CIRCUIT CELLAR ONLINE

## LESSONS FROM THE TRENCHES

**George Martin**

# Analog System Design

George likes poking fun at Windows98, comparing it to a challenging computer game, but this month, he turns his attention to an analog design project involving a custom car. Transducer interfaces and thermocouples became the topic of discussion for his article, along with noise and filtering. Get set for another analog endeavor as he takes us through the many considerations that come with the territory.

a man walks into an electronics store and asks the clerk for a new computer game. He wants one that's filled with lots of graphics, is challenging, and full of twists and turns. The clerk pauses for a moment and suggests Windows98! I'm the proud owner of WIN98 SE, so I believe I qualify to poke fun at Microsoft's expense. In the last few weeks, Microsoft stopped selling Windows95. It's time to move on.

This month, instead of going down a software or digital path, I'd like to talk about how I recently consulted on an analog design project. A customer called and told me he was putting together a custom car. It's actually a rally car for the street. If you ever come upon a Subaru with a rear wing, be careful, one in the country has about 300 hp and can fly. The car story is long, but his request has a lot of application.

He is a highly qualified software and computer engineer and would like to add a panel that displays all of the sensor readings. He starts asking about thermocouples and how to get them into the ADC. This is a good question but there are so many options to consider before I get into that.

So, let's take a step back for a moment. Any analog system will contain transducers that represent a real-world values such as temperature or oil pressure as voltage, current, or perhaps resistance. Easy-to-use transducers take no input power and have their outputs scaled to a value that can be connected to an ADC (i.e., an oil pressure transducer with 0 to 120 psi as 0 to 10 V). These transducers are convenient to design with but probably expensive.

What you are more likely to find is a transducer that has resistance output. The resistance is 1000 ohms at 0 psi and nonlinearly changes to 900 ohms at 120 psi. Or, a thermocouple that makes 0 V at freezing and 40 µV/°C.

When non-analog designers come up with inputs such as these, they are stumped. And, I usually find that they take an over-complicated path to a solution. So, let's try to layout a framework for analog system design.

## CONSIDERATIONS

There are two areas you must consider before you get into transducer selection—operating voltages and power supply.

Operating voltages are the voltages available for the circuitry. In the '70s and '80s, typical voltages were 15 and –15 V for the analog bias voltage and 5 V for the logic. The op-amps were powered with the ±15 V, and the signal range was typically 10 to –10 V. And, the ADC had –10 V as negative full scale and 10 V as positive full scale. The ADC was usually a separate IC and ranged from 10 to 12 bits.

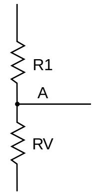
As devices got better, analog systems had RS-232 devices for I/O. The ±15-V supply became a ±12-V supply, and the signals were still scaled at ±10 V. Amplifiers had better performance specification. They could linearly handle signals going closer to the positive and negative rails. The ±12 V were used for the RS-232 drivers as well as the analog bias, with proper decoupling! Recently, the ADCs have moved onto the CPU and become more accurate and flexible as to the voltage inputs. Also, there are the RS-232 drivers that make their own ±12 V.

There is another approach to supply voltage selection, single-sided supply. A common design you will see in application notes is the 0- to 5-V design. The amplifiers are biased with 0 and 5 V. This is good because it reduces the number of supply voltages required in the system. However, we all know there's no such thing as a free lunch. The amplifiers cannot fully swing to 0 and 5 V. They get close but with little drive capability. And as the drive requirements increase (sinking or sourcing current), their ability to drive to the rails is decreased. So, one solution in a 5-V system would be to scale the analog voltage from 0.5 to 4.5 V. That would be a 4-V swing and the amplifiers could sink and source at those voltages. If cost is a factor (and it usually is), this might be a wise approach.

Another consideration is power supply. My specific design is a vehicle with a 12-V battery. If you look at DC-to-DC conversion, you'll find that there are buck, boost, and buck-boost converters. Buck converters produce a smaller output voltage than the input voltage, boost converters produce a larger output voltage, and buck-boost converters can produce an output voltage that is either smaller or larger than the input. Both buck and boost converters can be over 90% efficient, but buck-boost converters do not reach the same level of efficiency.

How important is efficiency in your design? In a car, it's probably not too important. In a battery-operated device, it becomes very important. Also consider the office product that has a wall-mounted transformer. Because the wall power 115 VAC can range from 90 to 130 VAC, the input to the power supply can vary in direct proportion. Then, an inefficient power supply that will run with a 90-VAC input will produce a lot of heat at the 130-VAC condition. And remember, heat kills!

**Figure 1—***Here's a simple voltage divider network that can be used to monitor the voltage across a transducer. Although it's simple, any noise that is picked up will affect the signal you are measuring.*



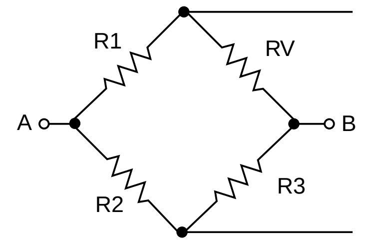


**Figure 2—***A better method is to use a bridge. Any change in the reference voltage as a result of noise or some other factor will not affect the ration of A to B.*

There is no one correct answer to the best bias voltages. You need to consider all the voltages that are required for your system along with the power supply requirements. Some of these voltage requirements come from the ICs you are going to use and others come from transducer interfacing, which I'll look at next.

## TRANSDUCER INTERFACES

The simplest transducer is a resistive element that changes with the parameter you need to measure. You could just run a voltage out to the transducer, place another resistor in series, and measure the voltage at the junction of the resistors (see Figure 1). The problem with this approach is that any noise that is picked up on either the reference voltage or ground directly affects your signal in an adverse way.

Consider a bridge for the transducer (see Figure 2). The reference voltage is connected to R1 and Rv and the return is connected to R2 and R3. If all resistors are nominally 1000 ohm, then the voltages at points A and B are the same and 50% of the reference voltage. If the reference voltage is reduced, the voltage at A and B are still the same, and A/B = 1.0. If resistor Rv changes from 1000 to 900 ohms, then the voltages at A is 50%, B is 47.4%, and the ratio of A/B is 1.06. If resistor Rv changes from 1000 to 1100 ohms, then the voltage at A is 50%, B is 52.4%, and the ratio of A/B is 0.95.

Any change in reference voltage or ground does not affect the ratio of A to B; you've got some noise immunity built-in. Also, by adjusting R3, you can change the starting ratio (zero engineering units) and the final ratio (max engineering units). So, you can get some offset and gain directly from the bridge. If you have a single-sided analog system (0 to 5 V), you might want the ratio to always be less than 1.0 (i.e., B is larger than A). Then you could put A/B (always a positive number) into an amplifier.

## THERMOCOUPLES

Let's turn to temperature and thermocouples. There are a lot of great references on the Internet for thermocouples, and you should do a search for a more involved discussion as to which thermocouple is best suited for each application. Basically a thermocouple is a junction of dissimilar metals (see Figure 3). The junction produces a voltage and that voltage is proportional to temperature, with 0 V produced at absolute zero.

Thermocouples have two basic characteristics. The first is that they produce about 40 µV for 1°C. If you're measuring the temperature of a furnace, the thermocouple might make a lot of volts. But, I also suspect you'd be interested in the exact temperature of the furnace not just an estimate to the nearest 100°. So, you need a high gain stage to get the microvolts into the A/D range.

The other characteristic is that there is a junction for the point of measure and also junctions when you change from the thermocouple wire

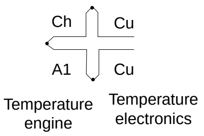


**Figure 3—***A thermocouple consists of a junction of two dissimilar metals. Well, at least it does until you connect it to your circuit!*

to copper wire for the circuit board. These junctions also produce voltages that affect the measurement.

Going around the loop in a clockwise direction, you have Cu-Ch at Temp-El (a copper Chromel junction at the temperature of the electronics), Ch-Al at Temp-Eng (a Chromel Alumel junction at the temperature of the engine), and Al-Cu at Temp-El (an Alumel copper junction at the temperature of the electronics). This can be written as follows:

$$V = (\text{Cu-Ch})_{\text{T-el}} + (\text{Ch-Al})_{\text{T-en}} + (\text{Al-Cu})_{\text{T-el}}$$

You can combine junctions at the same temperature, and note that reversing the sequence of the metals reverses the sign of the voltage:

$$V = (\text{Cu-Ch})_{\text{T-el}} + (\text{Al-Cu})_{\text{T-el}} + (\text{Ch-Al})_{\text{T-en}}$$
$$V = (\text{Al-Ch})_{\text{T-el}} + (\text{Ch-Al})_{\text{T-en}}$$
$$V = (\text{Ch-Al})_{\text{T-en}} - (\text{Ch-Al})_{\text{T-el}}$$

Because the voltage and temperature are linearly related, this reduces to:

$$V = (\text{Ch-Al})_{\text{T-en} - \text{T-el}}$$

In other words, the circuit directly measures the difference in temperature between the electronics and the engine.

In order to create a measurement relative to, say, 0°C, you need to subtract the voltage produced at the electronics junction(s). This is called cold junction compensation. In the old days, we used to have cold junction compensation blocks. These magic devices produced a voltage opposite of the offending junction. I've paid as much as $700 for one that handled 16 thermocouples.

Another approach I'd like to try is one in which you place a thermistor or IC temperature measuring device at the offending junction. If you know that temperature, you can calculate a cold junction compensation and have the CPU perform the correction. And, of course, there is an electronic solution. Maxim has a device to perform the correction.

## ADCS

Let's now look at ADCs. Two of the key parameters are the number of bits and the input voltage ranges. The number of bits is the precision of the device, but let me tell you that this one parameter can open a can of worms bigger than you've ever seen. You would expect that an 8-bit converter would have 256 unique output values for 256 unique input voltages. Then you would expect that increasing input voltages would produce increasing output values (monotonic or monoticity). Then you would expect that span of the input voltage for each output value would be the same. With a 10-V input range and 10 output values, each output value would span one input volt (not a very high precision device). If some of the output values only spanned 0.1 V on the input side, then others would span more than 1 V. This converter is monotonic, but not linear. And of course, no missing code would be a good deal.

The other ADC parameter is input range. Associated with input range is the reference voltage for the converter. The input range is just what it appears, 0 to 10 V, or –10 to 10 V. Many of the new converters have programmable input ranges, even programmable per channel. The reference voltage, which is sometimes generated by the ADC, is a requirement as an input. There are precision IC voltage references that are available if an external reference is required.

The ADC gives you the ratio of the input value to the reference voltage, so a 12-bit converter has 4096 output values. These range from 0 to 0xFFF, or 4095. And, an A/D reading of 4095 is equal to 4095/4096 of the reference voltage. Therefore, the following is true:

$$V = \frac{V_{\text{ref}}}{4095} \times \text{A/D reading}$$

I used to use references of 10.24 and 2.048 V to avoid the math of converting to decimal units and the associated rounding errors. But, I'm not so sure that's necessary anymore.

## ALMOST THERE...

Ready to put it all together? Let me throw in one more topic, noise and filtering. If you have a 12-bit ADC and you're going to measure an input signal, that signal will come with some noise. Let's first look at the frequency of the noise. If you're looking at oil pressure, there is no need to have any frequency greater than the engine speed, or perhaps a multiple of engine speed. So, 6000 rpm is 100 Hz, and if you picked a multiple of 12, then 1200 Hz is the maximum frequency you're interested in.

You should have a filter that attenuates frequencies greater than 1200 to a level of one part in 4096. This is so the noise does not show up in the A/D readings. There are a lot of filters and filtering techniques, but after the higher frequencies are in the A/D readings, there's no way to get them out. You can, however, sample at two or four times the Nyquist rate and then use a digital filter on the A/D readings. That would move your filter from 1200 Hz to 4 × 1200 = 4800 Hz, and you only have to filter down to one part in 1024. You can get the other two bits out in the digital filter. This makes for an easier analog filter design. Also, the factor of 12 put in the pressure reading probably comes from the number of teeth on the oil pump drive. You can pick up tooth chipping!

After you've selected a sampling rate and input filter for each of the channels, it's time to start the design. At this point, you can probably pick some supply voltages and input power supply design approaches.

If you look up thermocouples on the 'Net, you'll find a lot more information. Good luck in your analog endeavors.

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*output, data acquisition, and remote control. George is a charter member of the Ciarcia Design Works Team and most recently, he's been working on the people-tracking system for Bill Gates' new house. You can reach him at george.martin@worldnet.att.net*

## REFERENCE

Linear Technology's Corp., "LTC2401/LTC2402—1-/2-Channel 24-Bit µPower No Latency ΔΣ ADC in MSPO-10," January 2000, http://www.chipcenter.com/analog/images/prod474.pdf.

## SOURCE

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