by Daniel Malik

Unique Way to Measure Temperature

A Heating Element Turned Sensor

Forget those expensive temperature sensors. Now you can use an ordinary heating element like a soldering iron to measure temperature. Daniel's upgraded soldering iron will be a great addition to your workbench.

There are many applications that involve the conversion of electric current into heat by means of a heating element with some degree of temperature control. Hot water boilers, kettles, and irons are typical examples. In this article, I'll explain how you can eliminate the need for a temperature sensor by using the heating element itself to accurately measure temperature (see Photo 1).

BASIC PRINCIPLE

I appreciate that electronics enthusiasts don't necessarily want to read about cooking and ironing. So, I'll describe a device you might be more comfortable thinking about: a soldering iron. All of the aforementioned appliances and tools have one important thing in common that makes them different from, say, a hair dryer. Any thoughts?

The important common factor is that the thermal resistance between the heating element and the heated medium is much lower than the thermal resistance between the medium and the ambient world. Thus, if electric current stops flowing through the heating element, the temperatures of the element and the medium will equalize long before the medium loses much of its temperature via heat radiation and conduction.

Because the resistance of all the conductors used for constructing heating elements has some temperature coefficient, you can measure the temperature of the heating element by measuring its resistance and comparing it to its resistance at, say, 25°C. This brings us neatly to the basic idea behind this project.

First, you turn on the heating element for a while. Then, switch it off and wait for the temperatures to equalize. After that, you must measure the resistance and calculate the temperature. And then do it again: switch on, switch off, measure, and so on. It's easy to see why this approach wouldn't work with a hair dryer. The air forced through a hair dryer moves quickly and has poor heat conductivity.

I can hear you asking the obvious questions. How difficult is it to measure the element resistance? How much does it change with temperature? Wouldn't a simple sensor be cheaper and easier to use? It depends on the application. I will address these concerns as I describe the soldering iron example.

Photo 1—*Check out my finished soldering station. Think of it as a heating element turned temperature sensor.*

WHAT'S MEASURED?

An archaeological excavation conducted in my garage one Saturday afternoon revealed a nice 50-W soldering pen. The resistance of the heating element is 12.3 Ω at room temperature. It crawls to 13.0 Ω when the element is heated to 300°C. The difference in resistance needs to be measured with at least 7-bit accuracy to achieve approximately 3°C resolution over the 100°-to-450°C operating range. This means that the resolution of the resistance measurement must be better than 5.5 mΩ!

Is it worth the trouble? Inexpensive thermistors can't be used at temperatures much higher than 150°C. Thermocouples and platinum sensors can be used at much higher temperatures, but they're expensive and not exactly trivial to use. It's also important to achieve good contact (low-temperature resistance) between the sensor and the medium (the tip of the soldering pen in this case), which might pose a mechanical challenge. My soldering pen also came with a nice heat-resistant cable, but it had only three conductors. I'd have to replace it in order to use a sensor. After considering all of these things, I was ready to spend time developing the resistance measurement technique.

But the question still holds for other applications. For example, mounting a simple thermistor on a hot water boiler will no doubt prove simpler than trying to measure the resistance of the immersion heater, which operates at mains voltage.

HOW TO MEASURE

Assume that I have convinced you that the approach makes sense. Before deciding which measuring method to use, you need to consider the technique's basic requirements.

The construction of the heating elements usually resembles wire-wound resistors. To pack long enough wire into a small space, the wire is wound into a coil that's mechanically supported by a piece of nonconductive material. This means that the element has considerable inductance and the measurement technique needs to ensure that the inductance of the element is distinguished from its resistance. This is important because surrounding objects may influence the inductance. Changes in such interference would lead to incorrect variations in the measurement results.

The heating element is connected to the power source by cabling (with or without connectors). It's important to make sure that changes in the cable/connector resistance aren't taken into account.

Power dissipation in the element during measurement needs to be low compared to the thermal resistance between the element and the heated medium. Otherwise, a significant difference in temperature would develop between the two and the measurement would be inaccurate.

MEASUREMENT TECHNIQUE

Resistance measurements are simple in principle. In fact, it's the same method you remember from your first physics class on electricity. You let a constant current flow through the resistor, and the voltage drop across it will be directly proportional to the resistance. However, this basic principle can't be applied directly because of the need for high accuracy. Eliminating the resistance of wiring and connectors would require employing the Kelvin method and four leads in the connecting cable. The resistance only changes by less than 6%, and evaluating such a small voltage change superimposed on a relatively high DC component with the required accuracy wouldn't be simple.

Fortunately, you can use a simple method developed in 1833 by Samuel Hunter Christie to overcome these problems. Sir Charles Wheatstone described the solution in 1843 in a paper on electrical measurements. It has been known as Wheatstone's bridge ever since then despite the fact that Wheatstone acknowledged that the invention wasn't his. What an injustice!

Figure 1a depicts the bridge configuration with one variable-resistive element. It's easy to see that the differential between V_1 and V_2 is going to be zero when R_1/R_2 equals R_3/R_4. This is satisfied, for example, when R_1 equals R_3 and R_2 equals R_4. After the variable resistance of R_2 starts to differ from R_4, the bridge becomes unbalanced. You can detect this by observing that V_1 is no longer equal to V_2.

By going through a lengthy and fairly boring calculation, you would discover that the voltage differential V_1 to V_2 has nonlinear dependency on the variation of R_2. The exact transfer function depends on the properties of the power supply used to power the bridge. An even longer and more boring calculation would reveal that the nonlinearity could be reduced by half

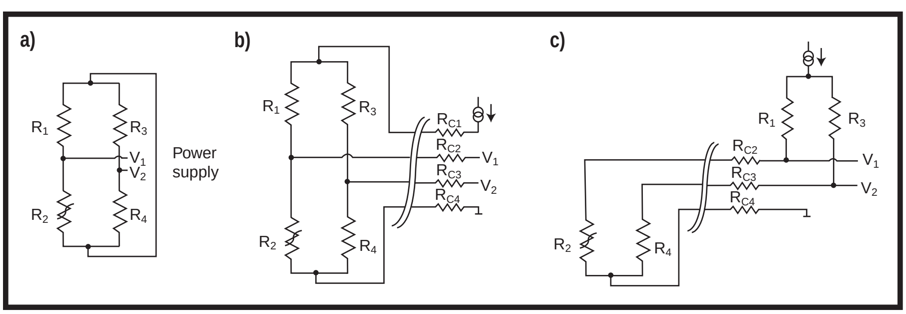

Figure 1a—*Here the bridge circuit has one variable element.* **b—***In this instance, all four bridge components are found in the soldering pen. It's the most obvious way of adding a cable to the circuit.* **c—***The new circuit topology involves a cable with only three conductors to complete the bridge circuit.*

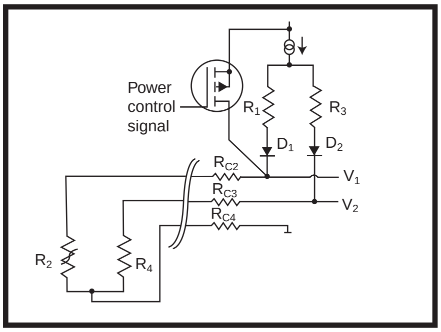

Figure 2—*It's a fairly simple solution, right? Simply add the power switch and protection diodes.*

by using a current source instead of a voltage source.

Using a current source to power the bridge has an additional benefit. You can reasonably expect that the voltage source supplying power to the entire application will be noisy to a greater (if you decide to use a switch-mode power supply to save space and weight) or lesser degree and not necessarily stable (mainly if an unregulated 50/60 Hz transformer supply is used). The current source will act as an additional filter blocking the noise and ripples from entering the sensitive analog portion of the circuit. Because the current source will provide DC current to the bridge, the inductances and capacitances in the circuit won't influence the result. You can therefore tick off the first condition from your list.

Figure 1b depicts a situation where all four bridge components are located inside the soldering pen. R_{C1} through R_{C4} represent the resistances of the cable wires and connector pins. R_{C1} and R_{C4} are connected in series with the current source. Therefore, they don't influence the result of the measurement because the current through the bridge always remains the same. R_{C2} and R_{C3} are connected in series with the voltage differential detection circuit.

You must try to design the circuit so that its input impedance is significantly higher than the cable/connector resistance. Then the current flowing through R_{C2} and R_{C3} will be small and have little dependence on R_{C2}/R_{C3} variance. Thus, the solution satisfies the second condition. It requires four conductors in the cable, however.

You can improve the situation by assuming that the cable conductors and connector pins all have the same properties. (This will be true in the majority of cases with the exception of coaxial and other special cables.) The new circuit topology is depicted in Figure 1c. Only half of the bridge is located in the soldering pen; it's separated from the other half of the circuit by the cable. R_{C2} and R_{C3} simply add to R_2 and R_4. If R_{C2} and R_{C3} are the same and also vary in the same way, the balance of the bridge won't be influenced by their presence. R_{C4} is connected in series with the current source, and therefore doesn't influence the measurement.

To satisfy the last requirement, design the current source to provide the optimum current for powering the bridge. You need to compromise between a high current, which would heat up the bridge elements too much, and a low current, which would make the voltage difference between V_1 and V_2 too low for accurate measurement.

COMPLETE THE CIRCUIT

So far, I've covered only the measurement technique. But for the application to be of any practical use, you need to add some circuitry to apply power to the heating element when you want to heat it up. Simply connecting a voltage source across the heating element would have some undesirable side effects. The relatively high voltage would also appear at the output of the current source (through R_1). As a result, the current source would have to be designed to be immune to it. More importantly, an extra current would start to flow through the rest of the bridge circuit. Because all of the resistors have a comparable resistance, the dissipated power would be considerable.

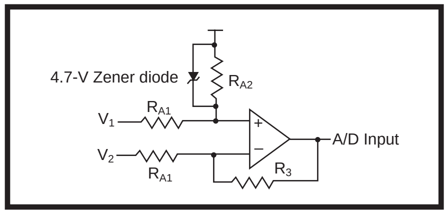

Figure 3—*An op-amp is used to create the differential amplifier that amplifies the voltage across the bridge circuit. The Zener diode protects it against overvoltage when the heating element is on.*

The solution to the problem is depicted in Figure 2. The high-side PMOS switch applies voltage to the heating element. Diode D_1 protects the bridge circuit when the power switch is on. The voltage drop across D_1 in one branch of the bridge is compensated by the addition of D_2 into the other branch. The voltage drop across a diode is primarily dependent on the current flowing through the diode and its temperature. The bridge is always close to a balanced state during measurement. Therefore, currents through the diodes are similar.

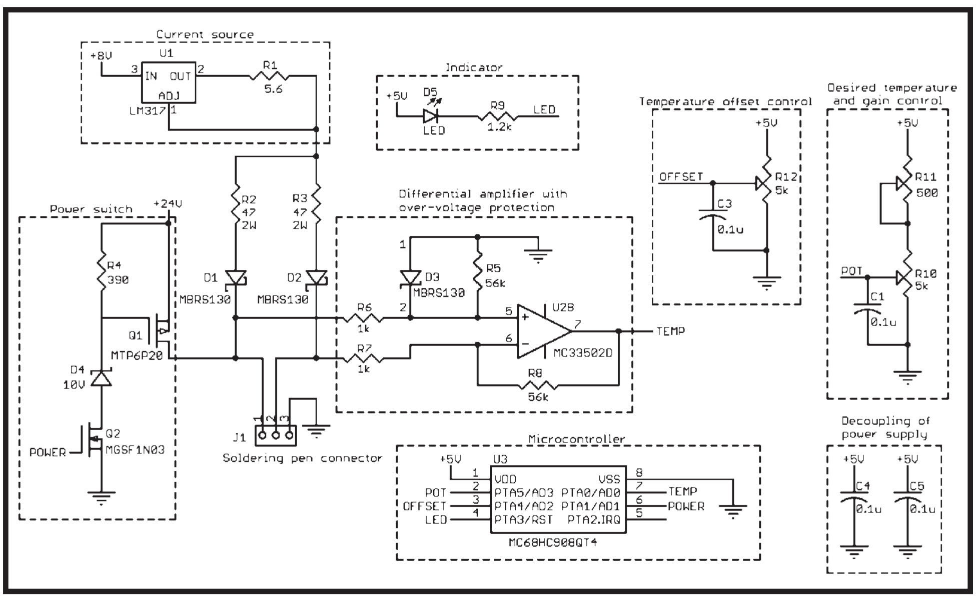

Figure 4—*The power supply is the only part not shown in the schematic of the soldering station. The current source is powered by 8 V to reduce power dissipation.*

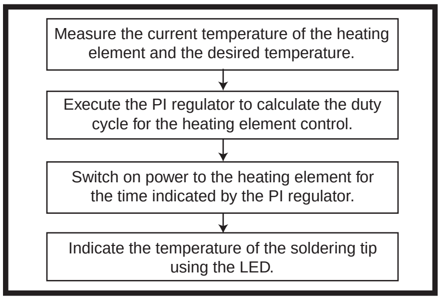

Figure 5—*The microcontroller executes this algorithm repeatedly in an endless loop.*

A slight difference in the diode currents will contribute to the additional nonlinearity of the circuit. Placing the diodes close together on the PCB will help to keep them at the same temperature. This is more important because you can deal with nonlinearity, but the temperature drift would be hard to compensate for.

Now you can apply voltage to the heating element and raise its temperature. The bridge circuit is now protected when the high voltage is switched on. There is only one piece of the measurement circuit missing: a differential amplifier. A differential amplifier will tell you how far the bridge is from a balanced state during measurement. Thus, it will indicate the temperature of the heating element.

The differential amplifier depicted in Figure 3 is a standard differential circuit based on an op-amp. The Zener diode protects the op-amp from overvoltage when power is applied to the heating element. A Zener voltage of 4.7 V is suitable for op-amps powered by a 5-V supply. The ratio between resistors R_{A2} and R_{A1} determines the circuit's amplification factor. This makes the circuit easy to trim so you can make the best use of the ADC's available input voltage range.

COMPLETE APPLICATION

The complete application is shown in Figure 4. In the measurement circuit, the current source is built from an adjustable linear regulator. The current is set to a little higher than 200 mA. The main power switch Q1 is connected to an additional transistor circuit to translate the control voltages down to the 0- to 5-V range the Freescale MC68HC908QT4 microcontroller is capable of generating.

The MC68HC908QT4 microcontroller is an inexpensive 8-bit HC08 device housed in an eight-pin DIL package that's easy to work with. The microcontroller is connected to an LED that indicates whether the soldering tip is below, equal to, or above the desired temperature. A potentiometer regulates the desired temperature. The remaining pieces of the circuit are two trimmers that are used to calibrate the offset and gain of the temperature regulation.

A schematic of the power supply I used isn't shown here. I used a small, lightweight custom switch-mode power supply. However, the circuit will work equally well with a mains transformer-based power supply.

This temperature measurement application is very simple. As a result, the small amount of code for the 'HC908QT4 is little more than 700 bytes. The basic algorithm is shown in Figure 5.

PROVEN RELIABILITY

I'm pleased with my new soldering station. The tip temperature regulation is accurate to ±2°C over the entire operating range, which is more than enough even for soldering fine-pitched SMD components.

I've been using the station for all of my soldering jobs ever since I finished it. It has proven to be a reliable tool. Now you can build one for your workbench.

Daniel Malik (danmalik@centrum.cz) earned a Master's degree in electronics at the Czech Technical University in Prague. He's currently a senior applications engineer in Scotland. Daniel's interests include 8- and 16-bit applications and modern communication interfaces like USB and FlexRay.

PROJECT FILES

To download the code, go to ftp://ftp.circuitcellar.com/pub/Circuit_Cellar/2006/191.

SOURCE

MC68HC908QT4 Microcontroller
Freescale Semiconductor, Inc.
www.freescale.com