BY UNDERSTANDING THE STAGES OF AN ANALOG-SIGNAL PATH, DIGITAL-SYSTEM DEVELOPERS CAN MORE ACCURATELY CAPTURE SENSOR DATA FOR A VARIETY OF APPLICATIONS.

BREAKING DOWN THE SENSOR-SIGNAL PATH

BY AARON GL PODBELSKI • CYPRESS SEMICONDUCTOR

Sensors are increasingly finding use in embedded systems. Although industrial products have long used them for manufacturing-control systems, consumer devices are now starting to employ them, as well. Manufacturers are integrating sensors into consumer products to create better user experiences—ranging from adding accelerometers in mobile phones to adding water-vapor sensors in microwave ovens. System designers, who previously worked only in the digital domain, are now finding themselves having to interface with analog sensors.

You must digitize a sensor's analog signal so that the system can use it, and the signal path goes through amplification, filtering, and digitization stages (**Figure 1**). Each stage usually involves a component with passives around it to perform properly for an application. Once you digitize the signal, you can pass it to a control system on the microcontroller or massage the data and pass it to a host processor through a communication protocol. The protocol can use the sensor data as necessary.

Every sensor has a different output signal and range. The output signal can be voltage-, current-, resistive-, capacitive-, or frequency-based, but few standards exist, and only specific industrial systems use them. Even similar sensors from the same manufacturer can have different outputs, and these differences can create problems for system designers. A designer must select a sensor that meets the requirements for the system. If the requirements change during the design, however, a sensor change may also be in order. In addition, a new sensor with a slightly different output would necessitate altering the amplification and filtering stages.

Most sensors output a low-level current- or voltage-based signal, so a simple resistive network adapts any current-based signal into a voltage. This article

simplifies some concepts and the component-selection process.

AMPLITUDE

The output of a sensor can be as small as several millivolts or as large as several volts. For proper digitization, the signal must be large enough for the ADC to effectively read it. In most cases, the sensor signal requires amplification. For example, a typical type-K thermocouple outputs 41 μV/°C, which you must greatly amplify if your design requires 1°C granularity. Thus, you must take ADC resolution into account to ensure that you sufficiently amplify the signal to obtain the desired granularity.

You base the selection of an amplifier mainly on the type you need—be it an instrumentation amplifier, a differential amplifier, an operational amplifier, or a PGA (programmable-gain amplifier). You also must determine the amount of gain your amplifier requires. A resistive network, with feedback, around the amplifier sets the amplifier's gain. The maximum gain for standard amplifiers is ideally limitless. A digital signal to the device usually sets the gain for a PGA. This signal alters an internal resistive network. The maximum possible gain for a PGA is 0.5 to 1000 times less than that of a traditional amplifier, but this range is more than acceptable in most cases.

AT A GLANCE

- Even similar sensors from the same manufacturer can have different outputs, and these differences can create problems for system designers.
- Noise arises from a number of sources, including board layout, radios, thermal components, and even the sensor itself.
- To use the sensor's filtered signal, you must quantify the analog signal into the digital domain using an ADC.
- You have the choice of using an external ADC or a microcontroller with an integrated ADC. External ADCs tend to have higher accuracy and higher performance in both speed and resolution.

With amplifiers, you must take into account another key specification: offset voltage. Offset voltage is the amount of alteration in volts of a signal that passes through the amplifier. For example, if you put a 500-mV signal into an amplifier with unity gain, or a gain of one, and an offset voltage of 10 mV, the resulting output would be 510 mV. If the output range of the sensor is 0 to 900 mV and the system does not need a very granular reading of the sensor, this offset may be negligible. If the range of the sensor is 450 to 550 mV, this offset is probably unacceptable. The smaller the offset voltage, the more costly the amplifier is. All amplifiers have an offset, but you need to know whether the system can tolerate it. You can reduce or eliminate the offset voltage using correlated double sampling.

FILTERING

All systems impart some noise on the sensor's signal. Noise arises from a number of sources, including board layout, radios, thermal components, and even the sensor itself. Signal noise causes the ADC to make inaccurate and unstable readings, and the noise level increases through the amplification stage, which exaggerates the error in the signal. You can qualify signal noise as low frequency, high frequency, or a known frequency. You most often need to address high-frequency-noise issues.

You can filter noise using passive analog filters, filter ICs, and digital filters (**Figure 2**). The most common method, passive filtering, involves creating a passive network of resistors, capacitors, and inductors. You must design passive filters, however, and you cannot easily alter them. Filter design can be as cumbersome as the order of the filter you need; a first-order Chebyshev filter takes much less effort to design than an eighth-order Bessel filter. So you should determine the order of the filter you need before selecting the method of filtering you will employ.

Some ICs allow you to digitally program the type of filter you need. These ICs use internal analog circuitry to create the filter and may have offset voltages associated with them. They also allow you to move the filter process after quantification with the ADC. Digital-filter design can be complex, but many

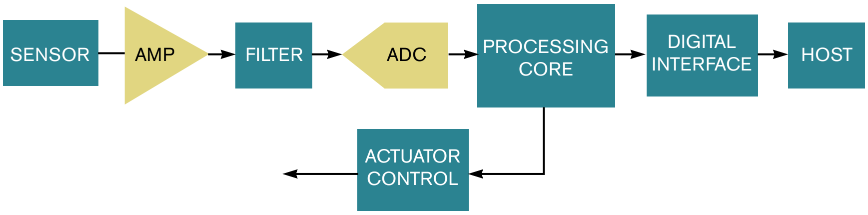

Figure 1 A sensor's analog-signal path goes through several stages: amplification, filtering, and digitization.

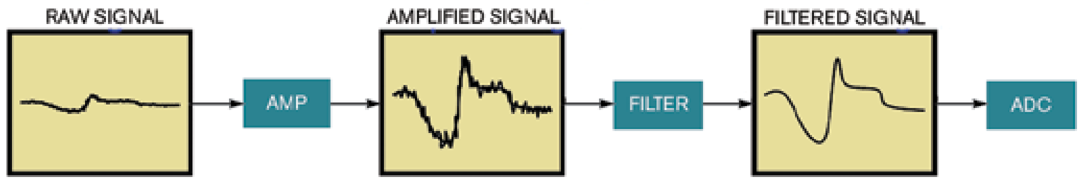

Figure 2 The sensor-signal path includes amplifiers, filters, and an ADC. You design the filter to remove noise and limit the bandwidth of the signal.

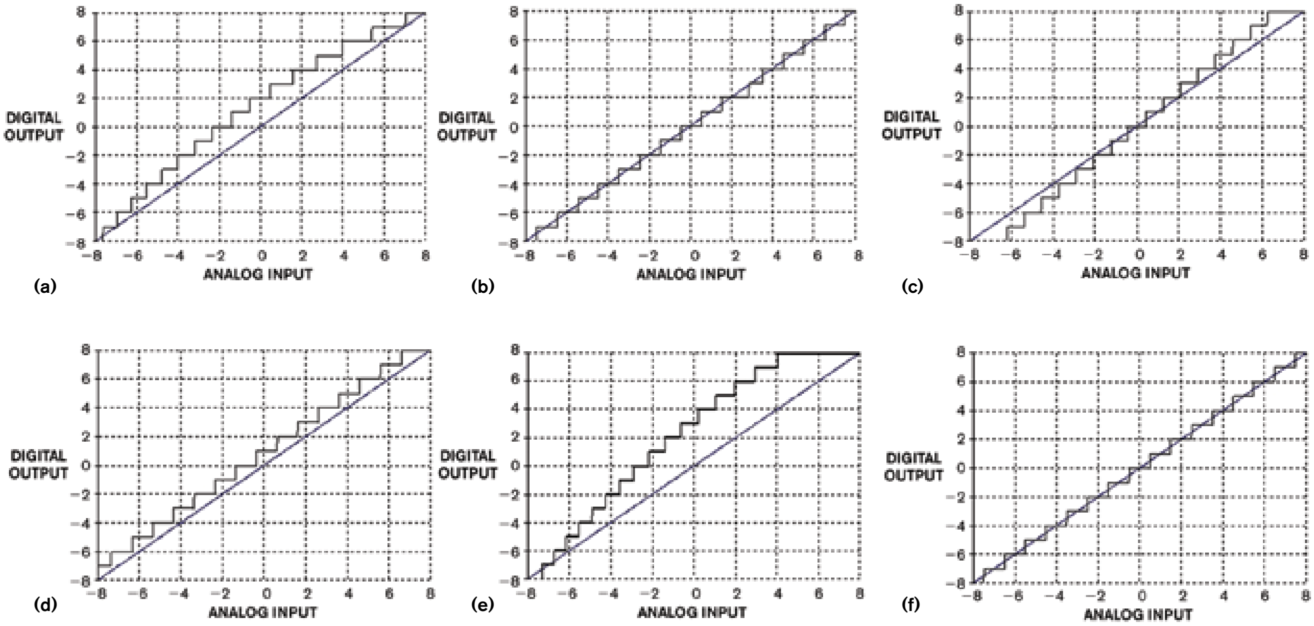

Figure 3 Combining INL error (a), DNL error (b), gain error (c), offset error (d), and total error (e) provides an understanding of the ADC in use compared with an ideal ADC (f).

tools allow for the easy design of high-order filters. Digital filtering can be an ideal means of removing noise; however, it often requires many CPU cycles, increasing power consumption. The system normally incurs high-frequency noise, necessitating the use of a lowpass filter. This filter attenuates any part of the signal that is higher frequency than the set cutoff frequency. Some sensor signals require the use of several types of filters in tandem with each other. Most sensor data sheets specify a basic interface circuit but do not mention the necessary filtering. System designers must create the system before fully understanding how much filtering is necessary.

DIGITAL CONVERSION

To use the sensor's filtered signal, you must quantify the analog signal into the digital domain using an ADC. Selection of an ADC mainly concerns the system's requirements for sampling speed and resolution. The necessary sampling speed relates to the sensor's bandwidth or how often the system needs updating. Resolution depends on the granularity you need for the ADC to react to the sensor's information. The system's usage model defines this speed and resolution requirement. For example, a generic gyroscope measures 360° of rotation at 0.67 mV/°, resulting in an output range of 241 mV. To remain upright, a hobbyist's helicopter might need information from a gyroscope at a granularity of 1° but with a throughput of 10k samples/sec. This requirement would necessitate a 10-bit ADC, which would provide 0.35°/bit. Note that the signal still has noise on it, however, and ±1 bit is acceptable. Conversely, a digital camera with image stabilization might require a granularity of 0.02° but with a throughput of 5k samples/sec to adjust the image sensor as a camera shakes. This requirement would necessitate the use of a 16-bit ADC, which would provide 0.005°/bit.

Manufacturers measure the accuracy of ADCs in terms of INL (integral nonlinearity), DNL (differential nonlinearity), offset error, gain error, and SNR (signal-to-noise ratio). When you combine these terms, they offer an understanding of the ADC's total error (**Figure 3**). For most applications, it is not necessary to look into these ADC specifications, but engineers should have a thorough understanding of these values for the ADC in use. You have the choice of using an external ADC or a microcontroller with an integrated ADC.

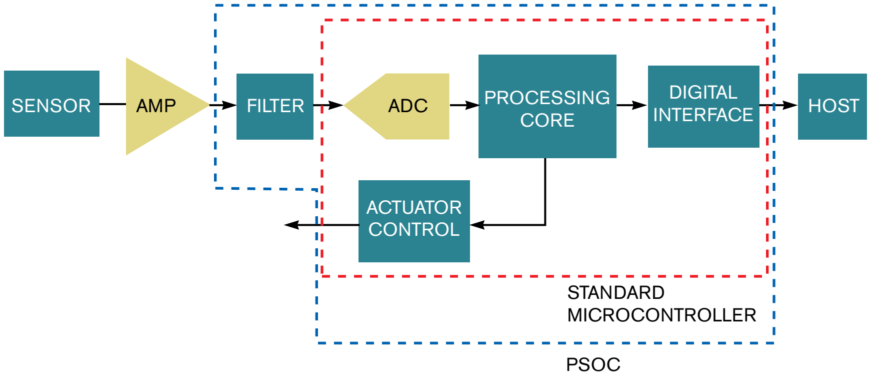

Figure 4 Developers can implement the amplification and filtering stages, integrating the entire analog-signal chain onto one device.

External ADCs tend to have higher accuracy and higher performance in both speed and resolution. Most sensor-application requirements align well with integrated-microcontroller ADCs, however.

Another option is to use configurable ADCs, which comprise programmable-logic blocks within a microcontroller. Integrated digital and analog programmable blocks allow for the dynamic definition of configurable peripherals for each sensor application. These blocks include counters, PWMs (pulse-width modulators), UARTs, SPIs (serial-peripheral interfaces), amplifiers, filters, ADCs, and DACs. Developers can also implement the amplification and filtering stages, integrating the entire analog-signal chain onto one device (**Figure 4**). Using configurable ADCs can result in cleaner designs than those using passive components. In addition, you can dynamically reconfigure these blocks, so you have the option of reusing these system resources for other functions.

Sensors continue to penetrate a range of markets, bringing you more control and greater flexibility. Sensors increase reliability through management of the environment, including, for example, temperature monitoring; improved performance through feedback mechanisms; and enabling new types of user interfaces. For many of these designs, the integrated ADCs on microcontrollers provide sufficient granularity and accuracy. Developers who are unfamiliar with analog design may encounter pitfalls along the analog-signal chain between the sensor and the microprocessor.

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Implementing the multiple stages of the analog-signal path can seem convoluted, especially to engineers accustomed to designing primarily in the digital domain. However, by breaking down the analog-signal path into the various amplification, filtering, and ADC stages, digital-system developers can more easily and accurately capture sensor data for a variety of industrial and consumer applications. In addition, readily available ICs, configurable ADCs, and filter-design tools can greatly simplify sensor design.EDN

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