Minimize measurement errors in RTD circuits

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Temperature is by far the most commonly measured physical parameter. With so many new ideas for connected devices in the works for consumer and industrial applications, you often need high-accuracy temperature measurements to ensure both product quality and safety. Many types of temperature sensors are available, and each one has its advantages and disadvantages. RTDs (Resistance Temperature Detectors) are one of the most common. To get the most from an RTD, you need to properly adapt it to an ADC for digitizing. These circuits can help you get quality temperature measurements from RTDs.

The RTD
RTD’s contain a resistive 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. For a typical platinum resistor, the temperature range is -200°C to 850°C. The most common RTD is the Pt100, which has a resistance of 100 Ω at 0°C.

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

RTD measurement circuits
The two most common methods to measure an RTD are constant current excitation (Figure 1) and constant voltage excitation (Figure 2).
Figure 1. A 2-wire constant-current excitation configuration. Simple, but wires add errors.
Figure 2. A 2-wire constant-voltage excitation configuration.

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.

As with many two-wire resistance measurements, an RTD's lead wires have resistance and long lead wires will greatly affect the measurement accuracy. Therefore, the actual resistance measured by the circuits shown in Figs. 1 and 2 is \((RTD + 2 \times R_{\text{WIRE}})\), where \(R_{\text{WIRE}}\) is the resistance of the lead wires.
wires, assuming both wires have the same resistance. Although theoretically acceptable, the same $R_{\text{wire}}$ implies that both wires are of the exact same length and made with the exact same material. Such an assumption can’t be guaranteed in critical temperature-sensing applications. For this reason, RTDs feature 3-wire, and 4-wire configurations to help reduce the measurement error contributed by lead wires.

**Figure 3** shows a typical 3-wire constant-current circuit while **Figure 4** shows a constant-voltage excitation circuit. In both cases, the ADC samples a resistance of $\text{RTD}+R_{\text{wire}}$ where $R_{\text{wire}}$ is the resistance of the return lead wire. The system eliminates $R_{\text{wire}}$ because the ADC inputs are typically high impedance and virtually no current flows through $R_{\text{wire}}$. Therefore, the ADC only measures the voltage across RTD and $R_{\text{wire}}$. Thus, $R_{\text{wire}}$ contributes to measurement error. Compared to 2-wire configuration, however, the error contributed by the lead wires reduces by roughly 50%.

![Figure 3](image)

**Figure 3.** Adding a third wire in 3-wire constant current excitation configuration. Reduces errors cause by removing the resistance from one side of the sensor.
Figure 4. A 3-wire constant voltage excitation configuration.

One method to further improve the measurement accuracy is by adding an analog switch to the circuit. The ADC then measures the voltage (Vx) at the output of the excitation signal and obtains a value for \( R_{WIRE1} \). By assuming \( R_{WIRE1} \) is approximately the same as \( R_{WIRE3} \), the resistance of \( R_{WIRE3} \) may be subtracted out. Referring to Fig. 3, in current excitation configuration, \( R_{WIRE1} \) resistance is

\[
\frac{V_x - V_1}{I_{REF}}
\]

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, use this equation.

\[
I_{REF} = \frac{V_{REF} - V_x}{R_{REF}}
\]

and
\[ R_{RTD} = R_{REF} \times \frac{2 \times V_{ADC \text{ input}} - V_x}{V_{REF} - V_x} \]

This method improves the measurement accuracy, but does require extra hardware and adds complexity to the software.

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 a 4-wire RTD.

![Figure 5](image.png)

**Figure 5.** 4-wire constant current excitation configuration.
Figure 6. 4-wire constant voltage excitation configuration.

For current excitation configuration,

\[ R_{RTD} = \frac{V_{ADC \, input}}{I_{REF}} \]

In this case, no current passes through \( R_{wire2} \) nor \( R_{wire3} \). Therefore, the voltage across \( R_{wire2} + RTD + R_{wire3} \) is the same as the voltage across the RTD. Unfortunately, when using a constant-voltage excitation configuration, because of the voltage divider effect, \( R_{wire1} \) and \( R_{wire4} \) will still create error in the RTD measurement, unless the ADC system has the ability to measure the voltage at the excitation voltage output (Vx). If the voltage at Vx is known, then the reference current can be calculated by:

\[ I_{REF} = \frac{V_{REF} - V_{x}}{R_{REF}} \]

where \( R_{REF} \) is 3.32 k in this case. Similarly,
\[ R_{RTD} = \frac{V_{ADC \text{ input}}}{I_{REF}} \]

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 (\(R_{\text{WIRE}}\) and \(R_{\text{WIRE}}\) 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.

**Heating errors and temperature conversion**

**Heating Error**

Although a RTD is a sensor, it is also a resistor. When current passes through a resistor, it dissipates power. The dissipated power heats up the resistor. This self-heating effect creates another measurement error. 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

\[ \Delta T = (I_{\text{REF}}^2 \times R_{\text{RTD}}) \times F \]

where \(F\) is the self-heating factor of the 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, \(R\) equals to 100 Ω. If the \(I_{\text{REF}}\) is set to 10 mA, the self-heating error becomes

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

Depending on the application, this error may or may not be acceptable. For high-accuracy measurements, lowering the excitation current reduces the self-heating error. For example, if \(I_{\text{REF}}\) is 1 mA, 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, which requires amplifying the RTD signal so that the ADC may extract more discrete signal levels. An alternative would be to use a higher resolution ADC.

Up to this point, all the formulas discussed involve with either \(I_{\text{REF}}\) or \(V_{\text{REF}}\). In many applications, \(I_{\text{REF}}\) or \(V_{\text{REF}}\) are stable. But, what if these excitation signals aren't? Instability may result from short term or long-term drift. Clearly, if the excitation signals drift from their expected levels, they will result in errors in all of the above calculations. Therefore, periodic calibrations are required. Of course, you could use a super stable voltage reference with ultra low temperature drift and long-term drift. Such devices, however, are often expensive. 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, \(R_{\text{RTD}}\) will be a function of \(R_{\text{REF}}\) instead of \(V_{\text{REF}}\) or \(I_{\text{REF}}\). 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, respectively.
Figure 7. This circuit uses a current-excitation configuration for ratiometric measurement.
Figure 8. This circuit uses a voltage excitation configuration for ratiometric measurement.

The general ADC conversion formula is:

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

where \( V_{IN} \) is the ADC input voltage, \( V_{REF} \) is the reference voltage (REFP-REFN), \( CODE \) is the ADC code, and \( N \) is the 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,
Substituting $V_{IN}$ into the ADC conversion formula yields,

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

Substituting $V_{REF}$ into the formula gives,

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

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, you must pick one with low temperature and low long-term drift.

**Resistance-to-temperature Conversion**

No matter how well the circuit measures the resistance of the RTD, all efforts are wasted if you don’t have a good method to accurately convert RTD resistance to temperature. One common method is to use a lookup table. If, however, the resolution requirement is high and the measuring temperature range is wide, the lookup table would be huge. Another method is to calculate the temperature.

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

$$R(t) = R_0 \times (1 + A \times t + B \times t^2 + (t - 100) \times C \times t^3)$$

- $R(t)$ is the RTD resistance
- $t$ is the temperature
- $R_0$ is the 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 \( t < 0^\circ C \) is:

\[
t = -1.6030 \times 10^{-13} \times r^6 + 2.0936 \times 10^{-10} \times r^5 - 3.6239 \times 10^{-8} \times r^4 - 4.2504 \times 10^{-6} \times r^3 + 2.5646 \times 10^{-3} \times r^2 + 2.2233 \times r - 2.4204 \times 10^2
\]

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.

RTD circuit

Implementing an RTD circuit

A reference design board such as that in Figure 9 implements the 4-wire ratiometric configuration and uses polynomial approximation to convert resistance to temperature. You can also modify design files and firmware as needed. Because the board contains an ADC, you can use it for industrial applications that use voltage, current, or thermocouple measurements. Measurement temperature ranges from \(-40^\circ C\) to \(150^\circ C\).

Figure 9. A universal-input reference design can measure voltage, current, and resistance. It can convert RTD and thermocouple readings into temperature units.
Figure 10 shows the temperature error measured by the MAXREFDES67# (Figure 9) 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. RTD probe (Omega P-M-1/10-1/4-6-0-G-3) connected to the board was placed in the Fluke 7341 calibration bath and calibrated at 20°C.

Figure 10. Error vs temperature measurements performed 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 parameter in industry. Precision system design, using techniques such as the ratiometric method and polynomial approximation, make for very accurate measurement systems. Not all industrial temperature-measurement applications need such accuracy, but it's there if you need it for say calibration or reference temperature systems.

Also See
- Designing with temperature sensors, part three: RTDs
- ADC Requirements for RTD Temperature Measurement Systems