 8-channel MCP6S28 PGAs provide additional channels. The thermistor input can be used to correct other sensors, such as humidity sensors.

Op Amp Buffer

The MCP6SX2 PGA, shown in Figure 3, can be replaced with a unity-gain buffer; Microchip's MCP6001 op amp would be a good choice. The advantages include simplicity and cost. The disadvantages are the inability to multiplex multiple input signals and the improvement in ADC temperature resolution due to changing the PGA's gain.

Remote Thermistor Issues

Thermistors that are located remotely from the PGA (e.g., not on the same PCB) may require design changes. Possible issues include:

- Shielding sensor pickup wires
- EMI filtering and protection
- Wiring resistance voltage drop
- Mismatch between thermistor ground and PCB ground

SUMMARY

Two different circuit designs using the MCP6SX2 PGA and an accurate NTC thermistor have been shown. The two designs trade off simplicity, accuracy and temperature range.

The first design is easier to implement, but has a smaller temperature range. It can be made more accurate, or cover a wider temperature range, with more expensive components and analog design effort.

While the second design's firmware takes more space in firmware, the analog design is very reasonable. It takes advantage of the PGA's flexibility and digital control to reduce the analog errors and increase the temperature resolution.

The MCP6SX2 PGA's input MUX and digitally-controlled gain significantly increase the utility of these circuits. Multiple sensors and/or input signals can be processed with one PGA, reducing component count. It also makes it easier to perform temperature correction on other sensors. The marginal cost of the NTC thermistor circuits is reasonable in this case.

REFERENCES

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APPENDIX A: THERMISTOR MODEL

The nominal response of the 2322 640 55103 thermistor [1] is shown in Table A-1.

TABLE A-1: NOMINAL THERMISTOR RESPONSE.

Thermistor Temperature (°C)	Thermistor Resistance (Ω)
-40	332.1 k
-35	240.0 k
-30	175.2 k
-25	129.3 k
-20	96.36 k
-15	72.50 k
-10	55.05 k
-5	42.16 k
0	32.56 k
5	25.34 k
10	19.87 k
15	15.70 k
20	12.49 k
25	10.00 k
30	8.059 k
35	6.535 k
40	5.330 k
45	4.372 k
50	3.606 k
55	2.989 k
60	2.490 k
65	2.084 k
70	1.753 k
75	1.481 k
80	1.256 k
85	1.070 k
90	915.4
95	786.0
100	677.3
105	585.8
110	508.3
115	442.6
120	386.6
125	338.7
130	297.7
135	262.4
140	231.9
145	205.5
150	182.6

The data in Table A-1 was fit to the following sets of equations. These equations make it possible to accurately interpolate values between the table entries, thus making the designs easier to evaluate.

EQUATION A-1:

Resistance-to-Temperature Equations:

$$X = \ln(R_{TH} / 1\Omega)$$

$$z = X_{SC} (X - X_{CTR})$$

$$T_{TH} \approx \frac{T_0}{1 + z(A_1 + z(A_2 + z(A_3)))} - T_{25}$$

where:

$$182.6 \Omega \leq R_{TH} \leq 332.1 \text{ k}\Omega$$

$$X_{SC} = -0.266457$$

$$X_{CTR} = 8.960245$$

$$T_0 = 303.960^\circ\text{C}$$

$$A_1 = -0.291639$$

$$A_2 = 0.010993$$

$$A_3 = -0.001042$$

$$T_{25} = 273.150^\circ\text{C}$$

EQUATION A-2:

Temperature-to-Resistance Equations:

$$Y = \frac{1}{T_{TH} + T_{25}}$$

$$z = Y_{SC} (Y - Y_{CTR})$$

$$X \approx B_0 + z(B_1 + z(B_2 + z(B_3)))$$

$$R_{TH} = (1 \Omega) e^X$$

where:

$$-40^\circ\text{C} \leq T_{TH} \leq +150^\circ\text{C}$$

$$T_{25} = 273.150^\circ\text{C}$$

$$Y_{SC} = -1038.499^\circ\text{C}$$

$$Y_{CTR} = 0.003326156 \text{ }^\circ\text{C}^{-1}$$

$$B_0 = 9.101806$$

$$B_1 = -3.756408$$

$$B_2 = -0.141435$$

$$B_3 = 0.003396$$

The piece-wise linear interpolation tables need values outside of the valid temperature range shown in Table A-1. These values are only used for convenience in setting up the interpolation tables and firmware routine; the manufacturer does not supply any data outside the -40°C to $+150^\circ\text{C}$ range. The above equations give accurate results within the valid temperature range.

Both sets of equations are based on a min-max polynomial fit on the normalized variable z. It is more difficult to achieve an accurate fit to the data using the variables X and Y.

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