High-accuracy temperature measurements call for PRTDs and precision delta-sigma ADCs

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Advanced industrial and medical applications require temperature measurements with accuracies of ±1 to ±0.1°C or better. You must perform this measurement with reasonable cost, over a wide range of temperature, and often with low power consumption. These applications commonly operate in temperature ranges of −200 to +1750°C and generally require the use of thermocouples and PRTDs (platinum resistance temperature detectors).

When absolute accuracy and repeatability are critical over temperature ranges of −200 to +800°C, PRTDs are the best choices for precision industrial and medical applications. Platinum is stable, and corrosion and oxidation do not affect it. Nickel, copper, and other metals also can be used for RTDs, but those materials are less popular because they are less stable and repeatable than platinum.

Modern PRTD standards, such as the IEC (International Electrotechnical Commission) 60751 and the ASTM (American Society of Testing and Materials) 1137, allow substantial interchangeability of sensors among systems based on their specified tolerance and temperature coefficients. These standards make it easy to replace a sensor with one from the same or a different manufacturer and ensure rated performance with minimal redesign or recalibration of the system.

Three common PRTDs are the PT100, PT500, and PT1000, which exhibit resistance values of 100, 500, and 1000Ω, respectively, at 0°C. Higher-resistance devices, such as the PT10000, are available at a slightly higher cost. PT100s were more popular historically, but today the trend is toward higher-resistance values that provide higher sensitivity and resolution at little or no extra cost. Typical of these is the PT1000, whose 0°C resistance is 1 kΩ.

Manufacturers such as Vishay Intertechnology and Jumo now offer PRTDs in the standard SMD (surface-mount-device) sizes, with typical prices in the low-single-digit-dollar range, depending on the value, size, and tolerance. Such devices substantially reduce sensor cost and provide designers with the flexibility to place PRTDs on any type of PCB (printed-circuit board). The following example includes Vishay Beyschlag’s popular and cost-effective, 1000Ω PTS1206 (Reference 1).
A traditional method for PRTD measurement is current-source excitation (Figure 1). For measurements at a distance and with dissimilar lead wires, the four-wire Kelvin-connection approach of Figure 1a gives the most accurate results by separating the current-carrying wires from the measurement wires. OUT, provides a 200-μA source for the PRTD, and OUT₂ remains floating in this configuration. Most industrial applications in which the RTD element is not close to the ADC require fewer wires because each wire adds to the system cost and reliability concerns.

Figure 1 A PRTD can sense temperature using an interface of four wires (a), three wires (b), or two wires (c), each delivering a differential signal to the ADC.

The three-wire temperature-sensing technique of Figure 1b is more economical and provides accurate readings if the lead wires are similar, so it is the most popular. The two matched current sources of the ADC cancel the IR errors due to lead-wire resistance. OUT₁ and OUT₂ both source a 200-μA current.

The two-wire technique of Figure 1c is the most economical, and is used only when the parasitic wire resistance is known and unchanging. You compensate for IR errors of the wires by computation within a microcontroller or a DSP. The higher resistance in a PT1000 PRTD makes it less sensitive to lead-wire resistance and lowers its self-heating error, so you can connect it directly to the ADC, even in a two-wire configuration. A delta-sigma ADC is suitable for sampling various types of PRTDs. Table 1 lists some important characteristics of this ADC.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MAX11200</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample rate (samples/sec)</td>
<td>10 to 120</td>
<td>Variable oversampling rate can be optimized for low noise and for −150-dB line-noise rejection at 50 or 60 Hz</td>
</tr>
<tr>
<td>Channels</td>
<td>One</td>
<td>GPIOs allow external multiplexer control for multichannel measurements</td>
</tr>
<tr>
<td>Maximum integral nonlinearity (ppm)</td>
<td>±10</td>
<td>Provides good measurement linearity</td>
</tr>
<tr>
<td>Offset error (μV)</td>
<td>±1</td>
<td>Provides almost zero offset measurements</td>
</tr>
<tr>
<td>Noise-free resolution</td>
<td>19 at 120, 19.5 at 60, 21 at 10</td>
<td>High dynamic range with low power</td>
</tr>
<tr>
<td>(bits at samples/sec)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{DD}$ (V)</td>
<td>Analog $V_{DD}$ (2.7 to 3.6) Digital $V_{DD}$ (1.7 to 3.6)</td>
<td>Analog and digital $V_{DD}$ ranges cover the industry's popular power-supply ranges</td>
</tr>
<tr>
<td>Maximum $I_{CC}$ (μA)</td>
<td>300</td>
<td>High resolution per unit power for portable-system applications</td>
</tr>
<tr>
<td>GPIOs</td>
<td>Yes</td>
<td>Allows external device control, including local multiplexer control</td>
</tr>
<tr>
<td>Input range</td>
<td>0 to $V_{DD}$, $+V_{DD}$</td>
<td>Input ranges are wide</td>
</tr>
<tr>
<td>Package</td>
<td>16-pin QSOP, 10-pin 18-mm^2 µMAX</td>
<td>10-pin µMAX works in space-constrained designs</td>
</tr>
</tbody>
</table>
As an alternative to current excitation, you can excite the PRTD with a precision voltage source. Voltage excitation is more desirable for higher-resistance PRTDs, and the same voltage reference that biases the ADC can be used to bias the PRTD. You can connect a PRTD directly to the ADC, with the ADC’s reference providing PRTD bias current through one precision resistor (Figure 2). The ADC measures temperature.

If the lead-wire resistances are orders of magnitude lower than the current-limiting resistor, $R_A$, and the PRTD resistance at $t^\circ C$, $R_T$, you can calculate the voltage across the sensor, as the following equation shows:

$$V_{RTD} = V_{REF} \times \left( \frac{R_T}{R_A + R_T} \right),$$

where $V_{REF}$ is the ADC’s reference voltage. The following equation provides another expression for the sensor voltage:

$$V_{RTD} = V_{REF} \times \left( \frac{A_{ADC}}{FS} \right),$$

where $A_{ADC}$ is the ADC output code and $FS$ is the ADC full-scale code—that is, $2^{23} - 1$ for the IC in a single-ended configuration. Combining the two equations lets you solve for $R_T$:

$$R_T = R_A \times \left( \frac{A_{ADC}}{FS - A_{ADC}} \right).$$

This equation makes clear that $R_A$ must meet certain precision requirements that the $R_T$ specification dictates.

### PRTD selection and error analysis

Lead-wire resistance can introduce errors. Because the PRTD is a resistive sensor, connecting copper extension wires between it and the control instrument introduces resistance and adds error (Figure 3). To estimate the errors in a two-wire circuit, multiply the total length of the extension leads by the resistance per foot for AWG copper wire (Table 2). For example, assume that you want to connect two 3-foot lengths of AWG #22 wire to a PRTD. You can solve for the lead-wire resistance using the following equation:

$$R_W = 2 \times (3 \text{ FEET}) \times (0.0161 \Omega/\text{FEET}) = 0.1 \Omega,$$

where $R_W$ is the wire’s resistance. For a PT100 in a 1206 package with 100Ω nominal resistance, the average sensitivity is 0.385Ω/°C. You can now calculate the wire error:
where $T_{\text{WER}}$ is the error in temperature reading due to the lead wires, which equals $R_w/S$, and $S$ is the average PRTD sensitivity. For a PT1000 in a 1206 package with 1000Ω nominal resistance, the average sensitivity is 3.85Ω/°C. You can now calculate the wire error:

$$T_{\text{WER}} = \frac{R_w}{3.85} = 0.26^\circ \text{C}.$$  

According to the IEC 60751 standard, a $T_{\text{WER}}$ of 0.026°C for the PT1000 is one order of magnitude less than the Class F0.3 tolerance of ±0.3°C, meaning that you can use a 3-foot, two-wire configuration directly with the PT1000 without any method of wire compensation. A $T_{\text{WER}}$ of 0.26°C for the PT100, however, is comparable with the ±0.3°C tolerance and therefore represents an unacceptable level of error for most precision applications. This example demonstrates the advantage of higher-resistance PRTDs in a two-wire circuit.

### Error due to PRTD self-heating

Another source of error for PRTDs is the self-heating of the RTD element as the excitation current flows through it. Excitation current flowing through the RTD resistance produces the voltage that you need to measure. This current should be as high as practical to ensure that the output voltage remains higher than the ADC’s voltage-noise level. At the same time, the excitation current generates a power loss that warms the temperature sensor, thereby increasing the RTD resistance above the level it would otherwise assume due to the temperature you are measuring. You can calculate this thermal error due to RTD power dissipation from the package’s thermal resistance, which you can obtain from the manufacturer’s data sheet. The thermal error due to self-heating is a function of the current, as the following equation shows:

$$T_{\text{TERR}} = I_{\text{EXT}}^2 \times R_T \times K_{\text{TPACK}},$$

where $T_{\text{TERR}}$ is the thermal error due to self-heating in degrees Celsius, $I_{\text{EXT}}$ is the excitation current through the resistive sensing element, $R_T$ is the PRTD resistance at the current temperature $T_c$ in degrees Celsius, and $K_{\text{TPACK}}$ is the selfheating error coefficient: 0.7°C/mW.

For a circuit such as the one in Figure 2, you determine an optimal value of current-limiting resistor $R_A$ using the above equation for $T_{\text{TERR}}$ plus a reference voltage you use in the measurement system—3V, in this case. Table 3 lists $R_A$ values for the 100Ω PTS1206 and the 1000Ω PTS1206. Using an $R_A$ of 8.2 kΩ for the 100Ω PTS1206 and 27 kΩ for the 1000Ω PTS1206, the maximum thermal error ranges from 0.025 to 0.029°C, an order of magnitude less than the Class F0.3 tolerance of ±0.3°C. It is evident that the average excitation currents are stable and predictable over the temperature ranges in Table 3.

Another conclusion that you can draw from Table 3 is that the maximum excitation currents dramatically differ from those of the 100 and 1000Ω $R_T$ models. The excitation currents for the 1000 and 100Ω units are 108 and 362.4 μA, respectively. Thus, 1000Ω is preferable for low-power portable instrumentation. Its excitation current is less than one-third that of the 100Ω unit. $R_A$
resistors should be metal-film types with ±0.1% or better tolerances, at least 0.25W power ratings, and low temperature coefficients. To ensure that the resistors deliver the desired characteristics, you should acquire them from a reputable source such as Panasonic, Rohm, or Vishay.

**Linearity error of PRTD**

PRTDs are nearly linear devices. Depending on the temperature range and other criteria, you can make a linear approximation by calculating the PRTD-resistance change over a temperature range of −20 to +100°C, as the following equation shows:

\[ R(t) = R(0)(1 + T \times \alpha) \]

where \( R(t) \) is the PRTD resistance at \( t^\circ C \), \( R(0) \) is the PRTD resistance at 0°C, \( T \) is the PRTD temperature in degrees Celsius, and the constant \( \alpha \) is 0.00385Ω/Ω/°C, according to IEC 60751. The constant \( \alpha \) is a mean-temperature coefficient between 0 and 100°C. Using this equation, you can make a set of PRTD calculations (Table 4).

<table>
<thead>
<tr>
<th>Table 4: PRTD calculations for −20 to +100°C</th>
</tr>
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<tbody>
<tr>
<td>( \alpha ) (Ω/Ω/°C)</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>0.0035</td>
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<td>0.0035</td>
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</table>

This table’s \( R_{PRTD} \) 1000 Linear column represents a linear approximation, according to the previous equation. The \( R_{PRTD} \) 1000 Nominal column lists the nominal PTS1206-1000 values according to manufacturing specification EN 60751:2008. The values in the Linearization Error column for the stated temperature range are all within the range of ±0.15%, which is better than the Class F0.3 tolerance of ±0.3°C for PTS1206.

Practical measurements per Table 4 using a delta-sigma ADC confirm that digital representations of the temperature-reading errors remain within the limits for Class F0.3 tolerance. For wider range and higher accuracy, the temperature-measurement PRTD standard EN 60751:2008 defines the behavior of platinum resistance versus temperature by the nonlinear mathematical Callendar-Van Dusen Equation.

For temperatures of 0 to 859°C, the linearization equation requires that you use two coefficients:

\[ R(t) = R(0)(1 + A \times t + B \times t^2) \]

For temperatures of −200 to 0°C, you add terms to that equation, which yields the following equation:

\[ R(t) = R(0)[1 + A \times t + B \times t^2 + (t - 100)C \times t^3] \]
where R(t) is the PRTD resistance at t°C, R(0) is the PRTD resistance at 0°C, and t is the PRTD temperature in degrees Celsius. You derive the A, B, and C calibration coefficients from measurements by RTD manufacturers, as specified by IEC 60751. A is $3.9083 \times 10^{-3}$°C$^{-1}$, B is $-5.775 \times 10^{-7}$°C$^{-2}$, and C is $-4.183 \times 10^{-12}$°C$^{-4}$.

The first equation for R(t) shows that nonlinearity errors increase for temperatures outside the band of 0 to 200°C (Figure 4). Using the second equation for R(t), in the first column of this page, reduces the error to negligible levels, except at low temperatures.

You can enlarge a portion of Figure 4 over a narrower temperature range (Figure 5). The errors within a smaller range of −20 to +100°C, when using the first equation for R(t) are within ±0.15%. These errors become nearly negligible when you use the second equation for R(t). Precision measurements over a wider temperature range of −200 to +800°C require the implementation of these linearization algorithms using these two equations.

![Figure 4 and Figure 5](image)

**Delta-sigma ADC measurement resolution**

These measurements require a low-power, 24-bit delta-sigma ADC with wide dynamic range and a high number of noise-free bits. Using such an ADC, you can calculate the resolution in temperature for the Figure 2 circuit using the following two equations:

\[
R_{\text{TLSB}} = \frac{V_{\text{REF}}(T_{\text{CMAX}} - T_{\text{CMIN}})}{FS(V_{\text{TRMAX}} - V_{\text{RTMIN}})},
\]

\[
R_{\text{TNFR}} = \frac{V_{\text{REF}}(T_{\text{CMAX}} - T_{\text{CMIN}})}{NFR(V_{\text{TRMAX}} - V_{\text{RTMIN}})},
\]

where $R_{\text{TLSB}}$ is the PRTD resolution at 1 LSB (least-significant bit), $R_{\text{TNFR}}$ is the PRTD’s NFR (noise-free resolution), $V_{\text{REF}}$ is the reference voltage, $T_{\text{CMAX}}$ is the maximum measurement temperature, $T_{\text{CMIN}}$ is the minimum measurement temperature, $V_{\text{TRMAX}}$ is the PRTD’s voltage drop at the maximum measurement temperature, $V_{\text{RTMIN}}$ is the PRTD’s voltage drop at the minimum measurement temperature, FS is the ADC’s full-scale code for the IC in a single-ended configuration, and NFR is the ADC’s noise-free resolution for the IC in the single-ended configuration.
You can tabulate the measurement resolution from the previous **equations** for $R(t)$ for the 100 and 1000Ω PTS1206 (**Table 5**). The **table** provides the calculated values of degrees Celsius/LSB error and degrees Celsius/NFR error for a temperature range of $-55$ to $+155^\circ$C. NFR represents the minimum temperature value that the ADC can differentiate. A 1000Ω $R_{\text{NFR}}$ of 0.007°C/NFR easily allows a temperature resolution of better than 0.05°C within the given range. This resolution is sufficient for most industrial and medical applications.

![Table 5: Temperature-Measurement Resolution](image1.png)

Another way to consider the ADC requirement for this application is to look at the expected voltage levels for different temperature points (**Table 6**). The last two rows show the range of differential voltage output for 100 and 1000Ω PRTD devices, respectively, and the notes below calculate how many noise-free codes the MAX11200 ADC produces. Note that the total range of output signal in PRTD applications is approximately 82 mV. The IC has input-referred noise of 570 nV at 10 samples/sec, which gives the application an NFR of 0.007°C over a 210°C span.

![Table 6: Temperature-Measurement Range for ADC in Figure 6](image2.png)

You can use a general-purpose output pin on the ADC to control the relay calibration switch. This action selects either the fixed $R_{\text{CAL}}$ resistor or the PRTD (**Figure 6**). This versatility improves system precision and reduces the required calculations to those for the initial values of $R_a$ and $R_t$. 
In recent years, the decline in PRTD price and package size has made these devices desirable for a variety of precision temperature-sensing applications. Such applications require a low-noise ADC if you want to directly connect the ADC and surface-mount PRTD. Together, the PRTD and a delta-sigma ADC provide a temperature-measurement system that’s ideal for portable sensing applications. Less wiring and lower thermal errors reduce the system complexity and cost, allowing you to implement a two-wire interface for distances as long as 2m.

References