Analog Signal Conditioning for Accurate Measurements

sealevel.com/support/analog-signal-conditioning-for-accurate-measurements

Q: Should I put some sort of circuit between my sensor and an analog-to-digital converter?

A: Yes. You probably need some signal conditioning. The explanation below goes on for a bit, but stay with it and you'll understand what you need and why you need it.

Before you make any connections, get the electrical specifications for the analog-to-digital converter (ADC) and for the sensor or sensors in your system. Let's assume the data-acquisition module uses a Maxim Integrated Products MAX197 12-bit ADC. This device can accept eight differential (2-wire) inputs or 16 single-ended (1-wire) inputs. Maxim's specifications show an input impedance of 21 kohms for single-ended inputs and 16 kohms for differential inputs.

Now let's assume your system uses an Analog Devices AD590 temperature sensor in a simple circuit (**Figure 1**) to produces a 1-mV/K output. The sensor serves as a variable-current source that passes 1 μA per Kelvin (K), or per degree Celsius (°C). The Kelvin scale uses the same increments as the Celsius scale, but it starts at absolute zero: 0K or -273°C. At 0°C, the Kelvin scale reads 273K and at 25°C it reads 298K. The Kelvin symbol does not include a degree mark. (For a temperature-scale comparison, visit: http://www.magnet.fsu.edu/education/tutorials/magnetminute/kelvin-transcript.html.)

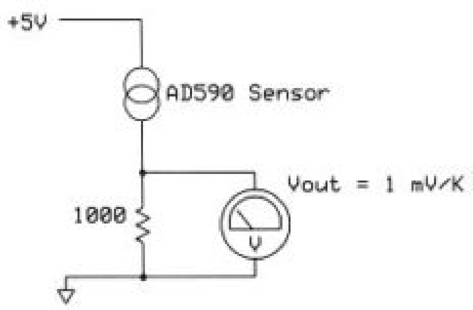

Figure 1. The current from this AD590 sensor passes through a precision 1000-ohm resistor. The resulting voltage represents temperature at a rate of 1 mV/K. So at 20°C (293K), you would measure 293 mV at the circuit output.

Now what happens when you connect the AD590 to a single-ended input on the MAX197 ADC (**Figure 2**)? Note this arrangement places the 1000-ohm resistor at the sensor in parallel with the ADC's input resistance; 21,000 ohms.

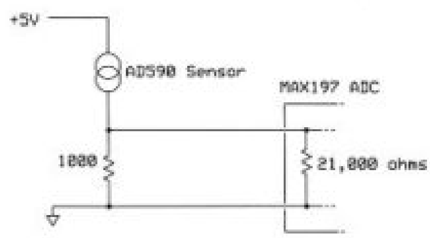

Figure 2. The connection of an AD590 sensor and MAC197 ADC creates a circuit with two resistances in parallel.

Could the ADC input resistance affect temperature readings? Ohm's Law lets us calculate the equivalent resistance for these two resistors:

$$R = \frac{R_{sensor} \cdot R_{ADC}}{R_{sensor} + R_{ADC}} = \frac{1000 \cdot 21000}{1000 + 21000} = 955\Omega$$

As a result, the complete circuit looks like that shown in **Figure 3**. If a 1000-ohm resistor provides a 293 mV output for a 20°C temperature, what happens when the circuit has a 955-ohm resistor instead?

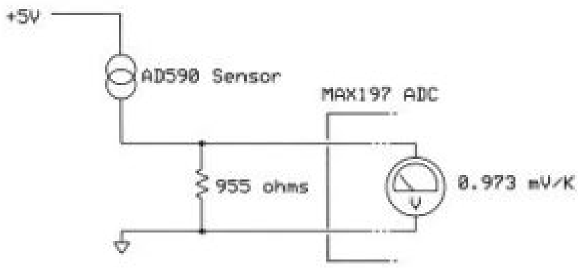

Figure 3. The equivalent circuit for the AD590 sensor and the MAX197 ADC.

Once again, Ohm's Law lets us calculate the voltage from the known current through the sensor and the parallel resistance. At 293K, the AD590 passes 293 µA, but with the 955-ohm resistor, what voltage goes to the ADC input?

$$I \cdot R = E \quad or \quad 293\mu A \cdot 955\Omega = 285mV$$
$$285mV \cdot 1K / mV = 285K$$

The voltage output does not match what we expected. In other words, the input impedance of the ADC will cause an 8-Kelvin error in the ADC reading. So you should not connect the AD590 sensor-circuit output directly to a MAX197 input.

Keep in mind the AD590 controls the small current flow and it–*not* the 1000-ohm resistor–creates a high-impedance output.

Q: So how do I overcome this impedance problem?

A: You need an amplifier with a low-impedance, or low-resistance, output that will provide sufficient current so the ADC input resistance does not affect the amplifier's output signal. In other words, if the amplifier produces a 2.20-volt output, for example, the 21,000-ohm input resistance of the MAX197 ADC should not affect the 2.20-volt signal. (Or if a slight difference occurs, it should be small enough that the ADC will not detect it.)

The data sheet for the AD590 sensor includes a circuit that uses an OP177 operational amplifier (op amp) to boost the sensor signal (**Figure 4**). The OP177 circuit produces a 100-mV/°C, or 100-mV/K, signal. The OP177 data sheet lists a typical open-loop output resistance of 60 ohms. This resistance in parallel with the 21,000-ohm input resistance of the MAX197 ADC yields a combined resistance of 59.8 ohms–a change of less than one percent.

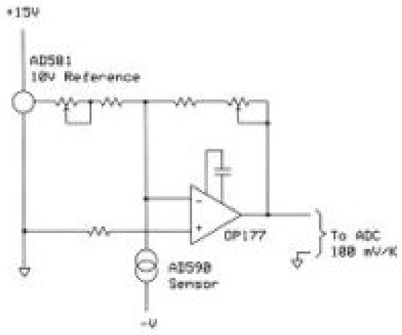

Figure 4. Example circuit for an AD590 sensor that uses an OP177 operational amplifier (op amp) to provide higher voltages to an ADC or other measurement circuit. (Courtesy of Analog Devices.)

If an op-amp data sheet lacks output-resistance information, you can perform an experiment to determine it. Let's assume an op amp produces a 2.20-volt output with nothing connected to the output–an open circuit. Place a 100-ohm precision resistor between the output and ground (**Figure 5**) and measure the op-amp output voltage and the current through the resistor. You can use a different resistance value if you wish. Caution: Use a digital meter with a high input impedance or the meter itself will alter the measurements.

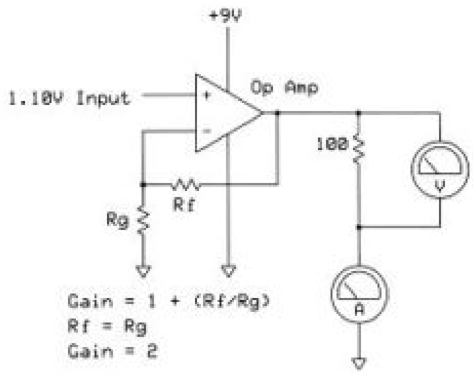

Figure 5. Test circuit for an op-amp output impedance, or resistance. In this circuit the non-inverting op-amp configuration amplifies the 1.10-volt signal by two.

Say the voltage drops from 2.20 volts to 2.17 volts for a current of 20 mA (0.02A) through the 100-ohm resistor. Use Ohm's Law to calculate the op-amp's output resistance. You know the current from the op-amp's output and you know the voltage difference between an open-circuit and a loaded-circuit condition:

$$R = \frac{E}{I} \quad or \quad R = \frac{2.20V - 2.17V}{0.020A} = \frac{0.03V}{0.02A} = 1.5\Omega$$

That's a sufficiently low output impedance that the ADC input resistance will not load the amplifier enough to alter the 2.21-volt output.

To learn more about op amps I recommend the book, "Op Amps for Everyone," by Bruce Carter and Ron Mancini. Elsevier-Newnes, 2013. ISBN-13: 978-0123914958. You can find a lot of useful information on the Internet, too.

Q: What if I don't have the time or experience to build and test op-amp circuits?

A: Use an instrumentation amplifier instead. This type of amplifier, often called an "in amp" or INA, provides a "gain block" that simplifies connections between sensors and ADCs. The INA827 amplifier from Texas Instruments provides a good example. One external resistor sets the gain or amplification factor. Op-amps on the other hand, require several carefully matched resistances. The INA827 offers amplification factors of five and as high as 100. Companies such as Analog Devices, Linear Technology, Microchip Technology, and Texas Instruments sell many types of in-amp integrated circuits (ICs), which make it easy to design and construct an in-amp "front end" signal-conditioning circuit for your ADC.

Unfortunately, only a few companies sell in-amp modules that let you set the gain with an external resistor you select. Most commercial in-amp modules offer only preset gains of, say, 1, 10, 100 and 1000. These modules also constrain input voltages to a preset range and produce an output voltage within a preset range. In other words, they don't offer much flexibility. For examples of modules that provide more flexibility, visit Omega Engineering or Ocean Controls (Australia).

If you decide to design and build an in-amp circuit, the evaluation boards and modules available from the in-amp IC manufacturers let you experiment with the ICs in working circuits. Digikey lists 13 in-amp evaluation boards, most for under $100. If you decide to use an in-amp IC, I might choose a prototype board that fits in a DIN-compatible enclosure. The "Electronics Salon" eBay store sells several such boards and housings that clip onto a standard DIN rail used in industrial-control equipment.

Q: Does an instrumentation amplifier offer advantages over an op amp?

A: Yes. In addition to using only one resistor to set the gain, or amplification factor, in-amps have a high input impedance, so they don't affect signals from high-impedance sensors such as an AD590. In amps also have a high common-mode AC/DC rejection ratio (CMRR). That means a signal common to both the positive and negative amplifier inputs gets greatly attenuated before it reaches the in-amp output. The INA827 in amp has an 88 dB CMRR for DC signals. The CMRR in amplifiers decreases at the frequency of input signals increases. An in-amp can remove common-mode AC signals such as 60- or 50-Hz electrical noise caused by nearby equipment. For more information about CMRR, visit: http://en.wikipedia.org/wiki/Common-mode_rejection_ratio.

The circuit in **Figure 6** illustrates an in amp connected in a bridge circuit that could measure strain, pressure, humidity, or another physical phenomena with a resistive sensor substituted for the Rs component. One side of the bridge connects to the in-amp positive input and the other side connects to the in-amp negative input. To start, assume all resistors in the bridge have the same value.

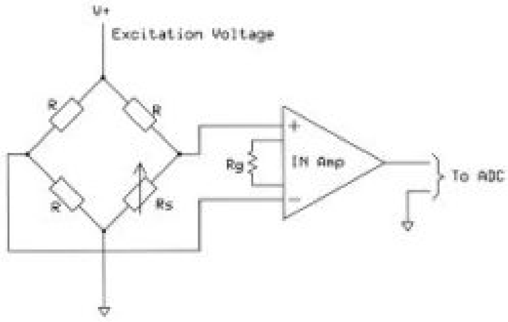

Figure 6. This bridge circuit indicates a resistance change in the sensor element (Rs) as a voltage difference between the two output signals applied to the in amp. The amplifier removes any common-mode voltage from the excitation source and puts out only the voltage difference between the two inputs. Resistor Rg determines the in-amp's gain.

As the sensor's resistance changes, the bridge circuit produces a small voltage *difference* between the two connections to the in amp. Both inputs also receive a part of the bridge's excitation voltage, say +3 volts. Thus, in this example the in-amp minus input "sees," a 2.000V signal, while the positive input "sees" 2.015V. The 0.015V difference between the two inputs provides the useful sensor information. Note that the in-amp circuit converted a *differential signal* to a *single-ended signal referenced to ground*. In-amps have a reference input, so if necessary you can offset the in-amp's output. I'll talk more about amplification and offset in my next column.

For more information about in amps, I recommend the following:

1. "A Designer's Guide to Instrumentation Amplifiers," 3rd edition, Analog Devices
2. "Getting the Most out of Your Instrumentation Amplifier Design," Texas Instruments
3. "Ultra-precise Instrumentation Amplifier Makes Robust Thermocouple Interface," (PDF) Design Note 302, Linear Technology.