

# Temperature Measurements

## E80 Spring 2012 Notes

### Introduction

Temperature is one of the most common physical quantities we may wish to measure. Beyond the obvious reasons that temperature is interesting, measuring temperature is also necessary to properly calibrate other sensors such as pressure.

Depending on the application, desirable temperature sensor characteristics may include:

- Accuracy
- Repeatability
- Wide temperature range
- Simple relationship between sensor output and temperature
- Easy calibration
- Fast response

This lecture describes the principles of operation of four of the most common temperature sensors: thermistors, thermocouples, integrated silicon linear sensors, and resistive temperature devices. It examines the signal conditioning necessary to read some of these sensors. It also explores temperature sensor transient response, which is important when attempting to sense rapidly changing temperature.

### Thermistors

A *thermistor* is a resistor whose resistance changes with temperature. Thermistors are inexpensive and can offer accuracies as good as  $\pm 0.1$  °C over a range of -100 to 450 °C. The resistive element is generally a metal-oxide ceramic containing manganese, cobalt, copper, or nickel, packaged in a thermally conductive glass bead or disk with two metal leads. Most materials produce a *negative temperature coefficient*, indicating that resistance drops with temperature, as shown in Figure 1.

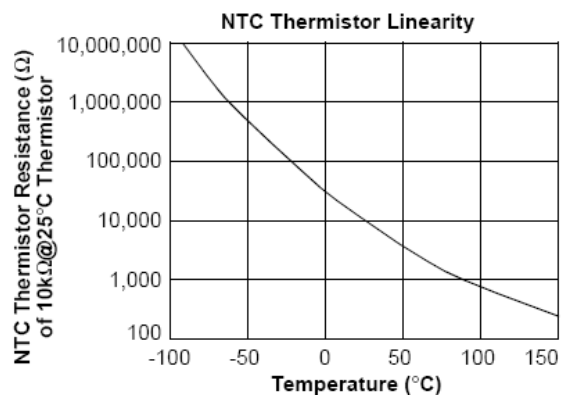


Figure 1: Thermistor resistance vs. temperature indicating 10 KΩ @ 25 °C, negative temperature coefficient, and nonlinear behavior. [Microchip-AN685]

Resistance drops in roughly a straight line on a semilogarithmic scale. A simple empirical model relating temperature to resistance is the Steinhart-Hart equation:

$$T = \frac{1}{A_1 + B_1 \ln \frac{R}{R_{ref}} + C_1 \ln^2 \frac{R}{R_{ref}} + D_1 \ln^3 \frac{R}{R_{ref}}}$$

where  $R_{ref}$  is the nominal resistance at a reference temperature  $T_{ref}$  (e.g. 25 °C) and  $A_1 = 1/T_{ref}$ . Note that there are many equivalent ways to express this relationship with different variable names and omitting  $R_{ref}$ . Moreover, the  $C_1$  term is typically small and is sometimes left out.

A thermistor produces a resistance, which must be converted to a voltage signal. This is usually done with a voltage divider [Microchip-AN685]. If the DAQ has a low input impedance, an operational amplifier may be required to buffer the voltage divider output.

If a large current runs through a thermistor, the thermistor will dissipate  $P = I^2R$  and heat up. This is called *self-heating* and will introduce an error into the measurement. The amount of heating is proportional to the power dissipated. The easiest way to avoid this problem is to use a large resistance.

## Thermocouple

According to the *Seebeck effect* (also called the *thermoelectric effect*), a temperature gradient along a conductor induces a voltage across the conductor. However, measuring this voltage involves attaching a second conductor to the hot end, which will see its own voltage induced and cancel out the voltage we wished to measure. Fortunately, the relationship between temperature difference and voltage varies with materials, so by using a second conductor made of a different material, a small voltage difference can be found at the ends. This device, a two-terminal element consisting of two different metal wires joined at the end, is called a *thermocouple*.

The effect is weak, typically 10's of microvolts / °C, but can be amplified to a more useful range. Thermocouples operate over a very wide range of temperatures, are inexpensive (just two pieces of wire), and can stand up to harsh conditions. You can make your own thermocouple by joining two wires of dissimilar metals. If the wire is thin, they can respond to temperature changes very quickly.

Thermocouples measure the difference in voltage between two points. To know the absolute temperature at a given point, one must know the temperature at the other point. Typically we measure the temperature at the *hot junction* at the tip of the thermocouple where the two metal wires are joined. The other end is called the *cold junction*. We must know or measure the temperature at the cold junction, either by immersing the cold junction in a liquid bath of a known temperature or by using a thermistor or other thermal sensor to measure the temperature at the cold junction. The temperature at the cold junction should be converted to an equivalent voltage, then added to the measured voltage. The sum should then be converted back to find the

actual temperature at the hot junction. This is called *cold junction compensation*. If a system has multiple thermocouples, they can all share a single cold junction for simplicity.

The relationship between the temperature difference and the thermoelectric voltage is somewhat nonlinear. It is often described by a look-up table rather than an analytic function.

Thermocouples produce a very small output voltage that must be mightly amplified to reach the full scale of a typical DAQ. Moreover, the output impedance is high, so the amplifier must have very high input impedance. Instrumentation amplifiers are well-suited to this job. Figure 2 shows an instrumentation amplifier connected to a thermocouple. The circuit produces an output of

$$V_{out} = \left(1 + \frac{100k\Omega}{R}\right)(V^+ - V^-) + V_{ref}$$

Remember that  $V_{out}$  should be positive. If the thermocouple may be measuring temperatures colder than the cold junction, it is helpful to set  $V_{ref} > 0$  so the output isn't clipped.

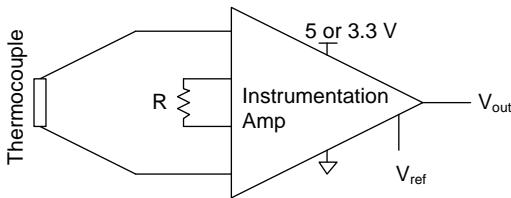


Figure 2: Instrumentation Amplifier for measuring thermocouple

For example, a type-E thermocouple has one conductor made of nickel-chromium and one of copper-nickel. It produces a voltage difference of about  $59 \mu\text{V} / ^\circ\text{C}$ . The accuracy is  $1.0 - 1.7 ^\circ\text{C}$ .

### Integrated Silicon Linear Sensors

An *integrated silicon linear sensor* is a three-terminal device. It has power and ground inputs and produces an output voltage linearly dependent on temperature. They are convenient to use because they don't require signal conditioning or calibration, but tend to be less accurate and operate over a narrower temperature range.

For example, the Microchip MCP9701A in Figure 3 has an accuracy of  $\pm 2^\circ\text{C}$  over a range of  $0 - 70 ^\circ\text{C}$ . It accepts  $V_{DD}$  in the range of  $3.1 - 5.5 \text{ V}$  and produces an output of

$$V_{out} = 400 \text{ mV} + (T - 0 ^\circ\text{C})(19.5 \text{ mV} / ^\circ\text{C})$$

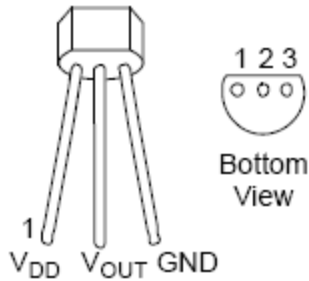


Figure 3: Microchip MCP9701A [Microchip-MCP9700]

### Resistive Temperature Detectors (RTD)

A *resistive temperature detector* (RTD) is a two-terminal platinum device with a positive, nearly constant temperature coefficient. It is particularly stable and repeatable, and more linear than most sensors. However, it is more expensive than other sensors. The best RTDs have a resistance of 100  $\Omega$  at 0  $^{\circ}\text{C}$ . and a temperature coefficient of 0.00385  $\Omega/\Omega/^{\circ}\text{C}$  [Microchip-AN687]:

$$R = R_0(1 + \alpha)(T - T_0)$$

where  $R_0$  is the nominal resistance (e.g. 100  $\Omega$ ),  $T_0$  is the nominal temperature (e.g. 0  $^{\circ}\text{C}$ ), and  $\alpha$  is the temperature coefficient.

In other words, the 100  $\Omega$  RTD increases to 103.85  $\Omega$  at 10  $^{\circ}\text{C}$ . Over a range of -100 to +200  $^{\circ}\text{C}$ , this simple model is accurate to about 3.1  $^{\circ}\text{C}$ .

An even better model adds second and third-order terms to compensate for small nonlinearities [Microchip-AN687].

The RTD needs to be driven by a small current (< 1 mA) to produce a voltage output without too much self-heating, as shown in Figure 4. The circuitry to generate this precise current is a bit complicated.

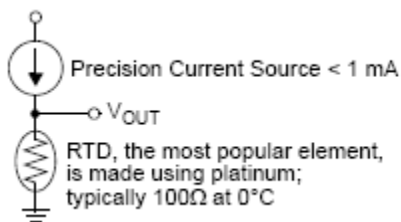


Figure 4: RTD Circuit [Microchip-AN687]

### Other Devices

A variety of other devices can be used to measure temperature.

*Diodes* have a current-voltage relationship that is exponentially related to temperature. They are used in microprocessors to detect that the chip is starting to overheat and to throttle back power consumption before the chip is damaged.

An *infrared pyrometer* measures the infrared light emitted by a hot object. It can be used to measure very hot objects and can operate from a distance. Infrared cameras perform a similar function.

### **Calibration**

Each sensor has some uncertainty in the parameter values. For the highest accuracy, the individual sensor should be calibrated at one or more known temperatures and the parameters should be chosen to best fit the measurements, usually in a least squares sense. Matlab can perform this fit using the `regress` command. Excel can also do it using the Solver.<sup>1</sup> LabVIEW has similar capability.

A model with N parameters requires calibration at N temperatures. An easy way to set a temperature is with a liquid bath. The bath should be well-mixed so it is at a consistent temperature. Temperatures of 0 and 100 °C are particularly easy to produce using an ice bath and boiling water, respectively. Deionized water is somewhat conductive and will disturb resistance measurements if component leads are not insulated. Some thermocouples have insulated leads to avoid this problem.

### **Thermal System Transient Response**

A temperature sensor cannot track changing temperatures instantaneously. This can lead to significant errors for rapidly changing systems.

In general, objects contain an amount of heat energy proportional to their temperature. This is called the *thermal mass* of the system and has units of Joules/ °C. The thermal mass depends on the physical mass and also on the composition of the object; for example, a kilogram of water has nearly 10 times the thermal mass of a kilogram of iron because it takes more energy to heat or cool the water by a given amount.

The rate at which heat energy can flow in or out of an object is called the *thermal resistance* and has units of °C/ Watt. For example, an insulated house has a higher thermal resistance than an uninsulated house, meaning less heat energy flows out of the insulated house into the cold winter night. Similarly, a sensor in still air has a higher thermal resistance than it does in blowing air, which in turn is higher than in a water bath.

We can write the governing equations for a thermal system. Let T be temperature (in °C) and P be power (in Watts). Then a thermal mass M requires the application of power (i.e. the flow of heat energy) to change temperature.

$$P = M \frac{dT}{dt}$$

A thermal resistor of resistance R produces a temperature difference proportional to the power flowing through it:

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<sup>1</sup> Excel does not activate the Solver add-in by default when you install the software. To add it for Office 2010, choose File -> Options -> Add-Ins. Under Manage Excel Add-ins, click Go. Choose Analysis ToolPak and Solver Add-in. Under the Data tab, the Solver will now be visible.

$$T = PR$$

Observe that this has direct analogy to an electrical circuit, in which thermal mass corresponds to capacitance, thermal resistance to electrical resistance, temperature to voltage, and power (flow of heat energy) to current (flow of electrical charge).

Suppose a sensor has a temperature  $T_{\text{sensor}}(t)$  in an environment with a temperature of  $T_{\text{env}}(t)$ . Let the sensor has thermal mass  $M$  and thermal resistance  $R$ . If the sensor is not at the same temperature as the environment, heat energy will flow from the environment to the sensor to try to equalize the temperatures. This flowing heat energy is power. The power into the sensor causes a temperature change

$$P = M \frac{dT_{\text{sensor}}}{dt}$$

The thermal resistance relates the amount of power to the temperature difference:

$$T_{\text{env}} - T_{\text{sensor}} = PR$$

Combining these gives a first-order differential equation relating the two temperatures:

$$\frac{dT_{\text{sensor}}}{dt} + \frac{T_{\text{sensor}}}{MR} = \frac{T_{\text{env}}}{MR}$$

This has a frequency response

$$\frac{T_{\text{sensor}}}{T_{\text{env}}}(j\omega) = \frac{1}{1 + j\omega MR}$$

This is a low-pass response. The thermal time constant is  $\tau = MR$ . At low frequencies (small  $\omega$ , slowly varying temperature), the frequency response is 1, indicating that the sensor temperature tracks the environment closely. At high frequency (large  $\omega$ , rapidly changing temperature), the frequency response drops off, indicating that the sensor can't keep up. Fast and slow are relative to the thermal time constant.

The differential equation has a transient response that may be familiar from an RC circuit. The step response describes the behavior when the environment temperature abruptly steps from  $T_1$  to  $T_2$  (e.g. the sensor is moved from an ice bath to boiling water). It is

$$T_{\text{sensor}}(t) = T_2 + [T_1 - T_2] e^{-\frac{t}{\tau}}$$

The time constant  $\tau$  can be measured as the time to get within  $1/e$  of the final value. In the ice to boiling example, the time constant is the time for the sensor to reach  $100(1 - 1/e) = 63$  °C, as shown in Figure 5.

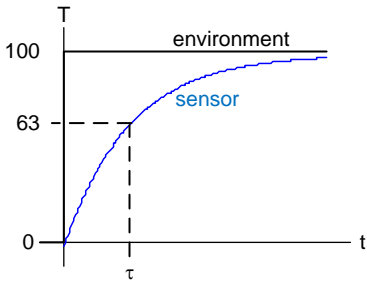


Figure 5: Thermal system step response

Similarly, the ramp response describes the behavior when the environment temperature linearly ramps from  $T_1$  to  $T_2$ . The sensor will lag behind, and the amount of the lag depends on the rate of temperature change and on the thermal time constant.

For example, if a slow sensor is placed into a rocket that is launched to high altitude, the sensor may not be able to track the rate of temperature change. However, if the sensor time constant is known, one could cleverly back out the actual temperature profile that would have produced the given measurements. This process is called deconvolution.

### Choosing a Temperature Sensor

Table 1 summarizes the characteristics of various temperature sensors. Thermocouples are typically used for very high temperature measurements or for their fast response. Thermistors are used for general purpose measurements. Integrated silicon linear sensors can be more convenient than thermistors because they compensate for the nonlinearities. RTDs are more expensive but provide the highest accuracy.

Table 1: Comparison of Temperature Sensors [Microchip-AN679]

	Thermocouple	RTD	Thermistor	Integrated Silicon
Temperature Range	-270 to 1800°C	-250 to 900 °C	-100 to 450°C	-55 to 150°C
Sensitivity	10s of $\mu\text{V} / ^\circ\text{C}$	0.00385 $\Omega / \Omega / ^\circ\text{C}$ (Platinum)	several $\Omega / \Omega / ^\circ\text{C}$	Based on technology that is -2mV/ $^\circ\text{C}$ sensitive
Accuracy	$\pm 0.5^\circ\text{C}$	$\pm 0.01^\circ\text{C}$	$\pm 0.1^\circ\text{C}$	$\pm 1^\circ\text{C}$
Linearity	Requires at least a 4th order polynomial or equivalent look up table.	Requires at least a 2nd order polynomial or equivalent look up table.	Requires at least 3rd order polynomial or equivalent look up table.	At best within $\pm 1^\circ\text{C}$ . No linearization required.
Ruggedness	The larger gage wires of the thermocouple make this sensor more rugged. Additionally, the insulation materials that are used enhance the thermocouple's sturdiness.	RTDs are susceptible to damage as a result of vibration. This is due to the fact that they typically have 26 to 30 AWG leads which are prone to breakage.	The thermistor element is housed in a variety of ways, however, the most stable, hermetic Thermistors are enclosed in glass. Generally thermistors are more difficult to handle, but not affected by shock or vibration.	As rugged as any IC housed in a plastic package such as dual-in-line or surface outline ICs.
Responsiveness in stirred oil	less than 1 Sec	1 to 10 Secs	1 to 5 Secs	4 to 60 Secs
Excitation	None Required	Current Source	Voltage Source	Typically Supply Voltage
Form of Output	Voltage	Resistance	Resistance	Voltage, Current, or Digital
Typical Size	Bead diameter = 5 x wire diameter	0.25 x 0.25 in.	0.1 x 0.1 in.	From TO-18 Transistors to Plastic DIP
Price	\$1 to \$50	\$25 to \$1000	\$2 to \$10	\$1 to \$10

## References

[Microchip-AN679] Microchip Application Note AN679, *Temperature Sensing Technologies*, 1998, <http://ww1.microchip.com/downloads/en/AppNotes/00679a.pdf>

[Microchip-AN684] Microchip Application Note AN684, *Single Supply Temperature Sensing with Thermocouples*, 1998, <http://ww1.microchip.com/downloads/en/AppNotes/00684a.pdf>

[Microchip-AN685] Microchip Application Note AN685, *Thermistors in Single Supply Temperature Sensing Circuits*, 1999, <http://ww1.microchip.com/downloads/en/AppNotes/00685b.pdf>

[Microchip-AN687] Microchip Application Note AN687, *Precision Temperature-Sensing with RTD Circuits*, 2008, <http://ww1.microchip.com/downloads/en/AppNotes/00687c.pdf>

[Microchip-MCP9700] Microchip MCP9700/01 *Low-Power Linear Active Thermistor ICs*, 2009, <http://ww1.microchip.com/downloads/en/DeviceDoc/21942e.pdf>