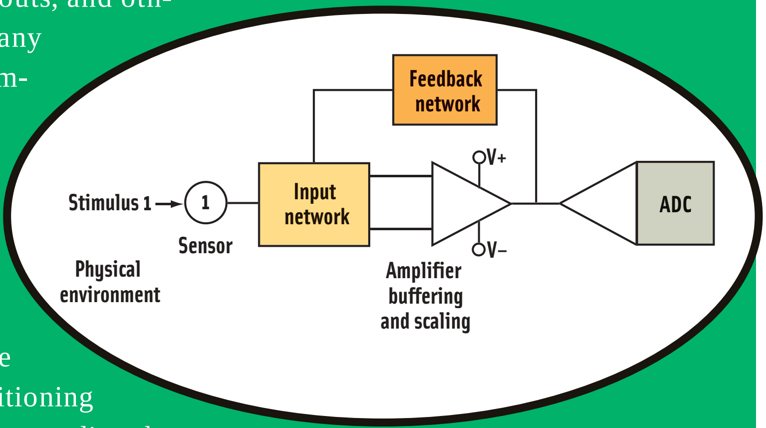
BASICS of Design

WORKING WITH ANALOG/MIXED SIGNALS

Gene Heftman, Contributing Editor

Sensor Interfacing—the Key to Successful Signal Conditioning

Signal conditioning often consists of converting an analog signal from a sensor in the physical world into a digital signal that can be used for data collection, controlling a process, performing calculations, producing display readouts, and other purposes. Analog sensors measure many types of physical phenomena such as temperature, pressure, force, flow, motion, position, pH (acid/base), and light intensity. Sensor signals usually can't be converted directly into digital data because their outputs are relatively small voltages, currents, or resistance changes that must be conditioned before being converted into digital data. Conditioning takes the form of amplifying, buffering, or scaling the analog signal to make it suitable for input to an analog-to-digital converter (ADC). That ADC then digitizes the signal and sends it to a microcontroller or other digital device for further data processing within the system (see figure, above). The key to making this chain work is selecting operational amplifiers that interface properly with the various types of sensors used in measurements. A designer must then pick an ADC that has the characteristics to process the signal from the input network and produce a digital output that satisfies the resolution, accuracy, and sampling rate of the data acquisition system.



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A. Sensors—The Starting Point

Sensors are classified according to the type of physical variable they measure: thermocouples, resistance temperature detectors (RTDs), and thermistors measure temperature; strain gages measure pressure or force; pH electrodes measure the acidity or alkalinity of a solution; and PIN photodiodes are used as photodetectors to measure light intensity. Sensors can be further classified as active or passive. An active sensor requires an external source of excitation (voltage or current), whereas a passive sensor generates its own electrical voltage without excitation. Common active sensors are RTDs, thermistors, and strain gages, while thermocouples and PIN diodes are passive sensors. To determine what specifications are necessary for the amplifier to interface with a sensor, a designer must consider the major sensor characteristics shown to the right.

SOURCE IMPEDANCE

- High source impedance is greater than 100 kΩ
- Low source impedance is less than 100 Ω

OUTPUT SIGNAL LEVEL

- A high signal level is greater than 500 mV full scale
- A low signal level is less than 100 mV full scale

DYNAMIC RANGE

The range over which the sensor's stimulus produces a measurable output signal. It depends on the type of sensor used.

B. The Amplifier's Role

Besides providing dc signal gain, the amplifier buffers and scales the sensor input before sending it to the ADC for conversion to a digital signal. The amplifier has two key responsibilities. One is to provide a suitable interface to the sensor, according to the sensor's characteristics. The other is to interface to the ADC based on the load presented to it. Included are the wiring distance between amplifier and ADC, capacitive loading effects, and input impedance of the ADC.

When selecting an amplifier to interface properly with a sensor, a designer must match the characteristics of the sensor with those of the amplifier. Certain amplifier characteristics are more critical to proper operation of the sensor-amplifier combination than others. These should receive higher priority when making tradeoffs on the type of amplifier chosen (see table, right). For example, a pH electrode is a high-impedance sensor, so the input bias current of the amplifier is a high-priority consideration (H in the table). The pH sensor provides a signal that must not be allowed to produce any appreciable current, so the amplifier must be a type that does not require high input bias current for its operation. A high-impedance MOS-input amplifier with low input bias current is the best choice to meet this requirement. On the other hand, gain-bandwith product (GBP) is a low-priority consideration (L in the table) for this application because the sensor operates at a low frequency and the frequency response of the amplifier should not prevent a true reproduction of the sensor's signal waveform.

SENSORS AND THEIR KEY AMPLIFIER SPECIFICATIONS

Sensor	Offset voltage	Offset-voltage drift	Gain-bandwidth product	Input bias current	Common-mode rejection ratio
pH electrode	M	M	L	H	M
PIN photodiode	M	M	H	M	L
Thermocouple	H	H	L	L	H
Strain gage	H	H	L	L	H

L = Low priority M = Medium priority H = High priority

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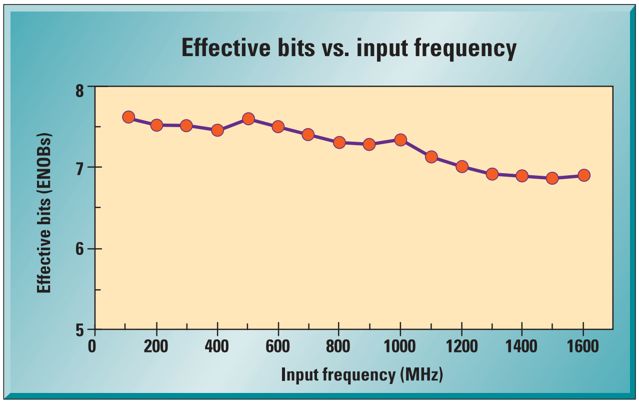

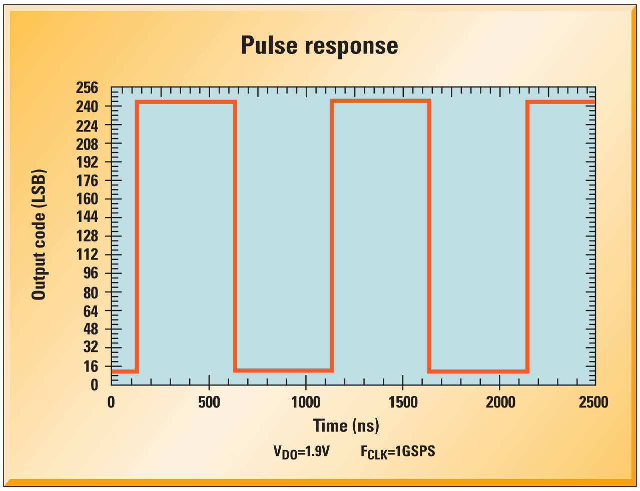

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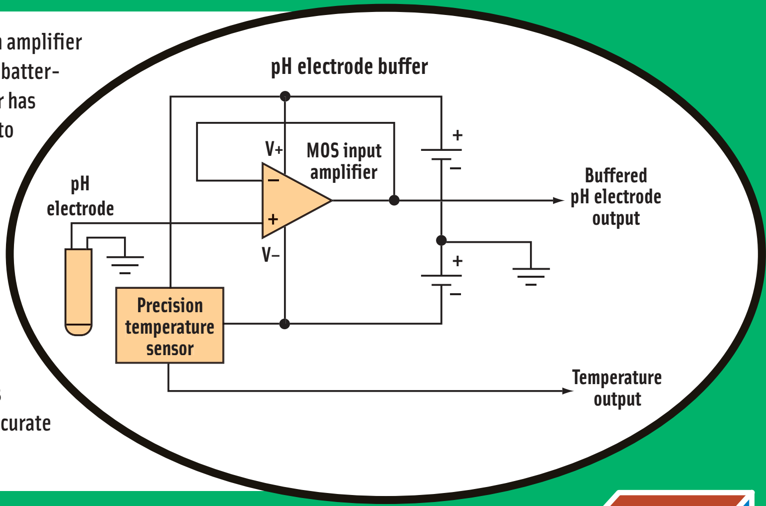
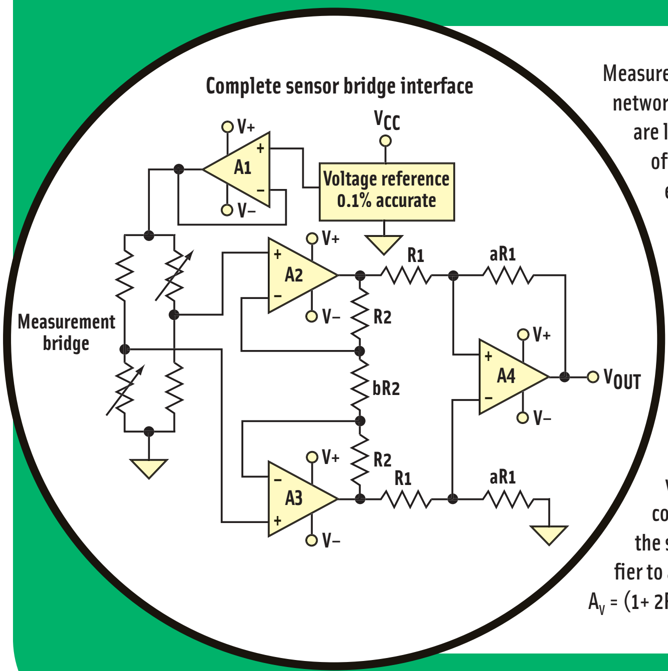
C. Matching The Sens

A high-impedance pH sensor can be paired with an amplifier that has a low-power circuit needing only two 1.5-V batteries to supply power (see figure, right). The amplifier has MOS-input transistors to present a high impedance to the sensor whose output impedance can be 1 MΩ or greater. Input bias currents for this amplifier are less than 0.1 pA, so amplifier operation takes very little current. Offset voltage for the amplifier is under 1 mV. The amplifier provides rail-to-rail operation and has high drive capability for sending a signal over long lines if the amplifier and ADC are far apart. An interesting addition to the circuit is a precision temperature sensor that measures the temperature of the pH sensor. This enables an accurate temperature-compensated value of pH to be made.





Measurements from commonly used sensors such as strain gages are taken via bridge networks, with strain gages forming two (or four) legs of the bridge. Strain gages are low source-impedance devices with low output signals ranging from hundreds of microvolts to a few millivolts. This circuit (see figure, left) offers a stable excitation voltage for the measurement bridge and high common-mode voltage rejection (CMR) for accurate measurement of the signal from the sensor, eliminating any common-mode voltages. Amplifier A1 is driven by a precision voltage reference with high accuracy and very low drift with temperature. This makes a very accurate, stable excitation source for the bridge. Because the common-mode voltage is about half the excitation voltage, the measured signal is just the small difference voltage between the legs of the bridge. Thus, amplifiers A2, A3, and A4 must provide high common-mode rejection ratio (CMRR) so that only the difference voltage is measured. Also, they must have low values of input offset voltage (V_{OS}), offset voltage drift with temperature [also known as offset-voltage temperature coefficient (TCV_{OS})], and input bias current to permit an accurate reading from the sensor. Amplifiers A1 through A4 are connected as an instrumentation amplifier to achieve these objectives. For this configuration, the voltage gain (A_V) is:
$A_V = (1 + 2R2/bR2)(aR1/R1)$, where a and b are ratios that determine overall gain.

sor And The Amplifier

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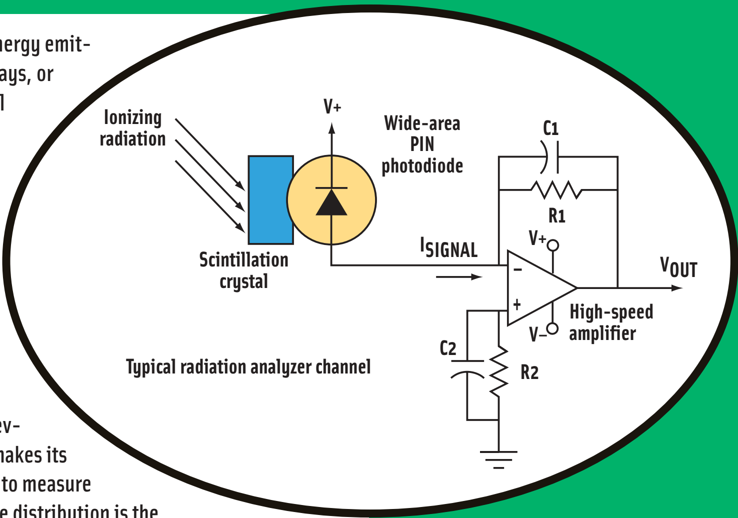
Radiation spectroscopy measures the distribution of energy emitted from a radiation source, which could be particles, X-rays, or gamma rays. The radiation strikes the scintillation crystal and emits a short burst of light in an intensity that's proportional to the energy. Then the light is converted to a current by a PIN photodiode. The amplifier (see figure, right) is used as a pre-amplifier and current-to-voltage converter for the output of the PIN photodiode. The circuit represents a single-channel analyzer used in basic radiation spectroscopy. The pulse amplitude of the signal contains the information of interest, so a low input offset voltage and offset voltage drift is important. The broad bandwidth provides the fast response to process the pulse, which can be as short as several nanoseconds. Output (V_{OUT}) from the pre-amplifier makes its way to a pulse-height analyzer (for example, a fast ADC) to measure and bin the number of occurrences of each peak value. The distribution is the spectrum for that particular source. The value of feedback resistor R1 depends on the maximum current from the PIN photodiode and the maximum output voltage into the ADC. Thus, R1 = (Max V_{OUT})/(Max I_{SIGNAL}). Capacitor C1 compensates the amplifier for the parasitic capacitance of the PIN photodiode. R2 and C2 are equal to R1 and C1 to compensate the input bias current of the amplifier's noninverting input.



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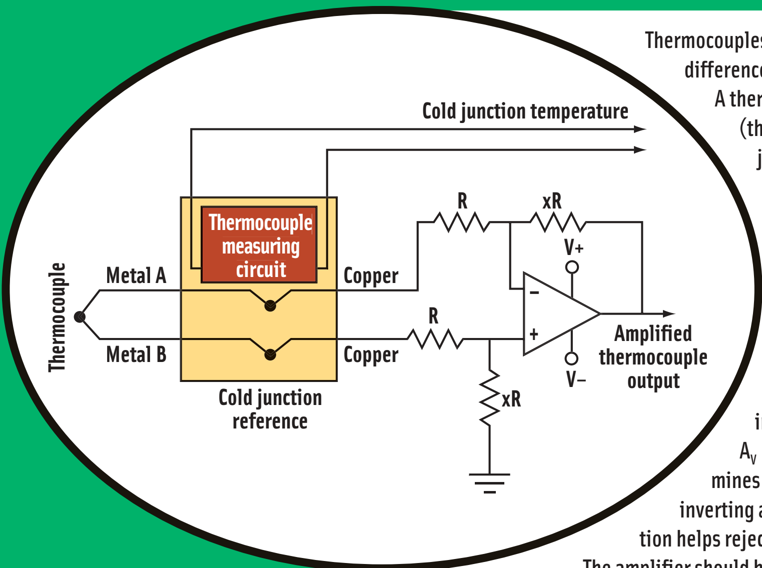

Thermocouples provide a voltage signal based on the temperature difference between the junctions of two different metal wires. A thermocouple temperature sensor has a sensing junction (the metal-A/metal-B connection) and a reference junction (the junction of metal A and metal B with copper conductors). Temperature of the cold junction reference is controlled or measured along with the thermocouple signal. The thermocouple has a small signal level ranging from about 10 µV/°C to about 80 µV/°C and has small source impedance. A single amplifier (see figure, left) configured as a differential amplifier amplifies the signal to the required level that is compatible with the ADC's input. The gain of the differential amplifier is:

A_V = xR/R, where x is the resistance ratio that determines the gain to be maintained between the amplifier's inverting and noninverting inputs. The differential configuration helps reject common-mode pickup by the thermocouple wires. The amplifier should have low offset voltage and low offset-voltage drift.

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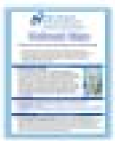

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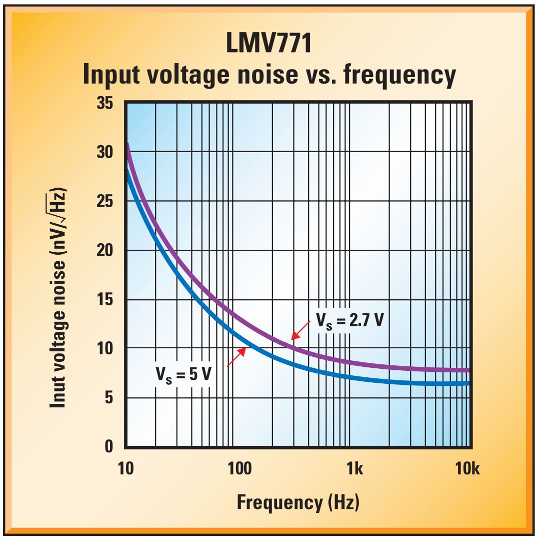

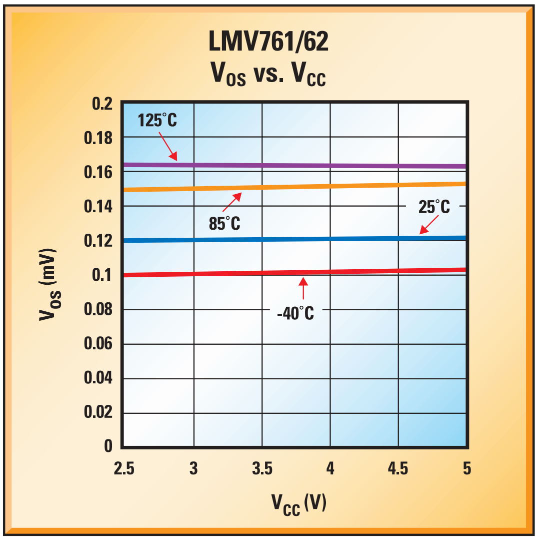

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D. The Final Stage—Analog-To-Digital Conversion

The ultimate goal of the signal-conditioning system is to get analog sensor data into digital form as rapidly, completely, and inexpensively as possible, and that task falls to the ADC. The type of ADC used varies with a number of factors. These include the resolution required (number of bits), speed (throughput rate of the data), ac or dc signal inputs, accuracy (dc and ac), latency (time between the start of a sampling cycle and the first valid digital output) and supply voltage levels. On the output side—the interface to a microcontroller or digital signal processor—important factors include whether it is serial or parallel, input voltage level capability of the processor, available supply voltages, and power consumption considerations.

Most signal-conditioning applications use either successive-approximation-register (SAR) or integrating ADCs. Both types handle dc signals well, with the SAR unit providing better support for fast ac signals (see table, right). SAR converters are the most versatile of all ADCs, as they combine high resolution (up to 16 bits) and high throughput capability.

Integrating ADCs have long operating times because of the conversion method they use, but they offer the distinct benefit of noise reduction through signal averaging. For moderate-frequency ac signals, delta-sigma (Δ-Σ) converters are best due to their high resolution and accuracy with these kinds of inputs. Their resolution is high (up to 24 bits) but comes at the expense of decreased speed (latency is very high). Two other types of ADCs—pipelined and subranging ADCs—are high-speed devices well-suited for converting high-frequency ac signals.

ADC CHARACTERISTICS AND APPLICATIONS

ADC type	DC accuracy	AC accuracy	Resolution	Speed	Latency	Applications	Comments
SAR	High	High	to 16 bits	Low-mid	None	DC/AC signals	Broadly used for DC and AC signals in signal-conditioning applications
Multi-slope integrating	High	Low	to > 20 bits	Very low	None	DC signals, low-frequency AC	Good AC rejection, latency is low, but conversion time can be very long. Used in DC load cell applications, weigh scales, etc
Delta-sigma (Δ-Σ)	Low	High	to 24 bits	Low-mid	Very high	Audio/AC signals	Often used in audio and load-cell vibration-analysis applications
Pipelined	Low	High	to 16 bits	High	Moderate	AC signals	Most useful for mid- to high-frequency AC signals
Subranging	Low	High	to 16 bits	High	Low	AC signals	Most useful for mid- to high-frequency AC signals

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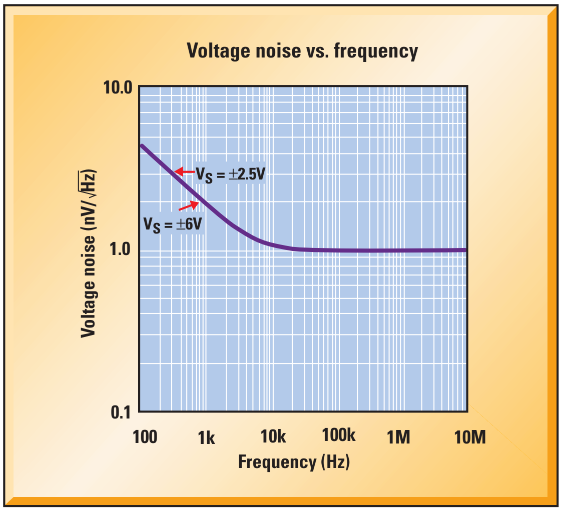

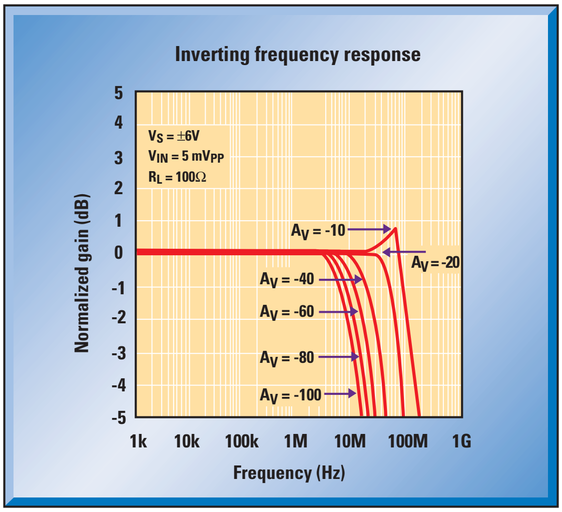

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