APPLICATION NOTE 6262

RTD MEASUREMENT SYSTEM DESIGN ESSENTIALS

Abstract: This application note describes the methods to minimize error in RTD temperature measurement.

Introduction

High-accuracy temperature measurements provide essential data for industrial automation applications to ensure both product quality and safety. Many types of temperature sensors are available, and each one has its advantages and disadvantages. This application note focuses on resistance temperature detectors (RTD), and explains the design essentials to optimize the measurement accuracy.

Resistance Temperature Detectors

RTDs contains an element whose resistance changes with temperature. Most elements are either platinum, nickel, or copper. A platinum RTD provides the best performance because platinum has the most linear and repeatable temperature-to-resistance relationship over a large temperature range.

Generally, RTDs generate more stable and repeatable outputs, compared to thermocouples and thermistors. Hence, RTDs achieve higher measurement accuracy.

High-Accuracy RTD Measurement Design Options

The two most common methods to measure an RTD are constant current excitation (**Figure 1**) and constant voltage excitation (**Figure 2**).

The goal is to accurately measure the RTD resistance and convert it to temperature using an equation or a lookup table. For ideal cases:

$$R_{RTD} = \frac{V_{ADC\ input}}{I_{REF}}$$ for constant current excitation,

or

$$R_{RTD} = \frac{V_{ADC\ input} \times R_{REF}}{V_{REF} - V_{ADC\ input}}$$ for constant voltage excitation.

However in practice, the lead wires of the RTD have resistance. Long lead wires greatly affect the measurement accuracy. Therefore, the actual resistance measured by the circuits shown in Figures 1 and 2 is:

$RTD + (2 \times R_{WIRE})$,

where R_{WIRE} is the resistance of the lead wires, assuming both wires have the same resistance. Although theoretically acceptable, the same R_{WIRE} implies that both wires are of the exact same length and made with the exact same material. Such an assumption cannot be guaranteed in critical temperature sensing applications. For this reason, RTDs feature 3-, and 4-wire configurations to help eliminate the measurement error contributed by lead wires.
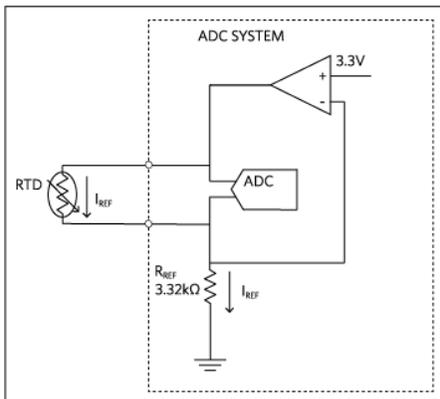
Figure 1. 2-wire constant current excitation configuration.
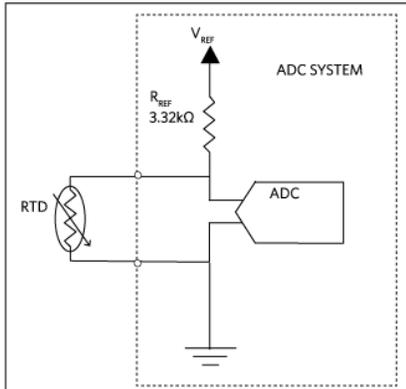
Figure 2. 2-wire constant voltage excitation configuration.

3-Wire RTD Configuration

Typical constant current and constant voltage excitation circuits for 3-wire RTD are shown in **Figure 3** and **Figure 4**, respectively. In both cases, the ADC samples a resistance of RTD + $R_{WIRE}3$ (where $R_{WIRE}3$ is the resistance of the return lead wire). The system eliminates $R_{WIRE}2$ because the ADC inputs are typically high-impedance and virtually no current flows through $R_{WIRE}2$. Therefore, the ADC only measures the voltage across RTD and $R_{WIRE}3$. $R_{WIRE}3$ contributes to measurement error. Compared to 2-wire configuration, however, the error contributed by the lead wires are reduced by roughly 50%.

One method to further improve the measurement accuracy is by adding an analog switch to the circuit. The ADC then measures the voltage (V_X) at the output of the excitation signal and obtains a value for $R_{WIRE}1$. By assuming $R_{WIRE}1$ is approximately the same as $R_{WIRE}3$, the $R_{WIRE}3$ can be subtracted out. Referring to Figure 3, in current excitation configuration, $R_{WIRE}1$ resistance equals to:

$$\frac{V_X - V_1}{I_{REF}}$$

And, the improved approximation of the RTD resistance is:

$$R_{RTD} = \frac{V_{ADC\ input}}{I_{REF}} - \frac{V_X - V_1}{I_{REF}}$$

For voltage excitation configuration:

$$I_{REF} = \frac{V_{REF} - V_X}{R_{REF}}$$

and

$$R_{RTD} = R_{REF} \times \frac{2 \times V_{ADC\ input} - V_X}{V_{REF} - V_X}$$

This method to improve the measurement accuracy does require extra hardware and adds complexity to the software.
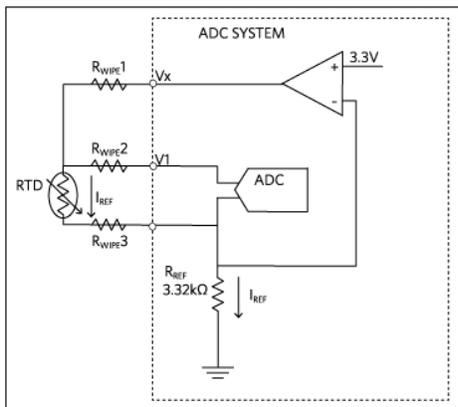
Figure 3. 3-wire constant current excitation configuration.
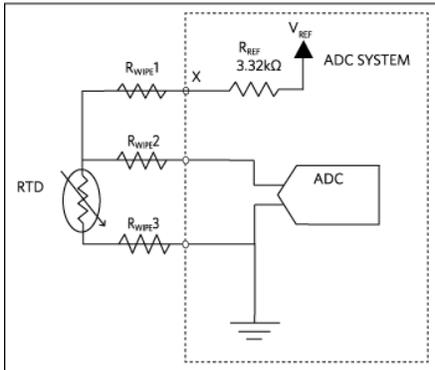
Figure 4. 3-wire constant voltage excitation configuration.

4-Wire RTD Configuration

A 4-wire RTD configuration provides the highest measurement accuracy. **Figure 5** and **Figure 6** show the constant current excitation and constant voltage excitation circuits, respectively, for 4-wire RTD. For current excitation configuration,

$$R_{RTD} = \frac{V_{ADC\ input}}{I_{REF}}$$

because no current passes through $R_{WIRE}2$ or $R_{WIRE}3$. Therefore, the voltage across $R_{WIRE}2$ + RTD + $R_{WIRE}3$ is the same as the voltage across the RTD. Unfortunately, when using a constant voltage excitation configuration, because of the voltage divider effect, $R_{WIRE}1$ and $R_{WIRE}4$ still creates errors in the RTD measurement unless the ADC system has the ability to measure the voltage at the excitation voltage output (V_X). If the voltage at V_X is known, then the reference current can be calculated by

$$I_{REF} = \frac{V_{REF} - V_X}{R_{REF}}$$

where R_{REF} is 3.32kΩ in this case. Similarly,

$$R_{RTD} = \frac{V_{ADC\ input}}{I_{REF}}$$

is the same as the formula for the current excitation configuration.

Many other factors in the signal chain affect the accuracy of measurement. These factors include the input impedance of the ADC system, the resolution of the ADC, the amount of current through the RTD, the stability of the voltage reference, and the stability of the excitation signals.

The inputs of the ADC system must be high impedance to avoid voltage drops across the lead wires ($R_{WIRE}2$ and $R_{WIRE}3$ in 4-wire configuration for example). If the ADC doesn't have high impedance inputs, buffers should be added in front of the inputs of the ADC.
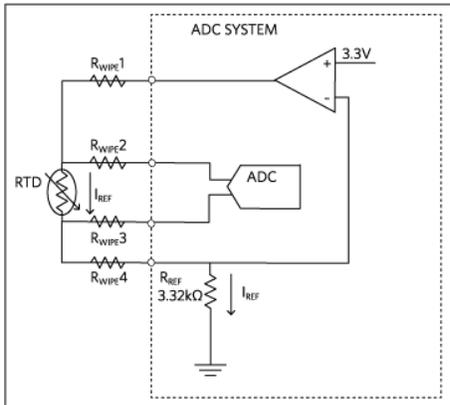
Figure 5. 4-wire constant current excitation configuration.
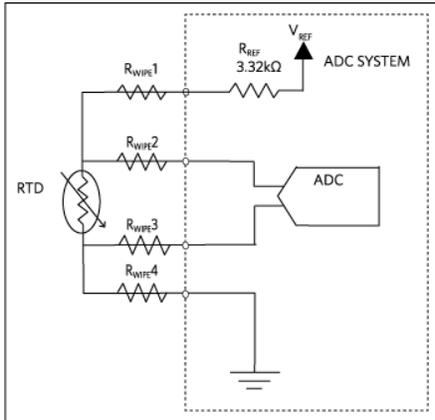
Figure 6. 4-wire constant voltage excitation configuration.

Heating Error

Although an RTD is a sensor, it is also a resistor. When current passes through a resistor, there is power dissipation. The dissipated power heats up the resistor. This self-heating effect creates error in the measurement. Excitation current must be carefully chosen to ensure the error created is within the error budget. The key formula to calculate the self-heating error is

$$\Delta T = (I^2_{REF} \times R_{RTD}) \times F,$$

where F is the self-heating factor of RTD, expressed in mW/°C. For example, a PT-100 platinum RTD with a 0.05°C/mW self-heating factor submerged in ice water. When the measuring temperature is 0°C, R_{RTD} equals to 100Ω. If the I_{REF} is set to 10mA, the self-heating error becomes

$$((0.01A)^2 \times 100\Omega) \times 50°C/W = 0.5°C.$$

Depending on the application, this error may or may not be acceptable. For high-accuracy measurements, a lower excitation current reduces the self-heating error. For example, if I_{REF} is lowered to 1mA, the self-heating error becomes 0.005°C. This level of error is much more tolerable. While reducing the excitation current reduces the self-heating error, it also reduces the voltage signal span across the RTD, thus requiring the RTD signal to be amplified so that the ADC can extract more discrete signal levels. An alternative would be to use a higher resolution ADC.

Up to this point, all the formulas discussed involve either I_{REF} or V_{REF}. But, what if these excitation signals are not stable? Instability can result from short term or long-term drift. Clearly, if the excitation signals become inaccurate, all the calculations above have errors. Consequently, periodic calibrations are required. Of course, an engineer could use a super stable voltage reference with ultra-low temperature drift and long-term drift. However, usually such devices are very costly. Alternatively, the ratiometric temperature measurement method eliminates errors caused by inaccurate excitation signals.

Ratiometric Temperature Measurement

A ratiometric measurement provides measurement of the resistance of the RTD as a ratio of the reference resistance, instead of measuring the resistance using an absolute voltage. In other words, R_{RTD} will be a function of R_{REF} instead of V_{REF} or I_{REF}. This uses the same excitation signal to generate both the voltage across the RTD and the voltage reference for the ADC. When the excitation signal changes, that change is reflected on both the voltage across the RTD and the reference inputs of the ADC. **Figure 7** and **Figure 8** show the ratiometric measurement circuits for current excitation and voltage excitation configurations.

The general ADC conversion formula is:

$$V_{IN} = V_{REF} \times \frac{CODE}{2^N}$$

where

V_{IN} = ADC input voltage
V_{REF} = reference voltage (REFP - REFN)
CODE = ADC code
N = resolution of the ADC.

V_{IN} equals the voltage across the RTD. For current excitation mode

$V_{IN} = I_{REF} \times R_{RTD}$ and $V_{REF} = I_{REF} \times R_{REF}$.

Substituting V_{IN} and V_{REF} into the ADC conversion formula yields,

$$I_{REF} \times R_{RTD} = I_{REF} \times R_{REF} \times \frac{CODE}{2^N}$$

and subsequently,

$$R_{RTD} = R_{REF} \times \frac{CODE}{2^N}$$

Similarly for voltage excitation,

$$V_{IN} = V_{REF} \times \frac{R_{RTD}}{R_{RTD} + R_{REF}}$$

Substituting V_{IN} into the ADC conversion formula yields,

$$V_{REF} \times \frac{R_{RTD}}{R_{RTD} + R_{REF}} = V_{REF} \times \frac{CODE}{2^N}$$

Solving for R_{RTD} gives,

$$R_{RTD} = \frac{CODE \times R_{REF}}{2^N - CODE}$$

In both cases, after the simplification, R_{RTD} becomes a function of R_{REF} and ADC code; hence, the accuracy of the RTD measurement depends on R_{REF}. For this reason, when selecting a reference resistor, the engineer must pick one with low temperature and long-term drift.
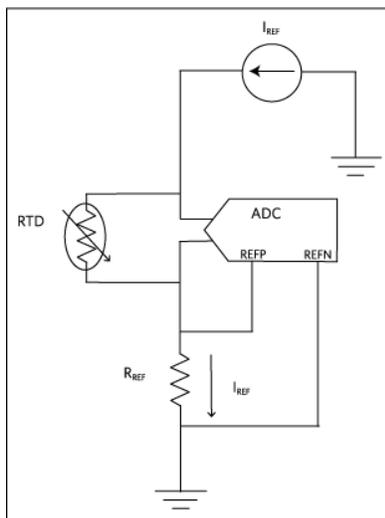
Figure 7. Current excitation configuration for ratiometric measurement.
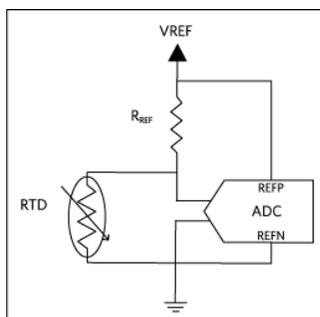
Figure 8. Voltage excitation configuration for ratiometric measurement.

RTD to Temperature Conversion

No matter how well the circuit measures the resistance of the RTD, all efforts are wasted if the engineer does not have a good method to accurately convert RTD resistance to temperature. One common method is to use a lookup table. However, if the resolution requirement is high and the measuring temperature range is wide, the lookup table becomes unwieldy, and the method less effective. Another method is to calculate the temperature.

For a platinum RTD, the Callendar-Van Dusen equation describes the relationship between resistance and temperature as:

$R(t) = R0 \times (1 + A \times t + B \times t^2 + (t - 100) \times C \times t^3)$,

where

$R(t)$ = RTD resistance
t = temperature
$R0$ = resistance of the RTD at 0°C

$A = 3.908 \times 10^{-3}$

$B = -5.775 \times 10^{-7}$

$C = -4.183 \times 10^{-12}$ when t < 0°C

$C = 0$ when t > 0°C

This equation provides the expected RTD resistance given a known temperature. If the temperature range of interest is above 0°C, then the constant C becomes 0 and the equation becomes a quadratic formula. Solving a quadratic equation is straightforward. But, if the temperature goes below 0°C and the C constant becomes non-zero, the equation becomes a difficult 4th order polynomial. In this case, polynomial interpolation approximation is a very useful tool. Here is a Microsoft Excel solution:

1. On a spreadsheet, create two columns of data. One column lists the temperature. The second column lists the corresponding RTD resistances calculated from the Callendar-Van Dusen equation.
2. Create an X-Y scatter plot.
3. Add a polynomial trendline for the plot. A higher order of the polynomial gives a more accurate approximation.
4. Select "Display Equation on Chart" in the "Format Trendline" menu.

The resulting polynomial equation for a PT100 for t < 0°C is:

$t = -1.6030e-13 \times r^6 + 2.0936e-10 \times r^5 - 3.6239e-8 \times r^4 - 4.2504e-6 \times r^3 + 2.5646e-3 \times r^2 + 2.2233 \times r - 2.4204e2$

Increasing the decimal places of the polynomial coefficients reduces error. With four decimal places, as shown in the formula above, the temperature approximation error is less than 0.005°C, tolerable for most applications.

Maxim Reference Design Solution
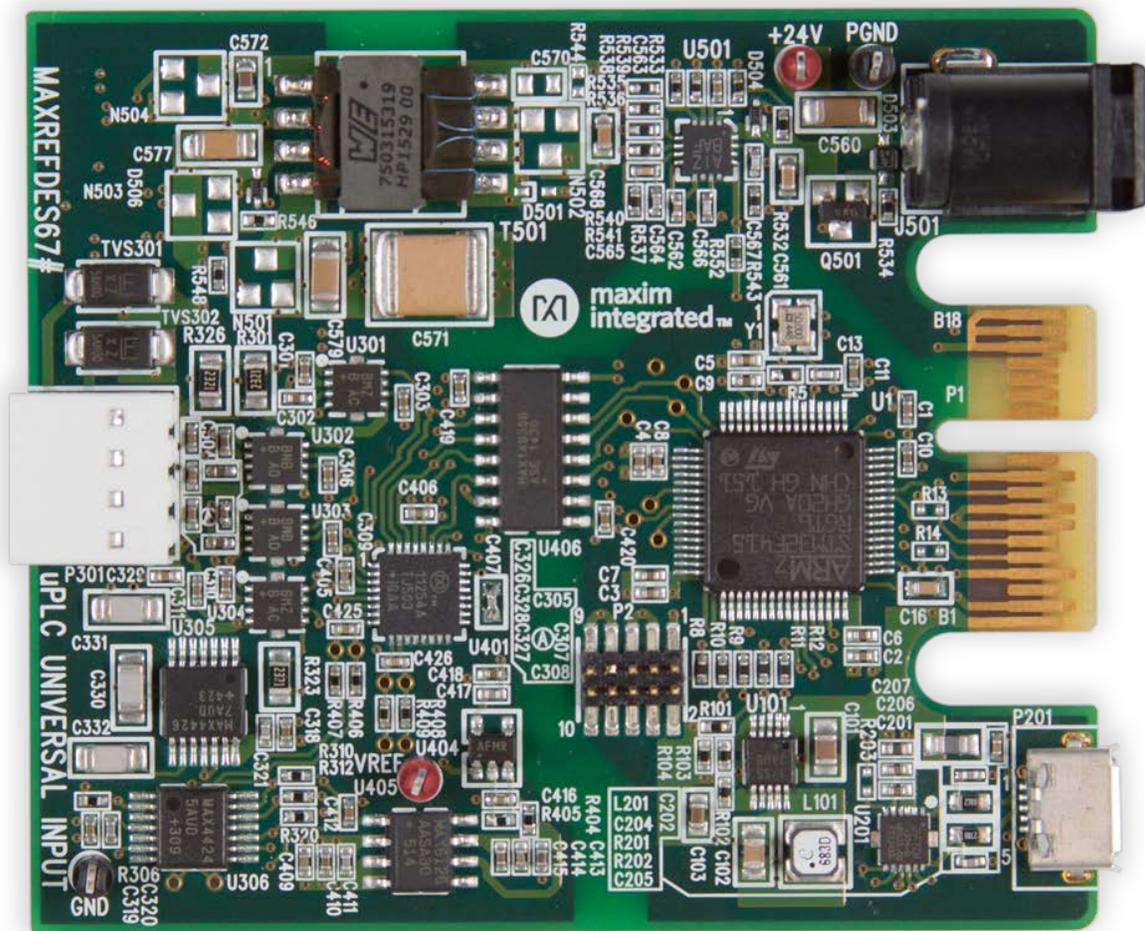
Figure 9. MAXREFDES67# System Board.

MAXREFDES67# reference design implements the 4-wire ratiometric configuration and polynomial approximation, as described above. In addition, design files and firmware are available for subsequent modification and implementation. Furthermore, this reference design (**Figures 9**, **10**, **11**) is a complete universal analog input for industrial applications. Besides RTD measurement, this unique 24-bit front-end also accepts bipolar voltage and current, and thermocouple (TC) inputs. Built in Maxim Integrated's ultra-small Micro PLC form factor, the MAXREFDES67# performs with an effective resolution up to 22.3 bits with temperature error as low as ±0.1% across a range of -40°C to 150°C. **Figure 12** shows the temperature error measured by the MAXREFDES67# RTD input versus temperature referenced to three different thermometers. The references are the Omega HH41 thermometer, the ETI reference thermometer, and Fluke 724 temperature calibrator, respectively. The MAXREFDES67# connected RTD probe (Omega P-M-1/10-1/4-6-0-G-3) was placed in the Fluke 7341 calibration bath and calibrated at 20°C.
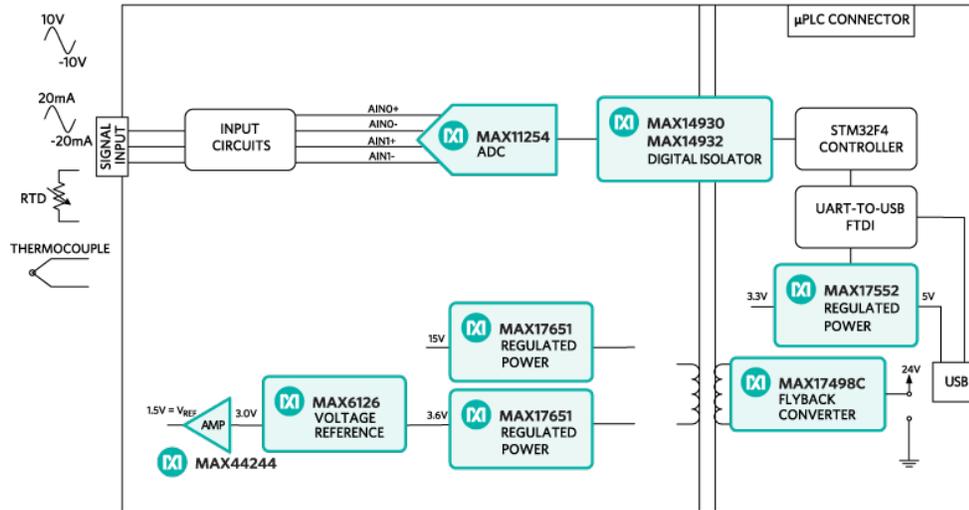
Figure 10. MAXREFDES67# Reference Design Block Diagram.
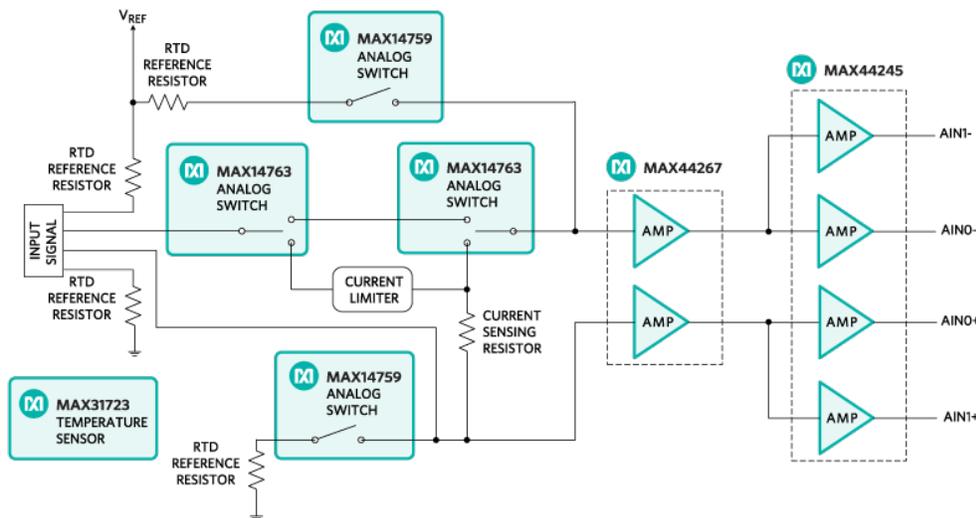
Figure 11. MAXREFDES67# Input Circuits Block Diagram.
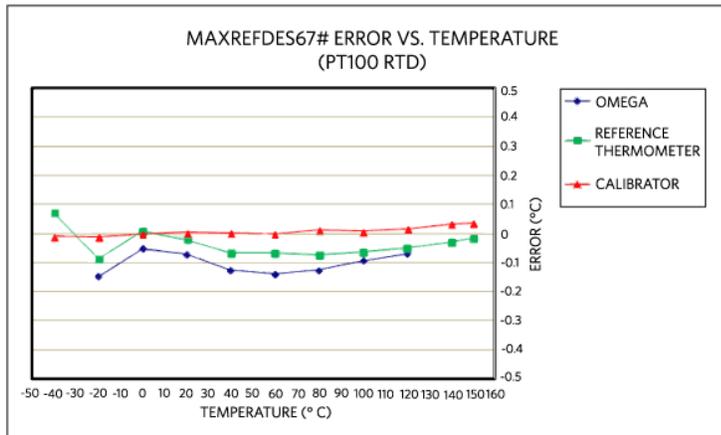
Figure 12. MAXREFDES67# error vs temperature, using an Omega P-M-1/10-1/4-6-0-G-3, 4-wire RTD calibrated at 20°C.

Conclusion

Temperature is the most measured industrial parameters. Though precision system design using techniques like the ratiometric method and polynomial approximation make very accurate measurement systems, with Maxim's reference design system, designers can now develop high-accuracy RTD temperature measurement or thermocouple measurement systems faster than ever before. The MAXREFDES67# allows modification and implementation, and is a complete universal analog input for industrial applications. Besides RTD measurement, it also accepts bipolar voltage, current and thermocouple inputs, performs with an effective resolution, and low measurement error making it more effective than other options.

A similar version of this application note appeared February 2016 on EDN Network.

Related Parts		
MAX11254	24-Bit, 6-Channel, 64ksps, 6.2nV/√Hz PGA, Delta-Sigma ADC with SPI Interface	Free Samples
MAX14759	Above- and Below-the-Rails Low On-Resistance Analog Switches	Free Samples
MAX14763	Above- and Below-the-Rails Low On-Resistance Analog Switches	Free Samples
MAX14930	4-Channel, 2.75kV$_{RMS}$ and 3.75kV$_{RMS}$ Digital Isolators	Free Samples
MAX14932	4-Channel, 2.75kV$_{RMS}$ and 3.75kV$_{RMS}$ Digital Isolators	
MAX17498C	AC-DC and DC-DC Peak-Current-Mode Converters for Flyback/Boost Applications	Free Samples
MAX17552	60V, 100mA, Ultra-Small, High-Efficiency, Synchronous Step-Down DC-DC Converter with 22µA No-Load Supply Current	Free Samples
MAX17651	60V, 100mA, Ultra-Low Quiescent Current, Linear Regulator	Free Samples
MAX31723	Digital Thermometers and Thermostats with SPI/3-Wire Interface	Free Samples
MAX44244	36V, Precision, Low-Power, 90µA, Single/Quad/Dual Op Amps	Free Samples
MAX44245	36V, Precision, Low-Power, 90µA, Single/Quad/Dual Op Amps	
MAX44267	+15V Single-Supply, Dual Op Amp with ±10V Output Range	
MAX6126	Ultra-High-Precision, Ultra-Low-Noise, Series Voltage Reference	Free Samples