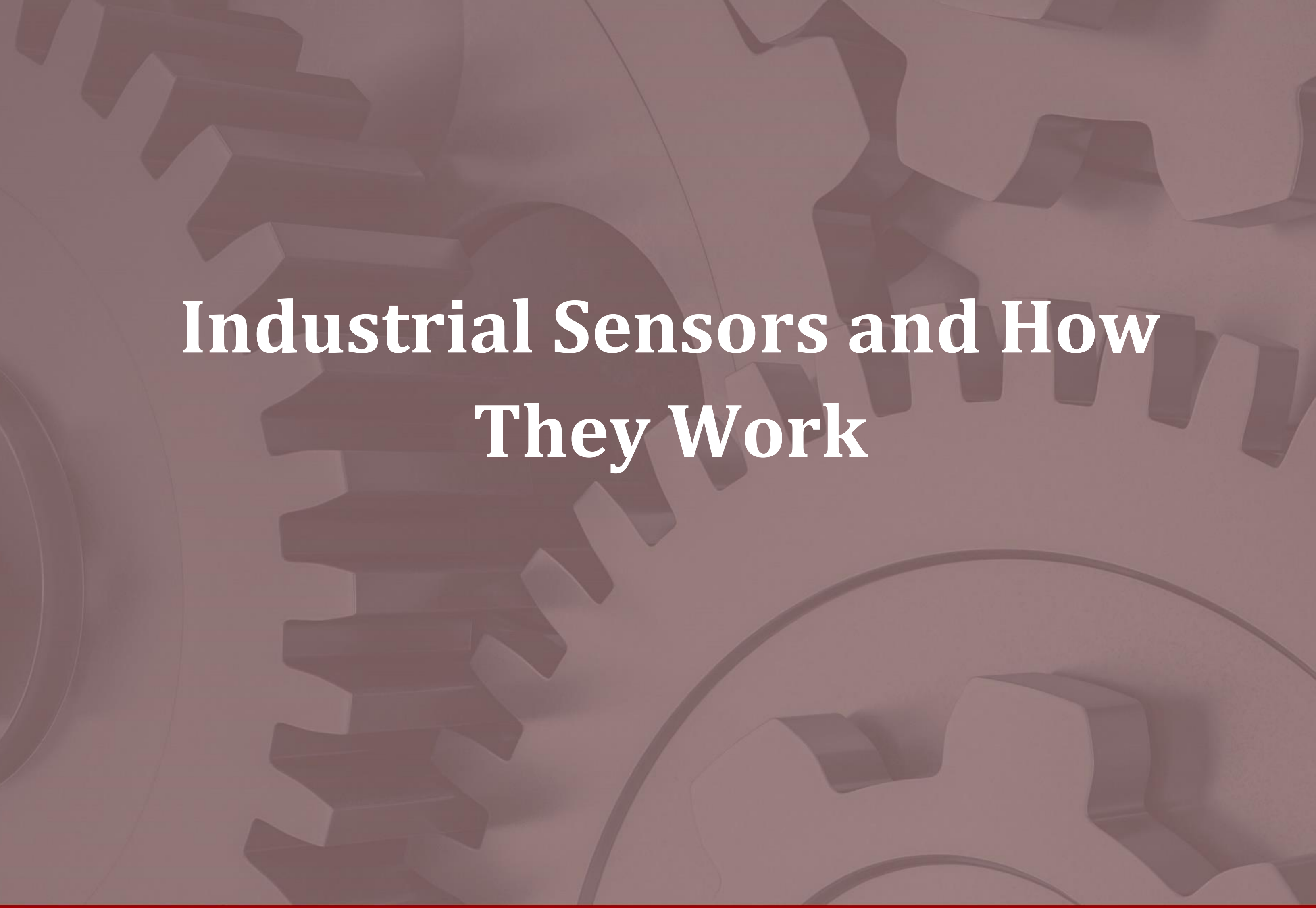

Industrial Sensors and How They Work

An Online Continuing Education Course for Engineers

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Industrial Sensors and How They Work

Robert J. Scoff, P.E.

1. Introduction

In today's industrial and commercial world, there are many processes that must be measured and controlled. The first part of this process is sensing. There are many sensors that that are used to do this. This course covers a few of the more common ones and describes how they work. With that in mind, let's get started with temperature measuring sensors. Remember, this course is only concerned with how these devices work.

2. Thermocouples

Thermocouples are one of the most common measuring devices used in the industrial world. A commonly used symbol for a thermocouple is shown in Figure 2.1.

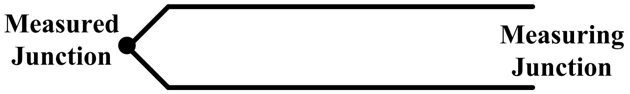

Figure 2.1 Commonly Used Symbol for a Thermocouple

All thermocouples are made of two different metals connected at a point which can be called **The Measured Junction.** Almost any two dissimilar metals will work to make a thermocouple, but in the industrial world there are only a dozen or so pairs of metals that are used. Now, when there is a **difference in temperature between the two ends** of the thermocouple, a voltage is generated that depends upon the magnitude of that difference in temperature. For instance, if the measured junction is held at 100 degrees Centigrade, and the measuring junction is held at 0 degrees Centigrade, a small voltage can be measured between the two ends of the measuring junction. A model of a thermocouple is shown in Figure 2.2.

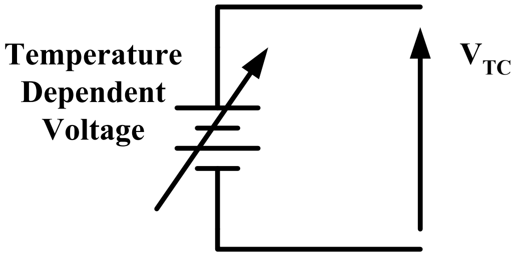

Figure 2.2 Electrical Model of a Thermocouple

For common thermocouple types, there are tables available that give that voltage versus temperature over the useful range of that thermocouple. The tables are usually given with the measuring junction at 0 degrees Centigrade or 32 degrees Fahrenheit. One of the reasons that this reference temperature is used is that the temperature of melting ice is one of the most stable and consistent constants of nature. It's also easy to replicate in a testing situation. The voltage that is generated is from 10 to 50 micro-volts per degree Centigrade. The voltage is also very exact. The thermocouple tables are often given with 4 or 5 significant figures.

Have you noticed that the measuring junction, often called the **Cold Junction**, needs to be kept at the temperature of melting ice to get accurate readings? For instance, if the measured junction was at 100 degrees Centigrade, and the cold junction was held at 10 degrees Centigrade, the thermocouple would generate a voltage that would equate to 90 degrees Centigrade. A meter that should be reading 100 degrees and is reading 90 degrees is not very useful. This error becomes larger as the measuring junction gets warmer. At the extreme, if both junctions were at 100 degrees, the actual temperature on the meter would be 0 degrees. If you realize that 0 degrees Centigrade is freezing water, and 100 degrees Centigrade is boiling water, you know that this is not a very accurate measuring method. Something needs to be done to cancel this Cold Junction effect. What is done is something called **Cold Junction Compensation**. What this means is that a temperature is added to the measured thermocouple temperature that is equal to the temperature of the cold junction. There are several ways to do this, but they all do the same thing. A voltage is added to the thermocouple generated voltage that is proportional to the temperature of the measuring junction. Figure 2.3 shows one way that this is done. In this method, a 4-resistor bridge circuit is added to the thermocouple. One of the resistors is temperature dependent. That makes the voltage across the bridge variable with temperature. The resistors are chosen so that, for a limited range, the voltage added in series with the thermocouple voltage is the same as the drop-in voltage because the measuring junction is not at zero degrees C.

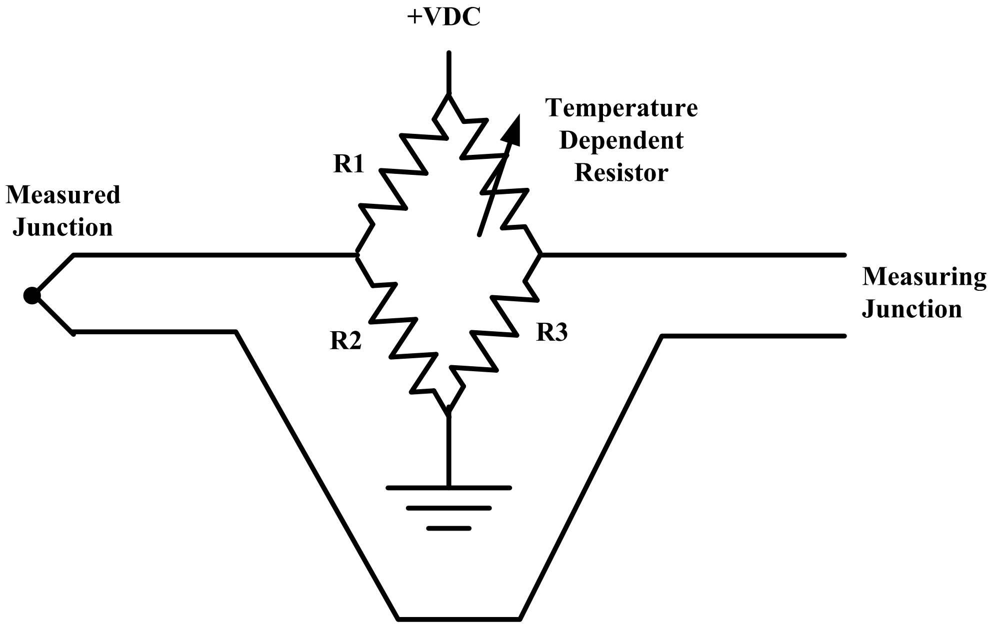

Figure 2.3   One Way to Temperature Compensate a Thermocouple

An important thing to note is that the temperature dependent resistor is **mounted physically close to the measuring junction**. This method has the advantage of not using any active components, just 4 resistors. There are other techniques for doing temperature compensation, but this is one of the most common. In all of them, the idea is the same. A voltage is added to the thermocouple voltage to make the voltage at the measuring junction proportional to the temperature at the measured junction.

There are no more than a dozen commonly used thermocouple types. Following is a list of 9 of the most commonly used thermocouple types, including the temperature range over which they are useful. The color associated with each thermocouple is the color of the insulation on the positive wire. **The color of the negative lead is always red.**

Type	Materials	°C Range	°F Range	Color
T	Copper/Constantan	-200 to 350	-328 to 662	Blue
J	Iron/Constantan	-40 to 750	-40 to 1382	White
K	Chromal/Alumel	-200 to 1200	-328 to 2282	Yellow
E	Chromal/Constantan	-200 to 900	-328 to 1652	Purple
N	Nicrosil/Nisil	-270 to 1300	-450 to 2372	Orange
C	Tungsten5%Rhenium Tungsten26%Rhenium	0 to 2320	32 to 4208	White
B	Platinum30%Rhodium Platinum6%Rhodium	0 to 1700	32 to 3092	Gray
R	Platinum13%Rhodium Platinum	0 to 1450	32 to 2642	Black
S	Platinum19%Rhodium Platinum	0 to 1450	32 to 2642	Black

Due to the physical characteristics of the materials used, there are certain applications where certain types of thermocouples are used. For instance, Type T Thermocouples are commonly used where high magnetic fields are present because both materials copper and constantan are non-magnetic. Type J, because one of the leads is iron, is not used where high magnetic fields are present. So, we might find a Type T measuring the temperature of a motor or transformer, but never a Type J, which is iron constantan. Type J is commonly found on plastic extrusion machines. Type K, which has a higher operating temperature, is often used in high temperature metal annealing processes. Types B, R, and S are often found measuring temperatures in ceramics heat treating processes.

All thermocouples are somewhat non-linear. This characteristic, along with the cold junction compensation, make knowing the exact temperature somewhat of an art form. Older thermocouple meters used non-linear analog meter scales. Then an approximate cold junction temperature was chosen as the temperature where the non-linear scale tracked the actual temperature. With the advent of micro-processors, look up tables were used to determine actual temperatures. Greater precision is now possible. The new digital meters can give temperatures to degrees and fractions of a degree**, but this precision does not necessarily mean accuracy.** When using thermocouples, it is always important to look at both the thermocouple characteristics and the operating temperature of the measuring junction.

3. Resistance Temperature Detector (RTD)

Another device for measuring temperature is a Resistance Temperature Detector. A RTD is simply a resistor that changes resistance with temperature in a predictable way. Then if the RTD is heated, its resistance can be measured, and its temperature known with a high degree of accuracy. Some materials that are used to construct RTD's are Platinum, Copper, Nickel, Balco (a 70% Nickel, 30% Iron alloy), and Tungsten. The most common material from which RTD's are made is Platinum.

Platinum RTD's are made of **99.99% pure platinum** (PT) and have a temperature coefficient (α) of **0.00385 Ohms/Ohm/^{o}C** or 0.385% per degree Centigrade. The most common resistances of Platinum RTD's are 100, 500, and 1000 Ohms (Ω's) at 0^{o} Centigrade. A 100 Ohm PT RTD will have a resistance of 138.5 Ohms at 100 ^{o}C. The simplified linear equation of resistance versus temperature is:

$$\mathbf{R = R_o (1 + \alpha \{T - T_o\})}$$

Where R is the resistance at the new temperature T, R_o is the resistance at temperature T_o (Usually 0^{o} Centigrade), and α is the temperature coefficient (0.00385 Ω / Ω / ^{o}C. The above equation is satisfactory for most applications above 0 degrees centigrade. For temperatures below 0 degrees Centigrade, there is a forth order polynomial that is used. This is because RTD's are non-linear below 0^{o} C. Also, for more accuracy, there is a second order polynomial that is sometimes used above 0^{o} C.

To measure temperature with a RTD, **the resistance must be measured**. The only reasonable way to do that is to force a current through the device and measure the voltage drop across it. Two problems occur. The first is that the device being measured (the RTD), will heat up if a current is forced to flow through it. From basic power theory, **Power equals Volts Times Amp**s. So, the RTD will get heated up by the process that is used to measure its resistance and thus its temperature.

That means that the temperature that is read is always higher than the actual temperature. The fortunate thing here is that the current can be made low enough so that this effect is not a significant source of error.

The second problem that occurs is that the wires leading from the RTD to the measuring instrument have resistance. Not only that, the resistance of these wires changes with temperature. This can cause a small error in measurement. To give some idea of the magnitude of this error, consider connecting a 100 ohm RTD to an instrument that is 100 feet away. That means that there is 200 feet of wire from the sensor to the meter. We must count 100 feet going to the sensor and 100 feet returning to the meter. Number 18 wire, a typical size of wire used in this application, has a resistance of about 7 ohms per 1000 feet. That means that there is an extra 1.4 ohms of resistance in series with the RTD. Figure 3.1 shows how this line resistance affects the RTD resistance.

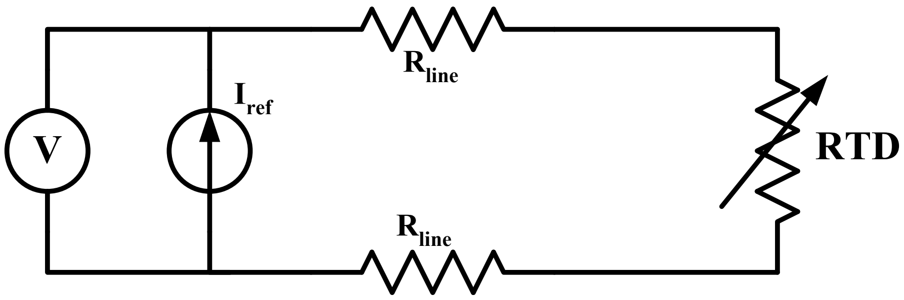

Figure 3.1 Typical RTD Measuring Circuit Showing Line Resistance

Instead of measuring 100 ohms at 0 degrees Centigrade would measure 101.4 ohms.
The voltmeter, V, represents the ce, I_{ref}, is also a part of the
measuring meter. C to the RTD, the lower the
error. Also, the bigg a resistance of 1 ohm
per 1000 feet, were u sensor and the meter
would only be 0.2 oh ly be 100.2 ohms.
Again, with bigger wir uation:

For a 100 Ω PT RTD, the of 0.52° C with # 10
wire at 0° C. Using α of

There are three techniq ire method, the
three-wire method, and wire method of
measurement. Figure 3. that one end of
the RTD has two connect en be shown to be:

$$V_{ba} = \frac{V_{ref}}{2} * \left\{ \frac{\Delta R}{2R(0) + \Delta R + 2R_{line}} \right\}$$

Circuits like this typical bridge use a precision voltage reference. If a 1.000-volt reference was used, the power dissipation of the 100 ohm RTD at 0° C would be about 2500 microwatts. This could cause **a self heating error**. Using a smaller reference voltage will cause a smaller self heating error. However, using a smaller reference voltage will make more amplification