Thermistor Temperature Transducer to ADC Application

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ABSTRACT

An interchangeable-thermistor temperature-measurement application is described and a basic framework circuit which can be modified to use alternative components is provided. When a potentiometer is used instead of a thermistor, the application can also be used to measure other process variables. A basic understanding of active and passive analog devices is assumed. Project collateral discussed in this application report can be downloaded from the following URL: http://www.ti.com/lit/zip/SLOA052.

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1 Introduction

One operational-amplifier (op-amp) application is converting and conditioning signals from transducers into signals that other devices, especially analog-to-digital converters (ADC), can use. The reason any conversion or conditioning is necessary is that the range and offset of the transducer and the ADC are rarely the same.

A very inexpensive temperature transducer uses a diode whose forward-biased junction voltage changes with temperature. When higher repeatability between devices or better linearity is needed, other types of transducers such as the interchangeable thermistor, should be considered.

This application uses an interchangeable negative-temperature-coefficient (NTC) thermistor. Because NTC thermistors are inherently nonlinear, several vendors supply thermistors containing more than one device, designed to linearize the temperature-dependence of the resistance. Because of their tight tolerances, these devices can be replaced by a part of the same type and still retain their accuracy—in other words, they are interchangeable. The values of some components and a spreadsheet for the calculation of others are given in the Appendix.

2 Transducer Information

The sensor selected for this application is a thermistor manufactured by RTI (part number ACC-004). It has a resistance of 32 650 Ω at 0°C and 678.3 Ω at 100°C capable of temperature measurement with a precision of ±0.2°C over the range 0–70°C. When less precision is required, other parts are available at a lower cost, e.g., part number ACC-024 with a precision of ±1°C. Specifications for this and like devices can be found in reference [1]. Information on similar devices supplied by Alpha Sensors Inc. is available in reference [2].

3 Current Source Information

In principle, a simple method for determining the resistance of a thermistor is to measure the voltage drop across it when it is connected to a dc power source through another resistor. However, this method is flawed because both the current and the voltage drop change when the thermistor's resistance changes. In addition, a further requirement when designing a thermistor circuit is ensuring that the current through the thermistor is kept small to avoid self-heating, with its resultant temperature offset.

To overcome these problems, the thermistor should be operated in the constant-current mode, with the small constant current (100 µA) supplied by a current regulator. The one chosen for this application is a Texas Instruments Tuscon REF200, which contains two current regulators and a current mirror (the current mirror is not used). This device is useful for configuring regulated-current sources of varying magnitudes for many applications. A data sheet for this device is available in reference [3].

One of the two current regulators supplies 100 µA ± 0.5% to the thermistor. From resistance and current information, the thermistor voltage at 100°C is 0.06783 V, and at 0°C it is 3.265 V.

Because any current used by the input to the amplifier affects the measured signal, an amplifier with high input impedance is necessary. The number of components in a circuit should be kept to a minimum because each component in the circuit increases cost, circuit errors, and complexity. Because fewer components are required to make a *noninverting* amplifier, versus an *inverting* amplifier (with high input impedance), the noninverting configuration was chosen. The output of the ADC is fed into a digital signal processor (DSP) where it is inverted if necessary.

In combination with R1a, R1b and U1a, the other current regulator is used to establish the reference voltage.

4 ADC Information

Systems engineering selected the TLV2544 ADC for this application. The device is a single-supply unit with an analog input range of 0–5 V. The amplified sensor signal should completely fill this span. The voltage required to power this device is from a single 5-V supply. Other ADC devices could be used with corresponding changes in input range, resolution and input impedance considerations. A data sheet for the TLV2544 is available in reference [4].

The TLV2544 is a 12-bit ADC, with the voltage value of each bit calculated to be 1.22 mV/bit:

$$\frac{\text{Input}}{\text{Resolution}} = \frac{5}{2^{12} - 1} = 1.22\,\text{mV/bit} \tag{1}$$

5 Op-Amp Choice

Since the analog input range for this ADC is 0–5 V and the power available is a single 5-volt supply, a rail-to-rail output (RRO) device is required for best performance. The op amp chosen for this application, Texas Instruments TLV2472, is also able to handle the full input range of the transducer because it is a rail-to-rail input (RRI) device. The data sheet for this op amp is available in reference [5].

In this application the ADC is powered by a single 5-V dc source. The analog input to the ADC is 0–5 volts. When a single supply is used, the output range will not quite be able to reach these limits even with a rail-to-rail op amp. The high output voltage with a 2-kΩ load is 4.85 V minimum and 4.96 V nominal. The low output voltage with a 2-kΩ load is 150 mV maximum and 70 mV nominal. Because the load on the ADC is about 20 kΩ, the actual limits are likely to be better than the nominal limits. Using the nominal limits, the number of codes that will be sacrificed at the high output is 0.04/0.00122 ≅ 33 bits and at the low output it is 0.07/0.00122 ≅ 57 bits. This is a total of 90 bits out of 4094, and it will allow each Celsius degree to be subdivided into 40 codes—much more resolution than the transducer's inherent precision of ±0.2°C.

6 Basic Equations

With these data, the gain of the circuit can be calculated by dividing the output-voltage range by the input-voltage range.

$$m = \frac{\text{OUTPUT}_{\text{MAX}} - \text{OUTPUT}_{\text{MIN}}}{R_{0°C}\, I_{\text{SENSOR}} - R_{100°C}\, I_{\text{SENSOR}}} = 1.564 \tag{2}$$

7 Defining the Circuit

Figure 1 is a schematic diagram of the op-amp circuit for this application.

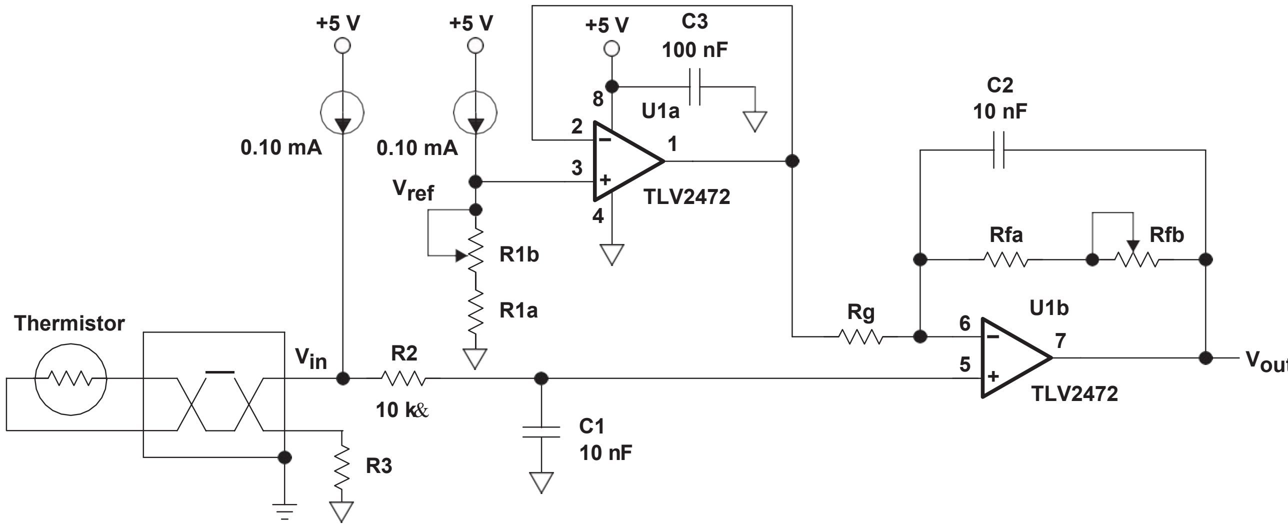


Figure 1. Schematic of Thermistor Temperature Transducer Application

The temperature of the thermistor is converted into a voltage that is increased by R3 and amplified by U1b. The resistor R3 is used because it forces a higher reference voltage. This reference voltage is developed by R1 and buffered by U1a. The higher reference voltage causes the output to move closer to the negative rail at the 100°C point.

Op amp U1a is a unity-gain amplifier whose output is the same voltage (but at a lower impedance) as its input. The nominal voltage for V_{REF} is 67.83 mV (thermistor voltage at 100°C) plus V_{R3} (the resistance of R3 multiplied by 100 μA). With R3 set at 3.01 kΩ, V_{REF} is calculated to be 0.406 Volts.

The basic voltage signals and resistors in Figure 1 are defined in equations (3), (4) and (5).

The other op amp, U1b, is used to amplify and filter the signal from the thermistor. The following equation defines the gain of this op amp:

$$|m| = \frac{R_F}{R_G} + 1 \tag{3}$$

Using the value m = 1.564 from equation (2) and letting R_G = 26.7 kΩ (a 1% value), R_F is found from equation (3) to be 15.056 kΩ. The closest 1% value for R_F is 15 kΩ.

Using the equation for a basic voltage divider, the following formula allows calculation of V_{REF} at 100°C:

$$\frac{R_{100°C} - V_{REF} - I_{SENSOR}}{V_{REF} - OUTPUT_{100°C}} = \left(\frac{R_F + R_G}{R_G}\right. \tag{4}$$

Substituting values for $R_{100°C}$, I_{SENSOR}, $OUTPUT_{100°C}$, R_G and R_F into equation (4) gives V_{REF} = 0.406 V. From Ohm's law, the value of R1 is:

$$R_1 = \frac{V_{REF}}{I_{VREF}} = 4.59\ k\Omega\ (1\%\ resistor) \tag{5}$$

8 Calibration Devices

Because the temperature coefficient of potentiometers is higher (worse) than that of resistors, it is wise to replace R_1 and R_F with a potentiometer in series with a resistor. These parts are designated R_{1A} and R_{FA} for the fixed resistors and R_{FB} and R_{1B} for the potentiometers. In addition, when a fixed resistor is used in series with a potentiometer, adjustment is less critical.

Between now and the end of an application's life, component values will drift as the components age. Therefore, when calculating values of R_F and R_1, the life expectancy should be taken into account.

8.1 Long-Life Applications

One-percent resistors may drift about 3%. The current regulators, temperature sensor and op amps will drift, too. The resistances R_1 and R_F are 4020 Ω and 15 kΩ, respectively, but because of the drift in circuit components, they each must be able to absorb a total of ±9% (3% + 3% + 3%) drift. This is done in each case by using a fixed resistor for 91% of the resistance, and a small pot to permit adjustment for the 9% drift. To ensure the ability always to compensate, the size of the pots is doubled. Gain is scaled with R_F and offset is zeroed with R_1 using the fixed and variable resistance values shown in equations (6)–(9). The fixed resistors have been selected to the nearest 1% values and potentiometers to the next higher value:

$$R_{FA} = 0.91 \times R_F = 13.7\ \text{k}\Omega\ \text{(1\% resistor)} \tag{6}$$

$$R_{FB} = 2 \times 0.09 \times R_F = 5\ \text{k}\Omega\ \text{(Cermet potentiomenter)} \tag{7}$$

$$R_{1A} = 0.91 \times R_1 = 3.65\ \text{k}\Omega\ \text{(1\% resistor)} \tag{8}$$

$$R_{1B} = 2 \times 0.09 \times R_1 = 1\ \text{k}\Omega\ \text{(Cermet potentiomenter)} \tag{9}$$

8.2 Short-Life Applications

If the design life of the circuit is significantly shorter than the theoretical end-of-life of the devices, the tolerances of the devices themselves (±1%) can be used for the calculations. The reference diode, temperature sensor and op amp will drift less, as well. Allow 2% for errors not caused by resistors for a maximum total possible drift of ±4% (1% + 1% + 2%). Again, if gain is adjusted with R_F and offset with R_1, values for the new resistors and potentiometers are calculated in equations (10) – (13) where fixed resistors have been selected for the nearest 1% values and the potentiometers for the next higher value:

$$R_{FA} = 0.96 \times R_F = 14.3\ \text{k}\Omega\ \text{(1\% resistor selection)} \tag{10}$$

$$R_{FB} = 2 \times 0.04 \times R_F = 2\ \text{k}\Omega\ \text{(Cermet potentiomenter)} \tag{11}$$

$$R_{1A} = 0.96 \times R_1 = 3.92\ \text{k}\Omega\ \text{(1\% resistor selection)} \tag{12}$$

$$R_{1B} = 2 \times 0.04 \times R_1 = 500\ \Omega\ \text{(Cermet potentiomenter)} \tag{13}$$

To calibrate the circuit, a resistance decade box (or individual resistors or potentiometers) is connected in place of the thermistor. This calibration device is adjusted to the resistance corresponding to various temperatures. Calibration is done by first adjusting the gain and then the reference voltage. There is some interaction between these adjustments. Because both the lowest (0°C) and highest (100°C) temperatures in the range coincide with the power rail, the adjustments should be made at 5°C and 95°C. Linearity can be checked at 25°C , 50°C and 75°C. Repeating this sequence provides verification of the calibration's precision.

9 Signal Filtering

When a transducer is connected to an input, the wiring is subjected to noise because of the electrical and magnetic environment surrounding the transducer and wiring. To prevent this noise from interfering with the measurements, some shielding is necessary. Noise can be reduced by using a twisted pair from the transducer to the conversion circuit, and shielding this pair (grounding the shield only at the instrument).

Without an input filter, the op amp will act as a radio frequency detector converting high-frequency signals from other devices into signals that will have low-frequency components. Putting a resistor and capacitor on the input forms a low-pass filter that prevents high-frequency signals from interfering with the temperature signal. The cutoff frequency of an RC filter is:

$$F_C = \frac{1}{2\pi RC} \tag{14}$$

Thus, for R_2 = 10 kΩ and C_1 = 10 nF, F_C is about 1600 Hz.

When resistor R_F (15 kΩ) and capacitor C_2 (10 nF) are connected from the output of U1b to its noninverting input, a low-pass filter is created. The purpose of this filter is to remove any noise generated by the components in this circuit as well as noise that was of low enough frequency to get past the previous filter. Additionally, it removes any frequency that is near or above the sampling frequency of the ADC and which would otherwise cause alias signals. The cutoff frequency of this filter is calculated from equation (14) to be 1060 Hz.

10 Decoupling

Power supply decoupling is important to prevent noise from the power supply from being coupled into the signal being amplified, and vice-versa. This is accomplished using a 6.8-µF tantalum capacitor in parallel with a 100-nF ceramic capacitor on the supply rails. The tantalum capacitor can be shared between multiple packages but one ceramic capacitor should be connected as close as possible (preferably within 0.1 inch) to each package.

11 References

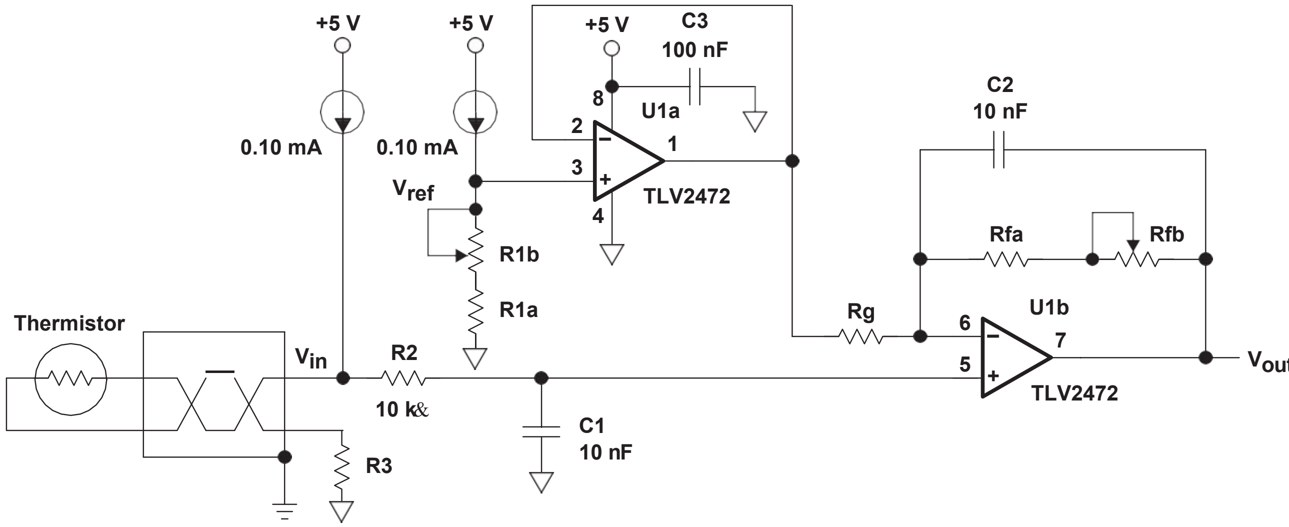
To reference Texas Instruments application notes, search for the literature number from http://www.ti.com/sc/docs/psheets/appnote.htm

1. http://www.rtie.rti-corp.com/accurv.htm
2. http://www.alphasensors.com/interchange.html
3. http://www.burr-brown.com/products/selection-trees/REF-current.html
4. http://www.ti.com/sc/docs/products/analog/tlv2544.html
5. http://www.ti.com/sc/docs/products/analog/tlv2472a.html
6. *Understanding Basic Analog – Ideal Op Amps*, Ron Mancini, Texas Instruments Application Report, Literature Number SLAA068A
7. *Single Supply Op Amp Design Techniques,* Ron Mancini, Texas Instruments Application Report, Literature Number SLOA030
8. *Active Low-Pass Filter Design*, James Karki, Texas Instruments Application Report, Literature Number SLOA049

9. *Application Of Rail-To-Rail Operational Amplifiers*, Andreas Hahn, Texas Instruments Application Report, Literature Number SLOA039A
10. *Sensor to ADC-Analog Interface Design*, Ron Mancini, Analog Applications Journal, p. 22, May, 2000, Literature Number SLYT015
11. *Mixed-Signal: Amplifiers: Operational Amplifiers* (complete op amp application index) http://www.ti.com/sc/docs/apps/analog/operational_amplifiers.html

Appendix A Calculations

The following spreadsheet output indicates values and equations used in this application report.



Given:									
$R_{0\ deg.C}$ =	32650.0	Ohm		OUTPUT max =	5	V			
$R100_{0\ deg.C}$ =	678.3	Ohm		OUTPUT min =	0	V			
Isensor =	100.0	microA							
V(0 deg. C) =	3.265								
V(100 deg. C) =	0.06783	1%							
R_3 =	3000	3010	Ohm	V_{R3} =	0.301	V			
m =	$\frac{OUTPUTmax-OUTPUTmin}{\left(R_{0\ deg.C}-R_{100\ deg.C}\right)Isensor}$								
m =	1.564								
Resistor values:									
m =	$R_F/R_G + 1$								
R_F =	$(m-1)R_G$								
R_F =	$5.944R_G$								
Gain resistsor values:		1%							
R_G =	27000	26700	Ohm						
R_F =	15055.68	15000	Ohm						
At 100 deg. C:	$\frac{V_{REF}-V_{R3}-OUTPUT_{min}}{R_{100\ deg.C} * Isensor}$		=	$\frac{R_F + R_G}{R_G}$					
		V_{REF}	=	0.40594					
R1 =	V_{REF}/Isesnsor								
		1%							
R1 =	4059	4020	Ohm						
End of life adjustment calculations					Expendable adjustment calculations				
		1%	Pot.				1%	Pot.	
R1a =	3694.0	3650		Ohm	R1a =	3897.	3920		Ohm
R1b =	730.7		1000	Ohm	R1b =	324.7		500	Ohm
Rfa =	13650	13700		Ohm	Rfa =	14400	14300		Ohm
Rfb =	2700		5000	Ohm	Rfb =	1200		2000	Ohm
	C =	0.01	microF						
	F_{IN} =	1/(2pi R_1C) =		1592					
	F_{Amp} =	1/(2pi R_FC) =		1061					
NOTE: Values in solid boxes are entered values while values in gray boxes are calculated.									

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