AN687

Precision Temperature-Sensing With RTD Circuits

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INTRODUCTION

The most widely measured phenomena in the process control environment is temperature. Common elements, such as Resistance Temperature Detectors (RTDs), thermistors [7], thermocouples [6] or diodes are used to sense absolute temperatures, as well as changes in temperature. For an overview and comparison of these sensors, refer to Microchip's AN679, *"Temperature-Sensing Technologies"* [5].

Of these technologies, the platinum RTD temperature-sensing element is the most accurate, linear and stable over time [1] and temperature. RTD element technologies are constantly improving, further enhancing the quality of the temperature measurement. Typically, a data acquisition system conditions the analog signal from the RTD sensor, making the analog translation of the temperature usable in the digital domain.

This application note focuses on circuit solutions that use platinum RTDs in their design (see Figure 1). The linearity of the RTD will be presented along with standard formulas that can be used to improve the off-the-shelf linearity of the element. For additional information concerning the thermistor temperature sensor, refer to Microchip's AN685, *"Thermistors in Single Supply Temperature Sensing Circuits"* [7]. Finally, the signal-conditioning path for the RTD system will be covered with application circuits from sensor to microcontroller.

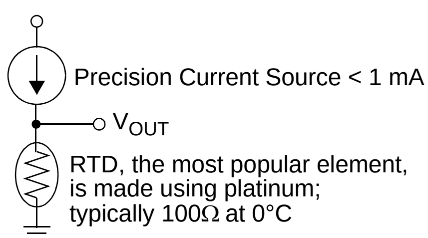

FIGURE 1: *RTD Temperature-sensing Elements Use Current Excitation.*

RTD OVERVIEW

The acronym "RTD" is derived from the term "Resistance Temperature Detector" [4]. The most stable, linear and repeatable RTD is made of platinum metal. The temperature coefficient of the RTD element is positive and almost constant.

Typical RTD elements are specified with 0°C values of 50, 100, 200, 500, 1000 or 2000Ω. Of these options, the 100Ω platinum RTD is the most stable over time and linear over temperature.

The RTD element requires a current excitation. If the magnitude of the current source is too high, the element will dissipate power and start to self-heat. Consequently, care should be taken to insure that less than 1 mA of current is used to excite the RTD element.

An approximation to the platinum RTD resistance change over temperature can be calculated by using the constant a = 0.00385Ω/Ω/°C (European curve, ITS-90). This constant is easily used to estimate the absolute resistance of the RTD at temperatures between -100°C and +200°C (with a nominal error smaller than 3.1°C).

EQUATION 1:

$$RTD(T) \approx RTD_0(1 + T \times \alpha)$$

Where:

$RTD(T)$ = the RTD element's resistance at T (Ω),

RTD_0 = the RTD element's resistance at 0°C (Ω),

T = the RTD element's temperature (°C),

α = 0.00385 Ω/Ω/°C

If a higher accuracy temperature measurement is required, or a greater temperature range is measured, the standard formula below (Calendar-Van Dusen Equation) can be used in a calculation in the controller engine or be used to generate a look-up table. Figure 2 shows both the RTD resistance and its slope across temperature.

EQUATION 2:

$$RTD(T) = RTD_0(1 + AT + BT^2 + CT^3(T - 100))$$

Where:

$RTD(T)$	=	the RTD element's resistance at T (Ω),
RTD_0	=	the RTD element's resistance at 0°C (Ω),
T	=	the RTD element's temperature (°C) and
A, B, C	=	are constants derived from resistance measurements at multiple temperatures.

The ITS-90 standard values are:

RTD_0	=	100Ω
A	=	3.9083×10^{-3} °C^{-1}
B	=	-5.775×10^{-7} °C^{-2}
C	=	-4.183×10^{-12} °C^{-4}, $T < 0$°C
	=	0, $T \geq 0$°C

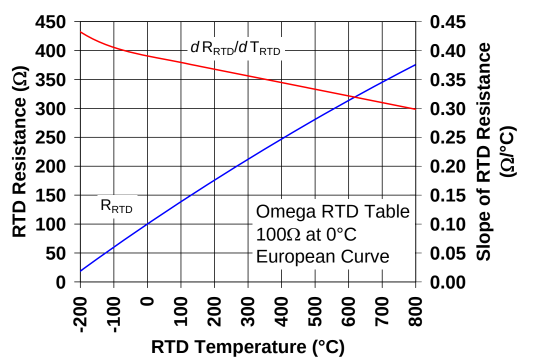

FIGURE 2: *The RTD sensing element's temperature characteristic has a positive temperature coefficient that is almost constant.*

When the RTD element is excited with a current reference, and self-heating is avoided, the accuracy can be ±4.3°C over the temperature range -200°C to 800°C. The accuracy of a typical RTD is shown in Figure 3.

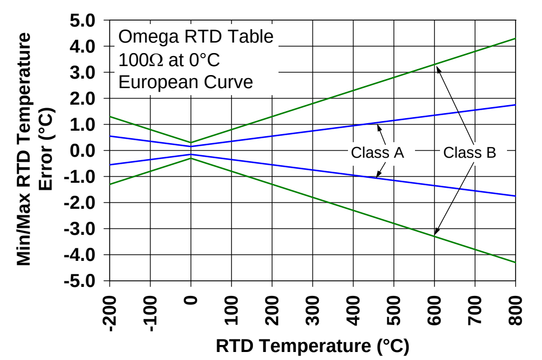

FIGURE 3: *The platinum RTD temperature sensor's accuracy is better than other sensors, such as the thermocouple and thermistor.*

The advantages and disadvantages of the RTD temperature sensing element is summarized in Table 1.

TABLE 1: RTD TEMPERATURE SENSING ELEMENT ADVANTAGES AND DISADVANTAGES

Advantages	Disadvantages
Very Accurate and Stable	Expensive Solution
Reasonably Linear	Requires Current Excitation
Good Repeatability	Danger of Self-Heating
	Low Resistive Element

RTD CURRENT EXCITATION CIRCUIT

For best linearity, the RTD sensing element requires a stable current reference for excitation. This can be implemented in a number of ways, one of which is shown in Figure 4. In this circuit, a voltage reference, along with two operational amplifiers, are used to generate a floating 1 mA current source.

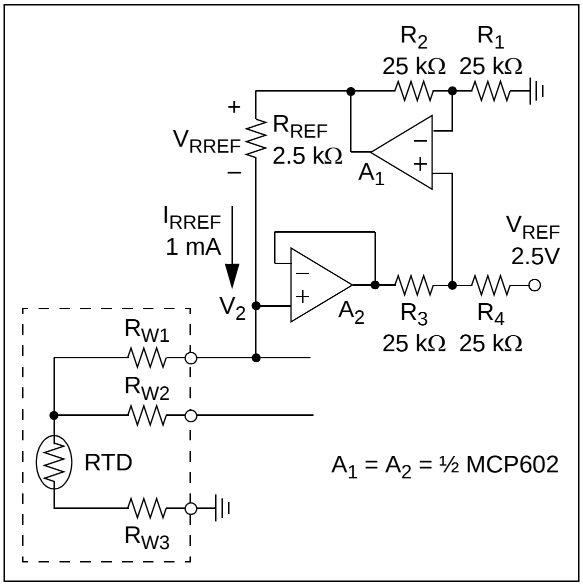

FIGURE 4: A current source for the RTD element can be constructed in a single-supply environment from two op amps and a precision voltage reference.

This is accomplished as follows. The op amp A_1 and the resistors R_1 through R_4 form a difference amplifier with a differential gain (G_{A1}) of 1 V/V (since the resistors are all equal). A 2.5V precision voltage reference (V_{REF}) is applied to the input of this difference amplifier. The output of op amp A_2 ($V_{OUT2} \approx V_2$) serves as the difference amplifier's reference voltage. The voltage at the output of A_1 is shown in Equation 3.

EQUATION 3:

$$V_{OUTA1} = V_{REF}G_{A1} + V_{OUTA2}$$

Where:

V_{OUTA1}	=	A_1's output voltage
V_{OUTA2}	=	A_2's output voltage
V_{REF}	=	Reference voltage at the input
G_{A1}	=	Differential Gain
	=	1 V/V

Now it is easy to derive the voltage (V_{RREF}) across the resistor R_{REF}, assuming $V_{OUT2} = V_2$; see Equation 4.

EQUATION 4:

$$V_{RREF} = V_{OUTA1} - V_2$$
$$V_{RREF} = V_{REF}$$

Where:

V_2	=	Voltage at A_2's input
V_{RREF}	=	Voltage across R_{REF}

The current used to bias the RTD assembly (I_{RREF}) is constant and independent of the voltage V_2 (which is across the RTD element); see Equation 5.

EQUATION 5:

$$I_{RREF} = V_{RREF}/R_{REF}$$
$$I_{RREF} = 1\ \mathrm{mA}$$

This current is ratio-metric to the voltage reference. The same voltage reference should be used in other portions of the circuit, such as the analog-to-digital (A/D) converter reference.

Absolute errors in the circuit will occur as a consequence of the reference voltage, the op amp offset voltages, the output swing of A_1, mismatches between the resistors and the errors in R_{REF} and the RTD element. The temperature drift of these same elements also causes errors; primarily due to the voltage reference, op amp offset drift and the RTD element.

RTD SIGNAL-CONDITIONING PATH

Changes in resistance of the RTD element over temperature are usually digitized through an A/D conversion, as shown in Figure 5. The current excitation circuit (see Figure 4) excites the RTD element. The magnitude of the current source can be tuned to 1 mA or less by adjusting R_{REF}. The voltage drop across the RTD element is sensed by A_3, then gained and filtered by A_4. With this circuit, a 3-wire RTD element is selected. This configuration minimizes errors due to wire resistance and wire resistance drift over temperature.

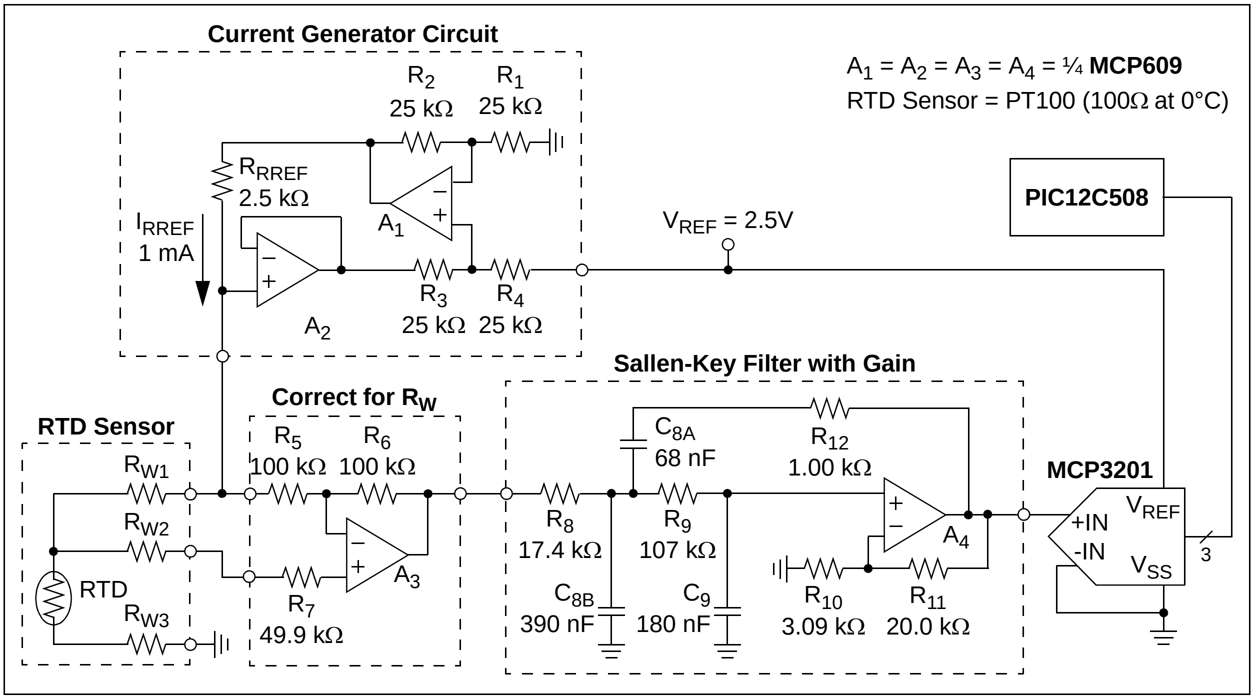

FIGURE 5: *This circuit uses a RTD element to measure temperatures from -200°C to 600°C. A current generator excites the sensor. An op amp (A_3) cancels the wire resistance error. Another op amp (A_4) gains and filters the signal. A 12-bit converter (MCP3201) converts the voltage across the RTD to digital code for the 8-pin controller (PIC12C508).*

In this circuit, the RTD element equals 100Ω at 0°C. If the RTD is used to sense temperature over the range of -200°C to 600°C, the resistance produced by the RTD would be nominally between 18.5Ω and 313.7Ω, giving a voltage across the RTD between 18.5 mV and 313.7 mV. Since the resistance range is relatively low, wire resistance and wire resistance change over temperature can skew the measurement of the RTD element. Consequently, a 3-wire RTD device is used to reduce these errors.

The errors contributed by the wire resistances, R_{W1} and R_{W3}, are subtracted from the signal with op amp A_3. In this configuration, R_1 and R_2 are equal and are relatively high. The value of R_1 is selected to ensure that the leakage currents through the resistor do not introduce errors to the current in the RTD element. The transfer function of this portion of the circuit is:

EQUATION 6:

$$V_{OUTA3} = (V_{IN} - V_{W1})(1 + R_6/R_5) - V_{IN}(R_6/R_5)$$

where:

V_{IN} = $V_{W1} + V_{RTD} + V_{W3}$,

V_{Wx} = the voltage drop across the wires to and from the RTD and

V_{OUTA3} = the voltage at the output of A_3

If nominal resistor values are assumed, then A_3's output voltage is significantly simplified:

EQUATION 7:

$$V_{OUTA3} = V_{RTD}$$

Where:

R_5 = R_6

R_{W1} = R_{W3}

The voltage signal at the output of A_3 is filtered with a 2^{nd} order, low pass filter created with A_4, R_8, C_{8A}, $C8_B$, R_9 and C_9. It is designed to have a Bessel response and a bandwidth of 10 Hz. R_{10} and R_{11} set a gain of 7.47 V/V. It reduces noise and prevents aliasing of higher frequency signals.

This filter uses a Sallen-Key topology specially designed for high gain; see [10]. The capacitor divider formed by C_{8A} and C_{8B} improve this filter's sensitivity to component variations; the filter can be unproduceable without this improvement. R_{12} isolates A_4's output from the capacitive load formed by the series connection of C_{8A} and C_{8B}; it also improves performance at higher frequencies.

The voltage at A_4's output is nominally between 0.138V and 2.343V, which is less than V_{REF} (2.5V). The 12-bit A/D converter (MCP3201) gives a nominal temperature resolution of 0.22°C/LSb.

CONCLUSION

Although the RTD requires more circuitry in the signal-conditioning path than the thermistor or the silicon temperature sensor, it ultimately provides a high-precision, relatively accurate result over a wider temperature range.

If this circuit is properly calibrated, and temperature correction coefficients are stored in the PIC, it can achieve ±0.01°C accuracy.

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