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Application Note 046

Measuring Temperature with RTDs – A Tutorial

Introduction

A resistance-temperature detector (RTD) is a temperature sensing device whose resistance increases with temperature. An RTD consists of a wire coil or deposited film of pure metal. RTDs can be made of different metals and have different resistances, but the most popular RTD is platinum and has a nominal resistance of 100 Ω at 0° C.

RTDs are known for their excellent accuracy over a wide temperature range. Some RTDs have accuracies as high as 0.01 Ω (0.026° C) at 0° C. RTDs are also extremely stable devices. Common industrial RTDs drift less than 0.1° C/year, and some models are stable to within 0.0025° C/year.

RTDs can be difficult to measure because they have relatively low resistance (100 Ω) that changes only slightly with temperature (less than 0.4 Ω/°C). To accurately measure these small changes in resistance, you may need to use special configurations that minimize errors from lead wire resistance.

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. Self heating is typically specified as the amount of power that will
raise the RTD temperature by 1° C, or 1 mW/°C. You can minimize self heating by using the smallest possible excitation current. The amount of self heating also depends heavily on the medium in which the RTD is immersed. An RTD can self heat up to 100 times higher in still air than in moving water.

The Relationship of Resistance and Temperature in RTDs

Compared to other temperature devices, the output of an RTD is relatively linear with respect to temperature. The temperature coefficient, called alpha (α), differs between RTD curves. Although various manufacturers may specify alpha differently, alpha is most commonly defined as the change in RTD resistance from 0 to 100° C, divided by the resistance at 0° C, divided by 100° C:

$$\alpha(\Omega/\Omega/°C) = (R_{100} - R_0)/(R_0 * 100° C)$$

where R_{100} is the resistance of the RTD at 100° C, and R_0 is the resistance of the RTD at 0° C.

For example, a 100 Ω platinum RTD with α = 0.003911 will measure 139.11 Ω at 100° C. Figure 1 displays a typical resistance-temperature curve for a 100 Ω platinum RTD.

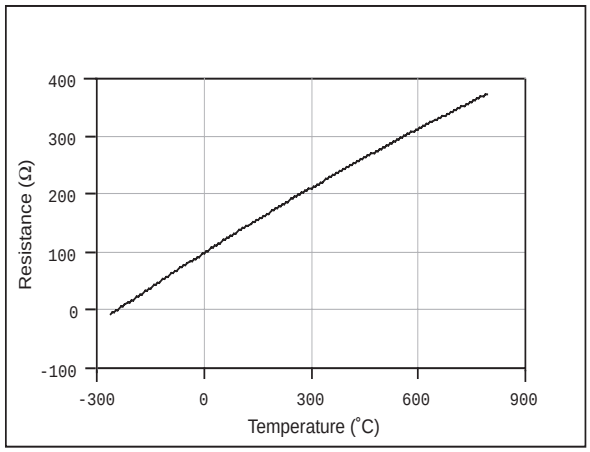


Figure 1. Resistance-Temperature Curve for a 100 Ω Platinum RTD, α = 0.00385

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Although the resistance-temperature curve is relatively linear, accurately converting measured resistance to temperature requires curve fitting. The Callendar-Van Dusen equation is commonly used to approximate the RTD curve:

$$R_t = R_0[1 + At + Bt^2 + C(t - 100)^3]$$

where R_t is the resistance of the RTD at temperature = t, R_0 is the resistance of the RTD at 0° C, A, B, and C are the Callendar-Van Dusen coefficients shown in Table 1, and t is the temperature in ° C. For temperatures above 0° C, the C coefficient equals 0. Therefore, for temperatures above 0° C, this equation reduces to a quadratic. If you pass a known current, I_{EX}, through the RTD and measure the output voltage developed across the RTD, V_0, you can solve for t:

$$t = \frac{2(V_0 - I_{EX}R_0)}{I_{EX}R_0[A + \sqrt{A^2 + 4B(V_0 - I_{EX}R_0)/I_{EX}R_0}]}$$

where V_0 is the measured RTD voltage and I_{EX} is the excitation current.

Most platinum RTD curves follow one of three standardized curves–the DIN 43760 standard (α = 0.00385), the U.S. Industrial or American standard (α = 0.003911), or the International Temperature Scale (ITS-90) that is used with wire-wound RTDs (α = 0.003925). The Callendar-Van Dusen coefficients for each of these three platinum RTD curves are listed in Table 1.

RTD Measurement Circuits

Because the RTD is a resistive device, you must drive a current through the device and monitor the resulting voltage. However, any resistance in the lead wires that connect your measurement system to the RTD will add error to your readings. For example, consider a two-wire RTD element connected to a measurement system that also supplies a constant current source, I_{EX}, to drive the RTD. As shown in Figure 2, the voltage drop across the lead resistance, R_L, adds to the measured voltage.

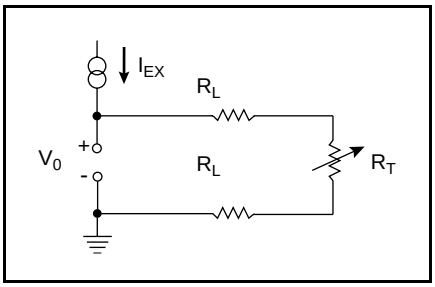


Figure 2. Two-Wire RTD Measurement

For example, a lead resistance of 0.3 Ω in each wire, R_L, adds a 0.6 Ω error to the resistance measurement. For a platinum RTD with α = 0.00385, the resistance equals a 0.6 Ω/(0.385 Ω/°C) = 1.6° C error.

If you are using lead lengths greater than 10 ft, you will probably need to compensate for this lead resistance. The preferred RTD measurement method is to use a four-wire RTD. One pair of wires carries the current through the RTD; the other pair senses the voltage across the RTD. Because only negligible current flows through the sensing wires, the lead resistance error of R_{L2} and R_{L3} is negligible. This configuration is illustrated in Figure 3.

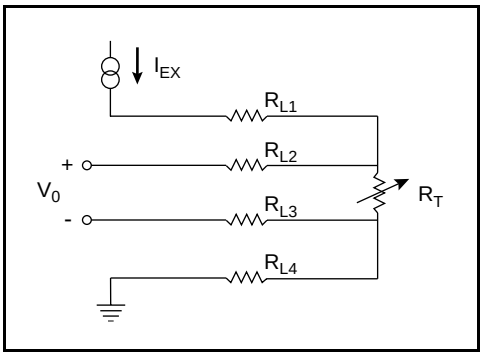


Figure 3. Four-Wire RTD Measurement

Table 1. Callendar-Van Dusen Coefficients Corresponding to Common RTDs

Standard	Temperature Coefficient (α)	A	B	C*
DIN 43760	0.003850	3.9080×10^{-3}	-5.8019×10^{-7}	-4.2735×10^{-12}
American	0.003911	3.9692×10^{-3}	-5.8495×10^{-7}	-4.2325×10^{-12}
ITS-90	0.003926	3.9848×10^{-3}	-5.870×10^{-7}	-4.0000×10^{-12}

* For temperatures below 0° C only; C = 0.0 for temperatures above 0° C.

To reduce costs, you may instead want to use a three-wire RTD. By using the three-wire RTD in a Wheatstone configuration with a current source, as shown in Figure 4a, you can compensate for the lead resistances. Notice that, in this bridge configuration, the effects of R_{L1} and R_{L3} cancel each other out because they are located in opposite arms of the bridge. Lead resistance R_{L2} does not add significant error because little current flows through it. Alternatively, you can use a current excitation source and connect the three-wire RTD as shown in Figure 4b. In this configuration, the resistance of only one lead, R_{L1}, adds error to the measurement.

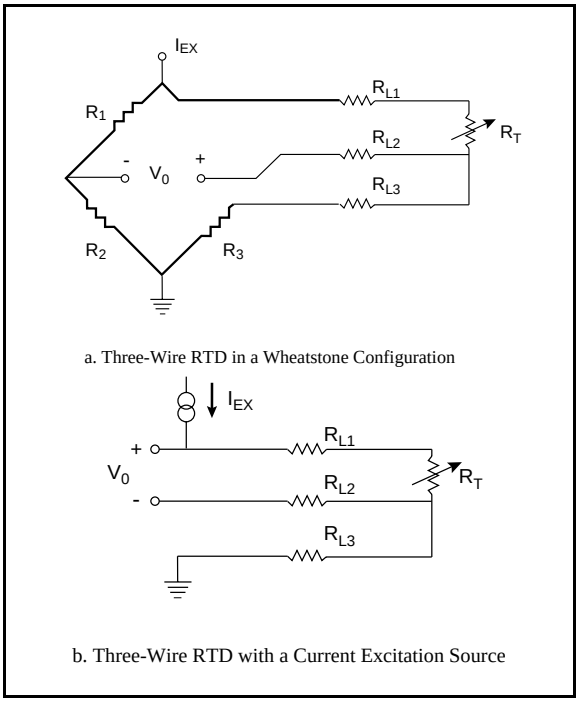


Figure 4. Three-Wire RTD Measurement with a Wheatstone Bridge and a Current Source

RTD Measurements with SCXI

Signal conditioning is generally required to interface an RTD to a measurement device such as a plug-in data acquisition (DAQ) board. Signal conditioning produces current excitation for the RTD, amplifies the output signal, and filters the signal to remove unwanted noise. You can also use signal conditioning to electrically isolate the RTD and the monitored sytem from the DAQ system and the host computer.

Signal Conditioning eXtensions for Instrumentation (SCXI) is a signal conditioning front end you can use with plug-in DAQ boards, or as a complete, external DAQ system. SCXI modules condition signals from a variety of signal sources, such as RTDs, thermistors, and thermocouples, and pass the conditioned signal to the plug-in DAQ board. The plug-in board can then acquire the signals directly into PC memory. Alternatively, you can connect the SCXI system to an RS-232 or RS-485 serial network to a PC for remote data acquisition.

The SCXI product line has a variety of analog and digital signal conditioning modules for various types of signals. The SCXI-1121 and SCXI-1122 are well suited for RTDs.

The SCXI-1121 is an isolated amplifier and multiplexer module with four isolated input channels. Each of the four channels has a jumper-selectable gain amplifier (gains from 1 to 2,000) and a lowpass filter (4 Hz or 10 kHz). The SCXI-1121 also has four channels of isolated voltage or current excitation. You can configure each channel independently to produce a constant 0.15 mA, 0.45 mA, 3.333 V, or 10.0 V source.

The SCXI-1122 is a 16-channel isolated multiplexer module with a programmable amplifier (gains from 0.01 to 2,000) and a single 1.0 mA current excitation source.

Example–Monitoring 16 RTDs with the SCXI-1121

For this example, assume that you want to use 16 100 Ω four-wire RTDs to monitor the efficiency of a production process. You can monitor all 16 RTDs with four SCXI-1121 modules installed in a four-slot SCXI-1000 chassis. The modules and chassis are connected to a plug-in PC DAQ board that acquires the analog signals from all four modules and stores the digitized readings into PC memory.

The plug-in board in this example is the AT-MIO-16F-5, which is a 12-bit, 200 kHz multifunction I/O board for IBM PC AT and compatible computers. The AT-MIO-16F-5 board is used in the example because of its accuracy, high scan rate, and self-calibration capability. You can also use similar multifunction I/O boards for the Macintosh and PS/2 platforms with the SCXI system. The SCXI chassis is connected to the AT-MIO-16F-5 with the SCXI-1345 shielded cable assembly, which is available in lengths up to 10 m. The RTDs are wired into SCXI-1320 terminal blocks, which have convenient screw terminals with strain relief. Figure 5 is a diagram of the system.

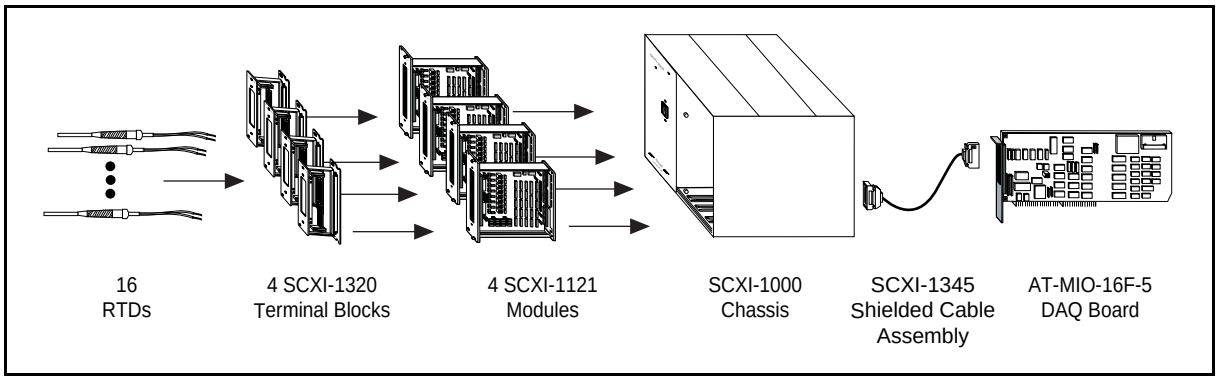


Figure 5. SCXI System for Monitoring 16 RTDs

An IBM PC/XT/AT or compatible computer controls the temperature monitoring system. Therefore, application software choices for controlling the system include National Instruments' LabWindows® for DOS or LabVIEW® for Windows. Alternatively, you can use a general-purpose programming language such as C, BASIC, or Pascal in DOS or Windows and control the DAQ hardware with the NI-DAQ® driver software that is included with all National Instruments plug-in DAQ boards.

Configuring an SCXI System for RTD Measurement

First, configure the SCXI-1121 modules for the RTD measurements. Configuring includes setting the excitation mode, gain, and bandwidth for each input channel of the SCXI-1121. Follow these steps to configure your SCXI-1121 modules:

1. Set the Excitation mode. Because you are using four-wire RTDs, configure each channel for constant current excitation. You can configure the current source for 0.15 mA or 0.45 mA. The lower current setting minimizes the RTD self-heating effect.

2. Set the gain. Determine what gain to apply to your RTD signal. Be careful to choose the gain so that the output of the SCXI-1121 does not exceed the ±5 V input range of the AT-MIO-16F-5, but produces the optimum resolution. For example, suppose you will operate your 100 Ω RTD at a temperature up to 300° C. At this temperature, the RTD resistance increases to about 220 Ω. With a 0.15 mA current source, the voltage output at 300° C will be 220 Ω * 0.15 mA = 33 mV. Setting the gain of the SCXI-1121 to 100 will generate a maximum voltage output of 3.3 V, which is within the ±5 V input range of the plug-in board.

3. Set the bandwidth. The SCXI-1121 has jumper-configurable filters on each channel. You can set each filter for a cutoff frequency of 4 Hz or 10 kHz. The 4 Hz filter is particularly useful for rejecting 60 Hz noise from power lines and lighting.

Table 2 summarizes a typical SCXI-1121 configuration for measuring RTDs.

Table 2. Typical Configuration for an SCXI-1121 Used with RTDs

SCXI-1121 Parameter	Typical Setting for a 100 Ω Four-Wire RTD
Channel gain	100
Bandwidth	4 Hz
Excitation mode	Current
Excitation level	0.15 mA
Bridge completion	Disabled

Note: These settings are configured on a per channel basis.

Connecting the RTDs to the SCXI-1121

Connect the RTDs to the SCXI-1121 module with a SCXI-1320 shielded terminal block. Alternatively, you can use the SCXI-1321 or SCXI-1328 terminal blocks, which have special capabilities for strain gauges and thermocouples, respectively, or the SCXI-1330 connector and shell. Figure 6 shows the wire connections used to correctly wire a four-wire RTD to channel 0 of an SCXI-1320.

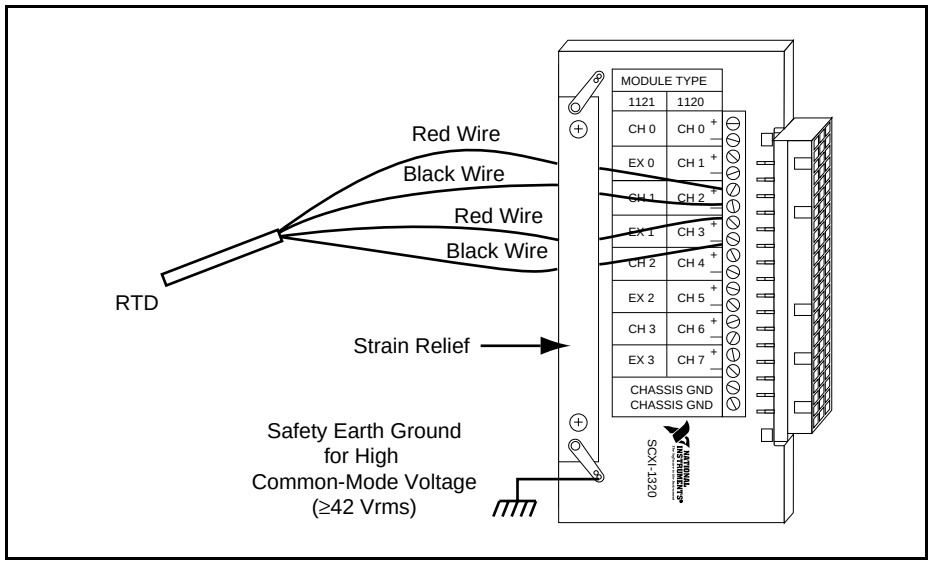


Figure 6. Connecting a Four-Wire Platinum RTD to Channel 1 of the SCXI-1320

Figure 7 contains wiring diagrams for connecting two-wire, three-wire, and four-wire RTDs to the SCXI-1121 module.

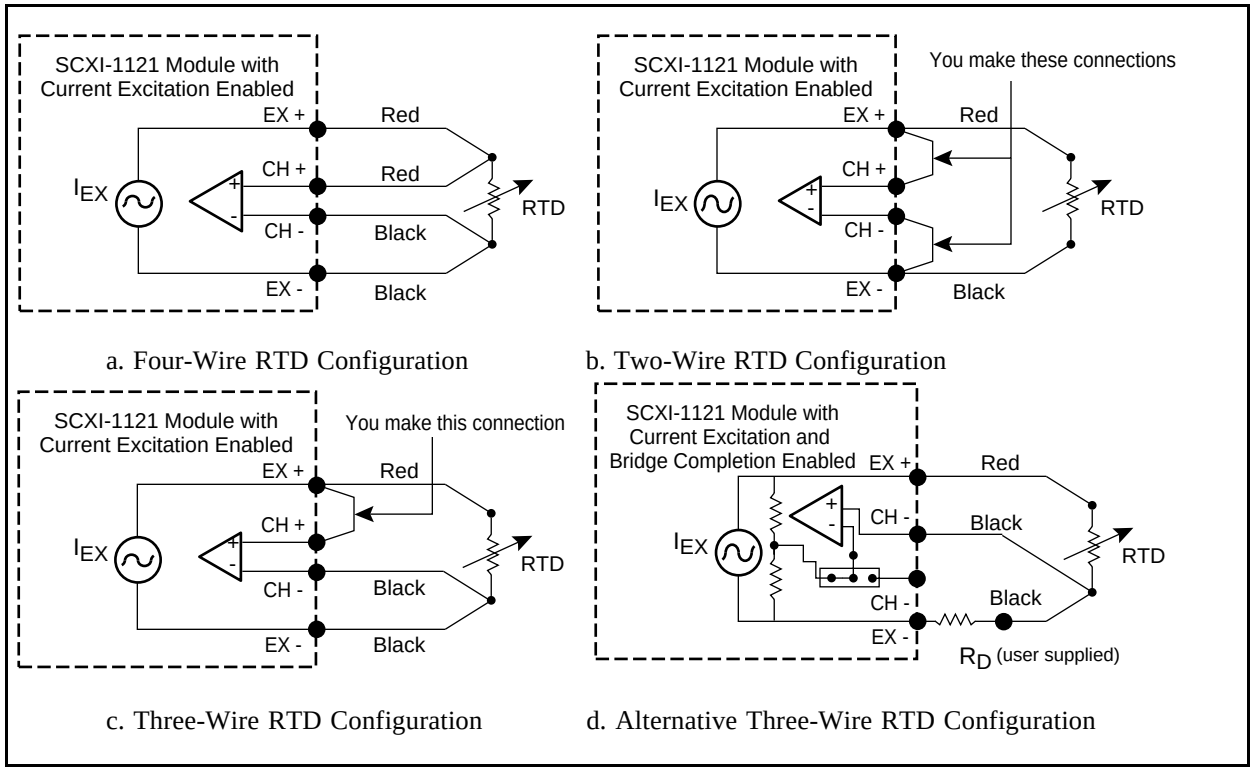


Figure 7. Wiring Diagrams for Two-Wire, Three-Wire, and Four-Wire Configurations

Measuring RTD Temperature

After you have configured and installed the plug-in DAQ board and SCXI-1121 modules and have correctly wired the RTDs to the SCXI terminal block, you can measure the temperature your RTDs sense.

You can use LabVIEW, LabWindows, or NI-DAQ software to easily monitor the voltages that the RTDs generate. The following software programming sequences are typical for taking an RTD measurement using each software package.

LabVIEW

Use this programming sequence with LabVIEW:

1. Run the NI-DAQ Configuration Utility and input the SCXI hardware configuration and jumper settings. This step informs the NI-DAQ driver software of which hardware is being used and how the modules are configured, including which gain value to use when scaling the data.

2. Measure the voltage from the RTD channel. You can use high-level VIs such as AI Sample Channel and AI Sample Channels, which are in the Easy I/O palette of the DAQ menu, to measure the voltage from one or more of the SCXI channels.

3. Scale the voltage measurement to a temperature reading. LabVIEW has a virtual instrument (VI) that uses the Callendar-Van Dusen equation to scale your voltage reading to a temperature reading. This VI, RTD Convert, is in the DAQ Utilities palette of the DAQ menu.

LabWindows/CVI

Use this programming sequence with LabWindows for DOS:

1. Run the NI-DAQ Configuration Utility and input the SCXI hardware configuration and jumper settings. This step informs the NI-DAQ driver software of which hardware is being used and how the modules are configured.

2. Measure the voltage from the RTD channel. For single-point voltage measurements, use the function sequence `SCXI_Load_Config`, `SCXI_Single_Chan_Setup`, `AI_Read`, and `AI_VScale`. The `AI_VScale` function returns the voltage measured on the RTD channel.

3. Scale the voltage measurement to a temperature reading. LabWindows has conversion functions that use the Callendar-Van Dusen equation to scale your voltage reading to a temperature reading. These functions, `RTD Convert` for single-point conversions and `RTD_Buf_Convert` for multiple conversions, are part of the Transducer Conversions instrument driver (`convert.fp`).

BridgeVIEW

1. Run the NI-DAQ Configuration Utility (WDAQCONF.EXE) and input the SCXI hardware configuration and jumper settings.

2. Use the DAQ Channel Wizard to configure each I/O channel. For each I/O channel, you configure scaling and assign a tag name. You can select RTD scaling from a pop-up dialog. The NI-DAQ Server will automatically scale voltage measurements from the SCXI-1121 into temperature using the proper RTD transfer function.

3. From within your BridgeVIEW application, read the tags assigned to your RTD inputs. Data will be returned in scaled temperature units.

NI-DAQ

Use this programming sequence with NI-DAQ:

1. Run the NI-DAQ Configuration Utility and input the SCXI hardware configuration and jumper settings. This step informs the NI-DAQ driver software of which hardware is being used and how the modules are configured.

2. Measure the voltage from the RTD channel. For single-point voltage measurements, use the function sequence `SCXI_Load_Config`, `SCXI_Single_Chan_Setup`, `AI_Read`, and `AI_VScale`. The `AI_VScale` function returns the voltage measured on the RTD channel.

3. Scale the voltage measurement to a temperature reading. NI-DAQ has source code

files that implement the Callendar-Van Dusen formula to scale your voltage reading to a temperature reading. These files are called `RTD.c`, `RTD.pas`, and `RTD.bas` for the C, Pascal, and BASIC programming languages.

Low-Cost RTD Measurements

The RTD application example in this application note uses the SCXI-1121 isolation amplifier. The SCXI-1121 module has four isolated and independently configurable excitation channels for each of the four isolated input channels. If channel-to-channel isolation is not important, you can configure a less expensive system by using the SCXI-1122, which includes one current excitation source to power multiple RTDs., as shown in Figure 8.

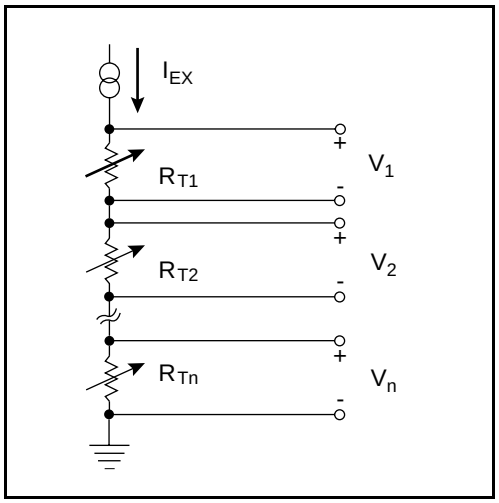


Figure 8. RTD Measurement with SCXI-1122

You can also use the current excitation channels of the SCXI 1121 module to power multiple RTDs connected to additional SCXI-1120 eight-channel isolation amplifier modules. A single SCXI-1121 excitation channel can drive a constant current supply through a load of up to 10 kΩ. If each RTD resistance will be limited to 250Ω, for example, a single SCXI-1121 excitation channel can power up to 40 RTDs in a serial configuration.

For simpler, low-channel count RTD applications that do not require the flexibility and expandability of SCXI, the SC-2042-RTD signal conditioning accessory delivers a very cost-effective solution. The SC-2042-RTD is an 8-channel signal conditioning board that cables directly to a plug-in DAQ board or PCMCIA card (Figure 9). The SC-2042 includes eight independent constant current sources to power eight RTDs with screw terminals for 4-wire connections. The SC-2042-RTD operates with a variety of DAQ devices in differential mode, including MIO Series and E Series boards, DAQCard-1200, DAQPad-1200, and the Lab-PC+.

Conclusion

RTDs are versatile temperature sensors that have high accuracy over a wide range of temperatures. Because RTDs are low-resistance devices, you must be careful when wiring and measuring RTDs to avoid errors caused by lead resistance. Signal conditioning such as current excitation and amplification is required to make RTD measurements with DAQ equipment. A National Instruments SCXI signal conditioning system has configurable current excitation, amplification, filtering, and electrical isolation for your RTD applications. With the SCXI system, you can condition multiple RTD signals and pass the multiplexed signal to a PC plug-in DAQ board.

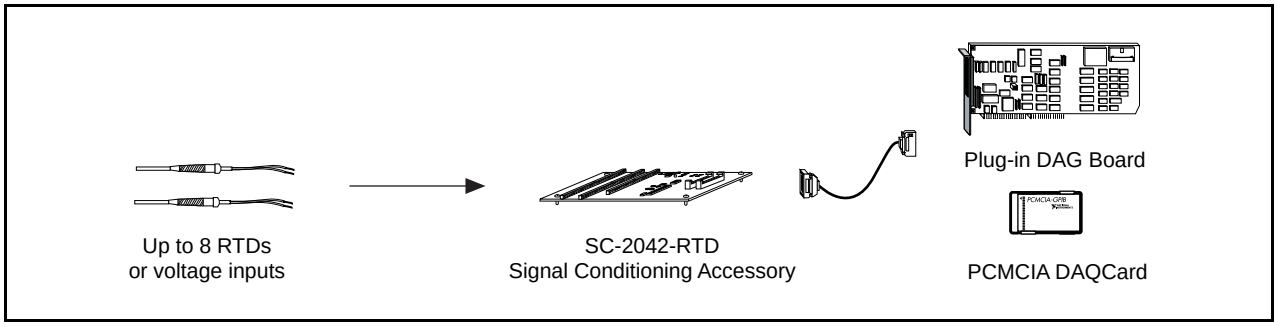


Figure 9. SC-2042-RTD Configuration