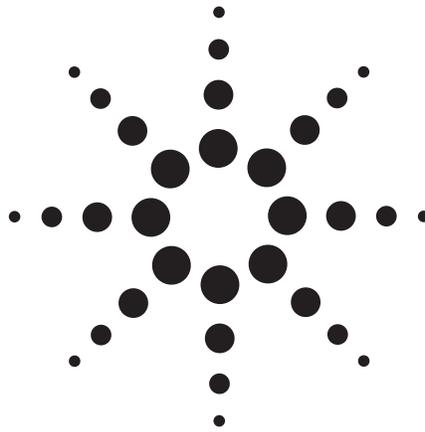


Selecting Temperature Transducers for Data Acquisition Systems

Application Note 1406



Introduction

Temperature can have a big effect on product reliability, so collecting temperature data is important in both R&D and manufacturing applications. However, making accurate, repeatable temperature measurements is not as simple as you might expect.

Temperature measurements, in general, are more complex than they appear at first glance. Typically, we think of temperature as a single number, but it is a statistical construct whose accuracy and repeatability can be affected by thermal mass, measurement time, electrical noise, and measurement algorithms. Accurately measuring temperature is difficult enough under ideal conditions, and real-life test conditions make it even harder.

Understanding the advantages and disadvantages of the various approaches to measuring temperature will help you get better results when you are collecting temperature data with a data acquisition system. Choosing the right temperature transducers and using them correctly can help you avoid problems and get results you can count on.

This application note provides an overview of the four most common types of temperature transducers used in data acquisition systems and discusses the advantages and disadvantages of each approach. It delves more deeply into the science behind thermocouple measurements, to help you overcome some of the inherent drawbacks in these popular transducers.



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Transducer types

The four most common types of transducers used in data acquisition systems are resistance temperature detectors (RTDs), thermistors, IC sensors and thermocouples. Each of them works best in certain measurement situations, so it is important to know when to use which type. Factors to consider include performance, useful range, cost and convenience. Table 1 summarizes the advantages and disadvantages of each type[1].

Resistance temperature detectors

RTDs operate on the principle that the resistivity of a metal is dependent on its temperature. Top-quality RTDs use platinum, which offers the most accurate and stable measurements available, up to about 500°C. Platinum RTDs are quite expensive, however. RTDs using nickel or nickel alloys are not as stable or as linear as platinum ones, but they are much more affordable and provide good accuracy.

RTDs do have a few disadvantages, including their susceptibility to self-heating errors. Resistance measurements require you to apply a current. This current produces heat that could distort your measurement results. A second disadvantage of RTDs is their low resistance. Because it is so low, the resistance of the leads you use to connect the RTD can create large errors.

If you use the two-wire technique illustrated in Figure 1a, you measure resistance at the terminals of your data acquisition system, which makes the lead resistance part of the unknown quantity you are trying to measure. If you use the four-wire technique illustrated in Figure 1b, you measure resistance

at the terminals of the RTD, which removes lead resistance from your measurement. Of course the four-wire technique requires twice as much wiring and twice as many data acquisition channels. As a compromise, you can use a three-wire technique; it is one wire simpler, but you sacrifice a little accuracy (see application note 290 for details)[1].

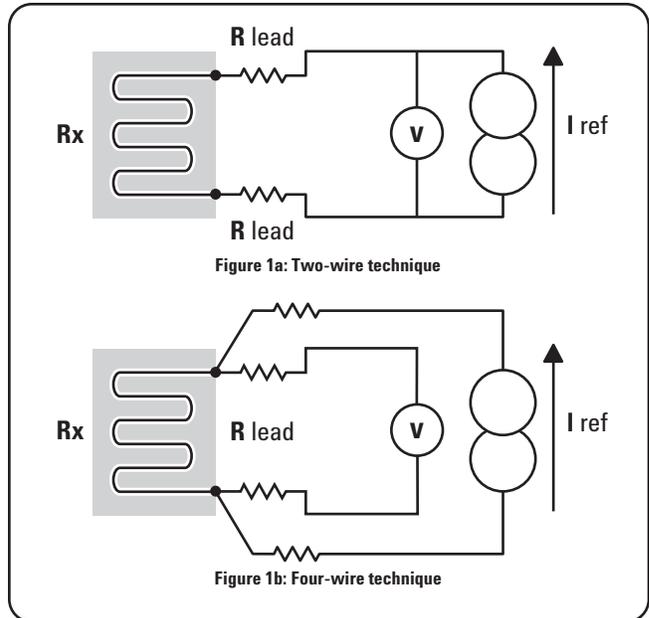


Figure 1: RTD two-wire and four-wire measurement techniques

	RTD	Thermistor	IC sensor	Thermocouple
Measurement type	Absolute			Relative
Advantages	<ul style="list-style-type: none"> - Most stable - Most accurate - More linear than thermocouples 	<ul style="list-style-type: none"> - High sensitivity - Fast - Two-wire measurement 	<ul style="list-style-type: none"> - Most linear - Highest output - Inexpensive 	<ul style="list-style-type: none"> - Self-powered - Rugged - Inexpensive - Wide variety of physical forms - Wide temperature range
Disadvantages	<ul style="list-style-type: none"> - Expensive - Slow - Current source required - Small resistance change - 4-wire measurement - Self-heating 	<ul style="list-style-type: none"> - Nonlinear - Limited temperature range - Fragile - Current source required - Self-heating 	<ul style="list-style-type: none"> - Limited to 250°C - Power supply required - Slow - Self-heating - Limited configurations - Large mass 	<ul style="list-style-type: none"> - Nonlinear - Low voltage - Reference required - Least stable - Least sensitive

Table 1: Comparison of common types of temperature transducers

Thermistors

Like RTDs, thermistors are temperature-sensitive resistors. Typically made of ceramic semiconductors, thermistors offer much higher impedance than RTDs, so lead error is not as pronounced. This makes it feasible to use the simpler two-wire technique with thermistors. Their high output (a small change in temperature produces a large change in resistance) yields high-resolution measurements and reduces the impact of lead resistance. Another advantage of thermistors is that their very low thermal mass minimizes thermal loading on your device under test.

However, the low thermal mass of thermistors also presents a disadvantage – the potential for higher self-heating from the current source used in the measurement. Other disadvantages of thermistors are their fragility and their high degree of nonlinearity. To achieve usable results with thermistors, you need to use a linearization algorithm.

IC sensors

IC sensors, on the other hand, are linear. They provide high output levels, are relatively inexpensive and offer good accuracy at room temperatures.

On the downside, you have fewer choices with IC sensors in terms of product configurations and

temperature ranges. In addition, IC sensors require a power source, making them susceptible to the same self-heating errors we encounter with RTDs and thermistors.

The relatively large size of IC sensors also can be a disadvantage. It is important to select a sensor that has a small mass compared to the mass you are measuring. Otherwise, the thermal mass of the sensor may affect the temperature reading. The larger mass of IC sensors also means their thermal settling times are longer.

The trend today is toward “smart sensors.” These are IC sensors that possess on-board intelligence to help with computation and communications tasks that were traditionally performed in the data acquisition system.

Thermocouples

Thermocouples are popular because they are more rugged than other types of transducers and offer a much broader temperature range. They do not need a power source, and their low cost makes them an attractive choice for large data acquisition systems. However, to get good results with thermocouples, it is important to understand how they work, so you can overcome some of their inherent drawbacks.

Thermocouple measurements

Thermocouple behavior is based on the gradient theory. As illustrated in Figure 2a, when one end of a wire is heated, it produces a voltage that is a function of the temperature gradient from one end of the wire to the other and the type of metal used for the wire.

A thermocouple is simply two wires made of different metals that are joined at one end and open at the other, as illustrated in Figure 2b. The voltage across the open end is a function of the temperature at the junction and the types of metals used in the wires. All dissimilar pairs of metals exhibit this voltage, called the Seebeck voltage after its discoverer, Thomas Seebeck. For small changes in temperature, the Seebeck voltage is linearly proportional to temperature:

$$V = \alpha T_x$$

where α , the Seebeck coefficient, is the constant of proportionality. However, over larger temperature ranges, the Seebeck coefficient is itself a function of temperature, making the Seebeck voltage nonlinear. As a result, thermocouple voltages are nonlinear.

While RTDs, thermistors, and IC sensors all measure absolute temperatures, thermocouples measure only relative temperatures. An example will help us explain relative temperature measurements.

For our example, we will use a common Type J thermocouple, which consists of one wire made of iron and one wire made of constantan, an alloy of 45 percent nickel and 55 percent copper.

When we connect to our two test leads – which are copper – we create two more thermocouples, and each contributes a voltage to the circuit (see Figure 3). Now we have three thermocouples and three unknown temperatures.

To solve this problem, we can add an opposing thermocouple and a reference junction at a known temperature, as illustrated in Figure 4. For our example, we will use another copper-iron junction for the opposing thermocouple, to match the copper-iron junction we created when we attached a copper lead to the iron lead of the original thermocouple. We will isolate the two junctions in an isothermal (constant temperature) block, so they will effectively cancel each other.

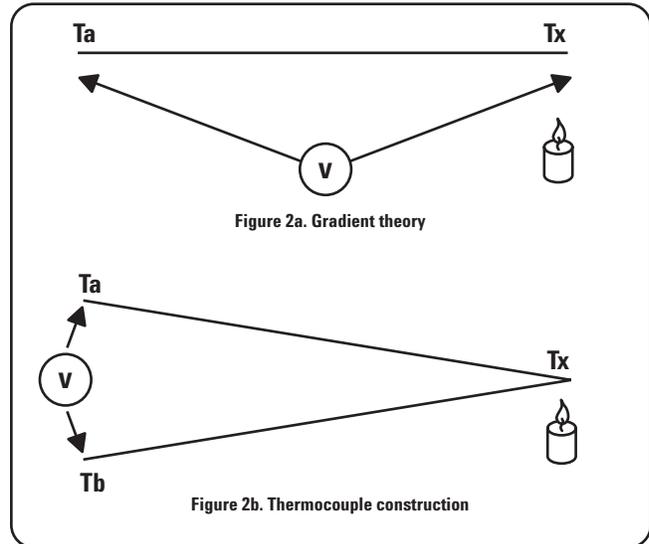


Figure 2: Thermocouple principles

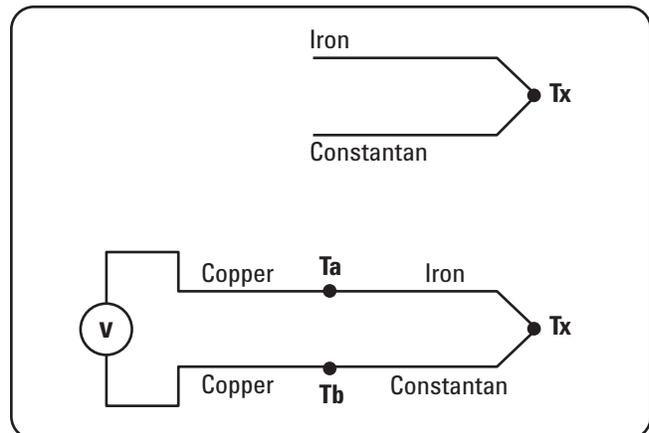


Figure 3: Adding leads causes two additional unknown junction temperatures

We now have just two junctions, the original junction from the thermocouple (T_x) and the reference junction (T_{ref}) we have just added. If we know the temperature at the reference junction, we can compute T_x . Many data acquisition systems that offer thermocouple measurements compute T_x automatically.

There are few practical, inexpensive reference points for temperature. The freezing and boiling points of water at 0° and 100°C are the only easy ones provided by Mother Nature. If you put the junction T_{ref} in an ice bath, you can force the temperature of T_{ref} to 0°C . In fact, all thermocouple tables are referenced to an ice bath.

Fortunately, it is possible to eliminate the ice bath and simplify the system. Instead of using the ice bath to force the temperature of T_{ref} to 0°C , we can measure T_{ref} with an absolute temperature device, such as an RTD, and compensate for it mathematically.

Another way to simplify the system is to eliminate the second thermocouple, as illustrated in Figure 5. If we extend the isothermal block to include T_{ref} , we set the temperature of the isothermal block to T_{ref} since the other two thermocouples in the block still cancel each other. To determine T_{ref} , we can measure the temperature of the isothermal block with an absolute temperature device.

Once we have determined T_{ref} , we can compute its equivalent voltage and subtract it from the measured voltage V , to simulate a T_{ref} of 0°C . Now it is possible to compute T_x using ice-bath-referenced thermocouple tables or equations. As we mentioned earlier, data acquisition systems that offer thermocouple measurements typically perform these computations.

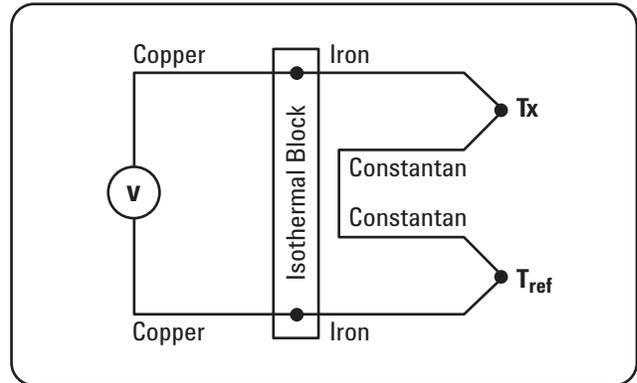


Figure 4: Thermocouple hookup canceling additional unknown junction temperatures

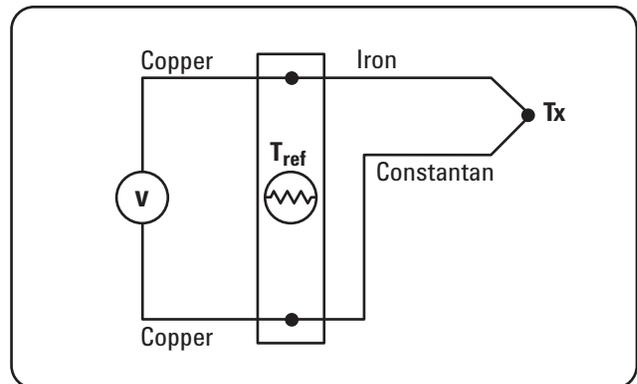


Figure 5: Simplified test setup with T_{ref} inside isothermal block

As you can see in Table 2, Seebeck coefficients and the resulting output voltages are small numbers. Because they are so small, it is difficult to measure absolute levels and relative changes accurately, and electrical noise will affect the accuracy of your temperature measurements more dramatically than with other transducer types.

Thermocouple Type	Seebeck Coefficient		Output Voltage at 100°C
	at 100°C	at 0°C	
B	$-0.25 \mu\text{V}/^\circ\text{C}$	$0.90 \mu\text{V}/^\circ\text{C}$	0.033 mV
E	$58.7 \mu\text{V}/^\circ\text{C}$	$67.5 \mu\text{V}/^\circ\text{C}$	6.32 mV
J	$50.4 \mu\text{V}/^\circ\text{C}$	$54.4 \mu\text{V}/^\circ\text{C}$	5.27 mV
K	$39.5 \mu\text{V}/^\circ\text{C}$	$41.4 \mu\text{V}/^\circ\text{C}$	4.10 mV
S	$5.4 \mu\text{V}/^\circ\text{C}$	$7.34 \mu\text{V}/^\circ\text{C}$	0.65 mV

Table 2: Seebeck coefficients and output voltages for common thermocouples

Improving transducer accuracy

With all four types of temperature transducers, reducing noise will help you improve the accuracy of your measurements. Reducing noise is especially critical when you are using thermocouples, since electrical noise affects thermocouple measurements most dramatically.

Before you can deal effectively with noise issues, it is important to understand the source of the noise. Typically, it comes from one of three sources:

1. *Common mode noise* is caused by a ground loop. Thermocouples are very susceptible to ground loops, as their metal junction may be directly attached to a machine or component that has a higher potential than the data logger. An electrical current can flow through both the high and low leads, through the data logger and back to the source via ground.
2. *Normal mode noise* is caused by magnetic fields creating a current in the measurement loop. Normal mode noise can occur when a thermocouple wire is run near high-current wires or machinery
3. *Electrostatic noise* is created by rotating machinery.

Once you have determined the noise source, you can decide on an appropriate solution. Each type of noise has a unique solution:

1. *Common mode noise* – select a data acquisition system with high impedance to ground, often specified as common mode rejection. You also can insert electrical insulation between the thermocouple and the noise source.
2. *Normal mode noise* – shorten leads, use twisted pair wiring, avoid running measurement wires near high-current sources
3. *Electrostatic noise* – use a shielded measurement wire

Conclusion

It is not difficult to make accurate and reliable temperature measurements with a data acquisition system if you choose the right sensor for your application. When you select your sensor, consider transducer cost, temperature range, accuracy, ruggedness, sensor output, thermal settling times and error modes, such as self-heating. Also, pay careful attention to the instrument system you choose. The correct sensor is useless if the data acquisition system cannot measure its output accurately and repeatably.

Reference

Glossary

B-type thermocouple – a thermocouple made of platinum and rhodium with a temperature range of 0 to 1820°C

Cold junction – a reference junction used in making thermocouple measurements. The cold junction is held at a known temperature, often 0°C, or is measured using an absolute temperature sensor. A thermocouple measures the relative difference between the reference junction and the unknown or hot junction.

Constantan – an alloy of 45% nickel and 55% copper. Its resistance varies little with temperature. Used with copper in T-type thermocouples.

E-type thermocouple – a thermocouple made of Chromel and constantan, with a temperature range of -270 to 1000°C

J-type thermocouple – a thermocouple made of iron and constantan, with a temperature range of -210 to 1200°C

K-type thermocouple – a thermocouple made of Chromel and Alumel, with a temperature range of -270 to 1372°C

Linearity – The output (Y) is proportional to the input (X): $Y = aX$
A linear A/D would produce a digital result proportional to the analog input.

N-type thermocouple – a thermocouple made of Nicrosil and Nisil, with a temperature range of -270 to 1300°C

Resistance temperature detector (RTD) – a metallic device that relies on the fact that the resistance of a metal changes with temperature

Resolution – a measure of the smallest change that an instrument can detect

Repeatability – the ability of an instrument to give the same reading under identical conditions

Sensitivity – a measure of the minimum change in an input signal that can be detected by an instrument

Sensor – a device that can detect a physical quantity (i.e. temperature) and produce a corresponding electrical signal

Settling time – the time it takes for a circuit to reach steady state

Stability – an instrument's or sensor's ability to maintain a constant output when you apply a constant input

Thermocouple – a temperature sensor consisting of two dissimilar metals joined together. When a temperature gradient exists (one end is a different temperature from the other), a voltage is generated. Different types of thermocouples are constructed from different metals, with differing temperature ranges and accuracies.

Thermistor – a ceramic temperature sensor that exhibits a change in resistance as a function of temperature. With most thermistors, resistance decreases as the temperature increases.

Transducer – a device that converts a physical quantity into an electrical signal; for example thermocouples, photocells, and strain gauges

T-type thermocouple – a thermocouple made of copper and constantan, with a temperature range of -270 to 400°C

References

1. "Practical Temperature Measurements," Application Note 290, Agilent Technologies publication number 5965-7822E, July 1997.
 2. NIST Monograph 175, National Institute of Standards and Technology, Washington D.C., 1993
- This application note is based on an article, "Choosing the Right Temperature Transducers for Your Data Acquisition System," written by Barry Scott, Agilent Technologies, and published in *Evaluation Engineer*, September 1997.

Related Agilent Literature

Product overview – 34970A Data Acquisition/Switch Unit, pub no. 5965-5290EN

Application Note 1412 – Selecting the Right Data Acquisition System, pub no. 5988-7506EN

This application note is based on an article written by Barry Scott, Agilent Technologies, and published in *Evaluation Engineering*, September, 1997.



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