

# SELECTING THE RIGHT SENSOR FOR TEMPERATURE MEASUREMENT

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**Abstract:** Temperature monitoring is central to the majority of data acquisition systems. Several factors must be considered when selecting the type of sensor to be used in a specific application: temperature range, accuracy, response time, stability, linearity, and sensitivity. Another important factor to consider is price, which varies with the accuracy rate and the mounting style of the device.

This paper presents the advantage and the disadvantage of the three basic types of contact temperature sensors-thermocouples, resistance-temperature detector (RTD), and thermistors-in temperature systems measurement. Also, it is presented the temperature signal conditioners that are developed to maintain the integrity of the sensor's output. Regardless of the types of sensors or transducers you are using, the proper signal conditioning equipment can improve the quality and performance of your system measurement.

**Keywords:** *thermocouple, resistance-temperature detector, thermistors, signal conditioning*

## 1.INTRODUCTION

Temperature sensors generate output signals in one of two ways: change in output voltage or change in resistance of the sensor's electrical circuit. Thermocouples and IR devices generate voltage output signals. RTDs and thermistors output signals via a change in resistance.

There are two methods of temperature sensing: contact and noncontact. Contact sensing brings the sensor in physical contact with the substance or object being measured; you can use this approach with solids, liquids, or gases. Noncontact sensing reads temperature by intercepting a portion of the electromagnetic energy emitted by an object or substance and detecting its intensity; you can apply this technology to solids and liquids.

If the object or medium being heated moves, has an irregular shape, or would be contaminated by contact with a sensor, then you should use IR sensing that intercepts heat energy emitted by an object and relates it to the product's known temperature

Temperature sensor signals are often incompatible with data acquisition hardware. To overcome this incompatibility, the sensor signal must be conditioned. The type of signal conditioning required depends on the sensor you are using. For example, a signal may have a small amplitude and require amplification, or it may

contain unwanted frequency components and require filtering. Common ways to condition signals include:

- Amplification
- Filtering
- Electrical isolation
- Multiplexing
- Excitation source

One example of a signal conditioning system for PC-based DAQ is Signal Conditioning eXtensions for Instrumentation (SCXI). SCXI is an instrumentation front end that connects either to a plug-in DAQ board, to a long-distance RS-232 or RS-485 network, or directly to the parallel port of the PC (Figure 1). SCXI modules condition signals from a variety of signal sources, such as thermistors, RTDs, thermocouples, and strain gauges. The conditioned signals are passed to a plug-in DAQ board that acquires the signals directly into PC memory. Alternatively, the signals can be digitized locally in the SCXI unit and communicated to the PC via the parallel port or serial communications.

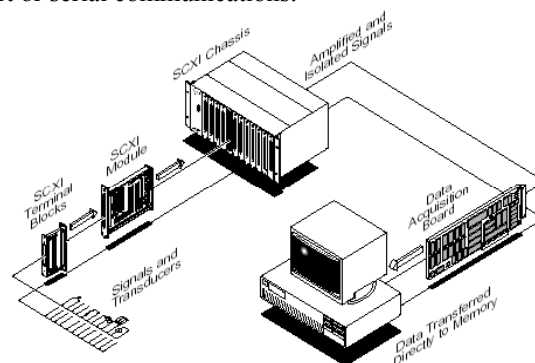


Figure 1. The SCXI Signal Conditioning Front-End System for Plug-In DAQ Boards

## 2.MEASURING TEMPERATURE WITH THERMOCOUPLES

These sensors have the widest operating range and are best suited for high temperatures. Thermocouples of noble metal alloys can be used for monitoring and controlling temperatures as high as 3100°F. These devices are also best for applications requiring miniature sensor designs. The inherent simplicity of the devices enables them to withstand extreme shock and vibration. Thermocouples can be configured in small sizes to offer near-immediate response to temperature changes.

A thermocouple is created whenever two dissimilar metals touch and the contact point produces a small open-circuit voltage as a function of temperature. This thermoelectric voltage is known as the *Seebeck voltage*,

named after Thomas Seebeck, who discovered it in 1821. The voltage is nonlinear with respect to temperature. However, for small changes in temperature, the voltage is approximately linear, or:

$$\Delta V \approx S \Delta T \quad (1)$$

where  $\Delta V$  is the change in voltage,  $S$  is the Seebeck coefficient, and  $\Delta T$  is the change in temperature.

To measure a thermocouple Seebeck voltage, you cannot simply connect the thermocouple to a voltmeter or other measurement system, because connecting the thermocouple wires to the measurement system creates additional thermoelectric circuits. Thermocouples require some form of temperature reference to compensate for these unwanted parasitic thermocouples. There are two techniques for implementing cold-junction compensation—hardware compensation and software compensation. Both techniques require that the temperature at the reference junction be sensed with a direct-reading sensor. A direct-reading sensor has an output that depends only on the temperature of the measurement point. Semiconductor sensors, thermistors, or RTDs are commonly used to measure the reference-junction temperature.

Thermocouple output voltages are highly nonlinear. The Seebeck coefficient can vary by a factor of three or more over the operating temperature range of some thermocouples. For this reason, you must either approximate the thermocouple voltage-versus-temperature curve using polynomials, or use a look-up table. The polynomials are in the following form:

$$T = a_0 + a_1 v + a_2 v^2 + \dots + a_n v^n \quad (2)$$

where  $v$  is the thermocouple voltage in *volts*,  $T$  is the temperature in degrees Celsius, and  $a_0$  through  $a_n$  are coefficients that are specific to each thermocouple type. Thermocouples are commonly used to monitor temperature with PC-based DAQ systems.

### 2.1. Signal Conditioning for Thermocouples

Signal conditioning for thermocouples should include the following functionality:

*-Improve the noise performance*—Low-level thermocouple signals are very susceptible to noise corruption. Therefore, it is very important that the signal conditioning and DAQ hardware are well shielded with very low-noise performance. In addition, the cable connecting the signal conditioning to the plug-in DAQ board uses shielded, twisted-pair cable for the best possible noise performance.

You can also improve the noise performance of your system by amplifying the low-level thermocouple voltages at as short a distance as possible from the thermocouple. Thermocouple wire can act like an antenna and pick up unwanted noise from the environment. Because thermocouple voltages are extremely small, typical electrical noise levels can seriously corrupt the measurement.

*-High Amplification*—Because thermocouple output voltage levels are very low, you should use as large a gain as possible for the best resolution and noise performance. Amplification, together with the input range of your analog-to-digital converter (ADC), determines the usable input range of your system.

Therefore, you should carefully select your amplification so that the thermocouple signal does not exceed this range at elevated temperatures.

Table 1 lists the voltage ranges from several standard thermocouple types; you can use this table as a guide for determining the best gain and input range settings to use.

*-Input Filtering*—To further reduce noise, the signal conditioning must include a low-pass resistor-capacitor (RC) filter for each input channel. These filters are useful for removing the 60 Hz power line noise that is prevalent in most laboratory and plant settings. to use.

*-Temperature sensor for cold-junction compensation*—Thermocouple measurements require sensing of the cold-junction, or reference, temperature at the point where the thermocouple wire is connected to the measurement system. Therefore, signal connection accessories should include an accurate cold-junction sensor, and should be designed to minimize any temperature gradients between the cold-junction sensor and thermocouple wire connections.

### 3. MEASURING TEMPERATURE WITH RTD

A resistance-temperature detector (RTD) is a temperature sensing device whose resistance increases with temperature. RTDs are known for their excellent accuracy over a wide temperature range. The RTD can work in a wide temperature range—some platinum sensors handle temperatures from  $-328^\circ\text{F}$  to  $1202^\circ\text{F}$ . RTDs are also extremely stable devices. RTDs are most commonly made from platinum, nickel, or copper. Copper and nickel versions operate at lower temperature ranges and are less expensive than platinum. Platinum is the most versatile material because of its wide temperature range ( $-200^\circ\text{C}$  to  $850^\circ\text{C}$ ), excellent repeatability, stability, and resistance to chemicals and corrosion.

Because an RTD is a passive resistive device, you must pass a current through the device to produce a measurable voltage. This current causes the RTD to internally heat, which appears as an error. You can minimize self heating by using the smallest possible excitation current.

Compared to other temperature devices, the output of an RTD is relatively linear with respect to temperature. The temperature coefficient, called alpha ( $\alpha$ ), differs between RTD curves.

$$\alpha (\Omega/\Omega/^\circ\text{C}) = (R_{100} - R_0) / (R_0 * 100^\circ\text{C}) \quad (3)$$

where  $R_{100}$  is the resistance of the RTD at  $100^\circ\text{C}$ , and  $R_0$  is the resistance of the RTD at  $0^\circ\text{C}$ .

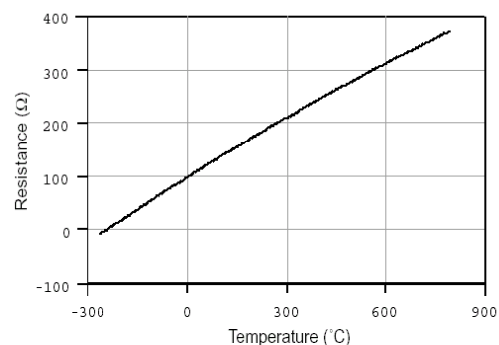


Figure 2. Resistance-Temperature Curve for a 100 Ω Platinum RTD,  $\alpha = 0.00385$

Table1

| Thermocouple Type | Conductor    |            | Temperature Range (°C) | Voltage Range (mV) | Seebeck Coefficient (μV/°C) |
|-------------------|--------------|------------|------------------------|--------------------|-----------------------------|
|                   | Positive     | Negative   |                        |                    |                             |
| E                 | Chromel      | Constantan | -270° to 1000°         | -9,835 to 76,358   | 58,70 at 0°C                |
| J                 | Iron         | Constantan | -270° to 1200°         | -8,096 to 69,536   | 50,37 at 0°C                |
| K                 | Chromel      | Alumel     | -270° to 1372°         | -6,548 to 54,874   | 39,48 at 0°C                |
| T                 | Copper       | Constantan | -270° to 400°          | -6,258 to 20,869   | 38,74 at 0°C                |
| S                 | Platinum-10% |            |                        |                    |                             |
|                   | Rhodium      | Platinum   | -50° to 1768°          | -0,236 to 18,698   | 10,19 at 600°C              |
| R                 | Platinum-13% |            |                        |                    |                             |
|                   | Rhodium      | Platinum   | -50° to 1768°          | -0,226 to 21,108   | 11,35 at 600°C              |

For example, a 100 Ω platinum RTD with  $\alpha = 0.003911$  will measure 139.11 Ω at 100° C. Figure 2 displays a typical resistance-temperature curve for a 100Ω platinum RTD.

Because the resistance to be measured is small, then the resistance in the leads to the device to be measured can be a significant source of error. To deal with this problem connection arrangements are available which allow the lead resistance to be measured and compensated for.

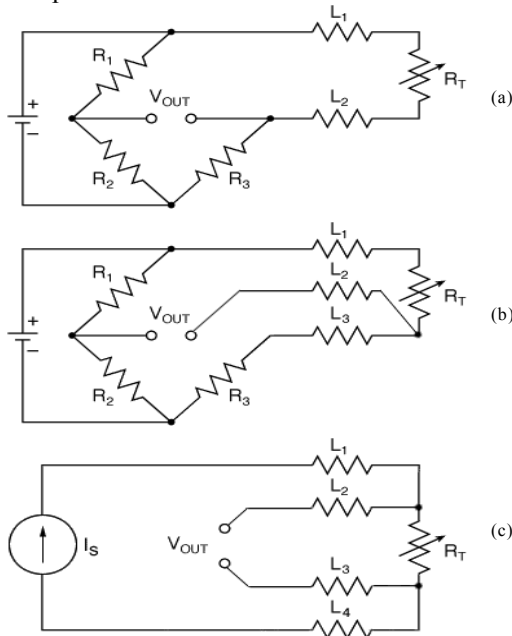


Figure 3. 2-Wire (a), 3-Wire (b) and 4-Wire (c) RTD Measurement

#### 4.MEASURING TEMPERATURE WITH THERMISTORS

Figure 3 shows a circuit where the thermistor is excited using a voltage source  $V_{REF}$ . The thermistor has a nominal impedance of 10kΩ at 25°C.

The circuit shown uses two resistors  $R_S$  and  $R_1$  in series with the thermistor. Resistor  $R_S$  is used to limit the thermistor power dissipation. Resistor  $R_1$  is used to linearize the output of the thermistor. The output voltage across  $R_1$  varies from 33mV at -50°C to +2.329V at +100°C.

Thermistors are non-linear devices and require linearization techniques to obtain accurate measurements. In general applications, linearization techniques can be implemented in one of two ways. Linearization can be performed in the digital domain using a look up table containing the manufacturer's

device characteristics to linearize the thermistor output. Linearization can also be performed in the analog domain with the addition of series or parallel resistors which forces the voltage or the resistance of a simple fixed-resistor-thermistor to have zero error along a linear temperature scale at three equidistant points.

Figure 3 uses a resistor  $R_1$  in series with the thermistor to linearize the output of the thermistor. This approach forces the voltage across  $R_1$  to have zero error along a linear temperature scale at three points across the required temperature range. The maximum error is determined by the temperature range of the application.

Using this method, the nonlinear negative temperature characteristics of a thermistor are converted to a linear relationship with peak errors of 12%.

In this application the temperature range is taken to be -50°C to +100°C. The errors are zero at -50°C, 25°C and +100°C and the errors elsewhere are distributed in an S-shaped curve.

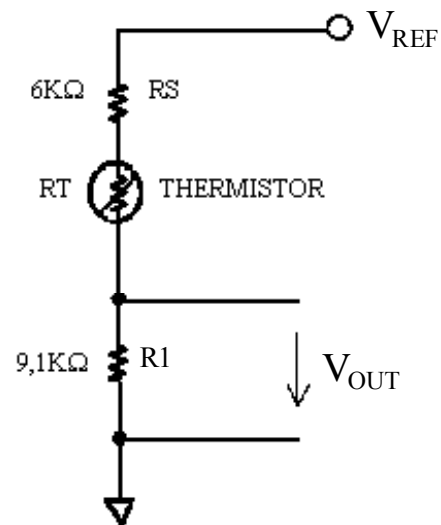


Figure 3. Voltage excitation of the thermistor and linearizing the output in the analog domain.

If the temperature range is reduced, the errors become appreciably smaller 0.01°C over a 10°C range, 0.05°C over a 30°C range, and 2.0°C over a 60°C range.

$$R_1 = \frac{[RT_{MID} \cdot (RT_{LO} + RT_{HI}) (2RT_{LO} \cdot RT_{HI})]}{[(RT_{LO} + RT_{HI}) - (2RT_{MID})]} \quad (4)$$

where:

$RT_{MID}$  = the thermistor impedance at the middle of the range

$RT_{LO}$  = the thermistor impedance at the low end of the range

$RT_{HI}$  = the thermistor impedance at the high end of the range

Self-heating effects of the thermistor can become significant and degrade the overall system performance. Self-heating effects are more pronounced in still air. If the thermistor is located in moving air, liquids or solids then the self-heating error is much lower. In order to keep the self-heating error within  $0.1^{\circ}\text{C}$  max, the current in the circuit should be limited so as to give a dissipation of  $0.1\text{mW}$  max in the thermistor RT.

In Figure 3 the point of maximum power dissipation and thus self heating effects are worst when the value of RT is equal to  $R_1$ . A series resistor  $R_S$  as shown in Figure 3 will limit the current in the circuit and thus keep the power dissipated in the thermistor to acceptable levels so that self heating effects in the thermistor can be ignored. A value of  $6\text{k}\Omega$  is sufficient to limit the current in the circuit and ensure that the max power dissipated in the thermistor is less than  $0.1\text{mW}$ .

## 5. SIGNAL CONDITIONING SYSTEMS FOR RTD AND THERMISTORS

The use of RTD and thermistors for temperature measurement with a PC-based DAQ system requires some signal conditioning hardware to interface the thermistor to the measurement device, such as a plug-in DAQ board.

Signal conditioning is defined here as any conditioning required to interface the RTD and the thermistor and its output signal to a DAQ board or module. The DAQ board or module performs the actual analog-to-digital (A/D) conversion. Briefly, signal conditioning for RTD and thermistors should include the following functionality:

*-Excitation current or voltage source*-A constant current or voltage converts the sensor resistance into a measurable voltage output. A higher level excitation source will generate a higher-level voltage output, but will also increase the self-heating of the sensor.

*-Signal amplification*-Most signal conditioners include voltage signal amplifiers. Amplification of the sensor voltage yields a high-level voltage signal that is less susceptible to noise corruption and more precisely digitized.

*-Lowpass filtering*-Lowpass filters reject unwanted noise in the sensor signal. The temperature information contained in the sensor voltage is relatively low bandwidth, or slowly changing. The measurement circuit, however, is likely to pick up higher frequency noise from the environment. The most common is 50 or 60 Hz noise from power lines and machinery. Lowpass noise filters are designed to remove this noise by attenuating any signal components with frequencies above some defined bandwidth.

*-Isolation*-Signal conditioning hardware with isolation serve to electrically isolate the RTD, the thermistor and other sensors from the measurement system. Isolation prevents ground loops, rejects large common-mode voltages, and in general protects the data acquisition system from high voltages.

*-Multiplexing*-A typical plug-in DAQ board has eight to 16 analog input channels. However, you can use external multiplexing systems, included in some signal conditioning systems, to expand the number of input channels that you can connect to a DAQ board. The multiplexing system sequentially switches multiple channels to a single-input channel of the DAQ board.

## 6. CONCLUSION

Temperature measurement and control begin with selecting the suitable sensor.

Temperature measurement systems using thermocouples need to provide a means of measuring the cold junction temperature (often using a platinum resistance device) and an algorithm for linearising the voltage readings to temperature.

The RTD are expensive compared to thermistors and thermocouples, but the total temperature measurement system cost is moderate. Thermocouples measure relative temperatures and therefore require reference junctions and circuits, whereas thermistors and RTDs can measure absolute temperatures in a more direct manner. An RTD system may actually cost less than a thermocouple system because it produces a higher level signal and does not require a reference.

Thermistors are ideally suited for temperature measurement applications that involve limited temperature ranges. Thermistors cost less than either RTDs or thermocouples. And they are well suited to sensing temperature at remote locations because the lead wire resistance is insignificant when compared with that of the thermistor, which is relatively high. These devices exhibit a significant change in resistance in response to small changes in temperature. This makes it possible for thermistors to make high-resolution measurements.

Thermistors are quite small, making them suitable for point-contact sensing. Combining the thermistor with a high-resolution A/D converter allows a highly accurate, high-resolution temperature measurement system.

But thermistors also have disadvantages. For one thing, they require linearization. And because thermistors are semiconductors, they are more likely to lose their calibration at high temperatures than are RTDs or thermocouples.

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