

The Engineer's Guide to Signal Conditioning

Overview

Many applications involve environmental or structural measurements, such as temperature and vibration, from sensors. These sensors, in turn, require signal conditioning before a data acquisition device can effectively and accurately measure the signal. Signal conditioning is one of the most important components of a data acquisition system because without optimizing real-world signals for the digitizer in use, you cannot rely on the accuracy of the measurement.

Signal conditioning needs vary widely in functionality depending on your sensor, so no instrument can provide all types of conditioning for all sensors. For example, thermocouples produce very low-voltage signals, which require linearization, amplification, and filtering, while strain gages and accelerometers need excitation. Other signals may need none of these but strongly rely on isolation from high voltages. The key to a successful signal conditioning system is to understand the circuitry you need to ensure an accurate measurement whatever your channel mix.

This document covers the specific conditioning requirements you need for the most common sensor types and discusses key considerations for developing and maintaining a conditioned measurement system.

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Fundamentals of Signal Conditioning

Most signals require some form of preparation before they can be digitized. Thermocouple signals are very small voltage levels that must be amplified before they can be digitized. Other sensors, such as resistance temperature detectors (RTDs), thermistors, strain gages, and accelerometers, require excitation to operate. All of these preparation technologies are forms of signal conditioning.

The following list offers common signal conditioning types, their functionalities, and examples of when you need them to help you assess your signal conditioning options.

Amplification

Amplifiers increase voltage level to better match the analog-to-digital converter (ADC) range, thus increasing the measurement resolution and sensitivity. In addition, locating external signal conditioners closer to the signal source, or transducer, improves the measurement signal-to-noise ratio by magnifying the voltage level before it is affected by environmental noise. Typical sensors that require amplification are thermocouples and strain gages.

Attenuation

Attenuation, the opposite of amplification, is necessary when voltages to be digitized are beyond the ADC range. This form of signal conditioning decreases the input signal amplitude so that the conditioned signal is within the ADC range. Attenuation is typically necessary when measuring voltages that are more than 10 V.

Filtering

Filters reject unwanted noise within a certain frequency range. Often, lowpass filters are used to block out noise in electrical measurements, such as 50/60 Hz power. Another common use for filtering is to prevent aliasing from high-frequency signals. This can be done by using an anti-aliasing filter to attenuate signals above the Nyquist frequency. Anti-alias filters are a form of lowpass filter characterized by a flat passband and fast roll-off. Because accelerometer and microphone measurements are commonly analyzed in the frequency domain, anti-aliasing filters are ideal for sound and vibration applications.

Isolation

Voltage signals well outside the range of the digitizer can damage the measurement system and harm the operator. For that reason, isolation is usually required in conjunction with attenuation to protect the system and the user from dangerous voltages or voltage spikes. Isolation may also be needed when the sensor is on a different ground plane from the measurement sensor, such as a thermocouple mounted on an engine.

Excitation

Excitation is required for many types of transducers. For example, strain gages, accelerometers, thermistors, and RTDs require external voltage or current excitation. RTD and thermistor measurements are made with a current source that converts the variation in resistance to a measureable voltage. Accelerometers often have an integrated amplifier, which requires current

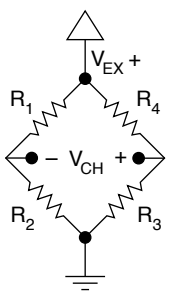


Figure 1.
Excitation Supplied
to a Wheatstone Bridge

excitation provided by the measurement device. Strain gages, which are very-low-resistance devices, are typically used in a Wheatstone bridge configuration with a voltage excitation source.

Linearization

Linearization is necessary when sensors produce voltage signals that are not linearly related to the physical measurement. Linearization, the process of interpreting the signal from the sensor, can be implemented either with signal conditioning or through software. A thermocouple is the classic example of a sensor that requires linearization.

Cold-Junction Compensation

Cold-junction compensation (CJC) is required for accurate thermocouple measurements. Thermocouples measure temperature as the difference in voltage between two dissimilar metals. Based on this concept, another voltage is generated at the connection between the thermocouple and terminal of a data acquisition device. CJC improves measurement accuracy by providing the temperature at this junction and applying the appropriate correction.

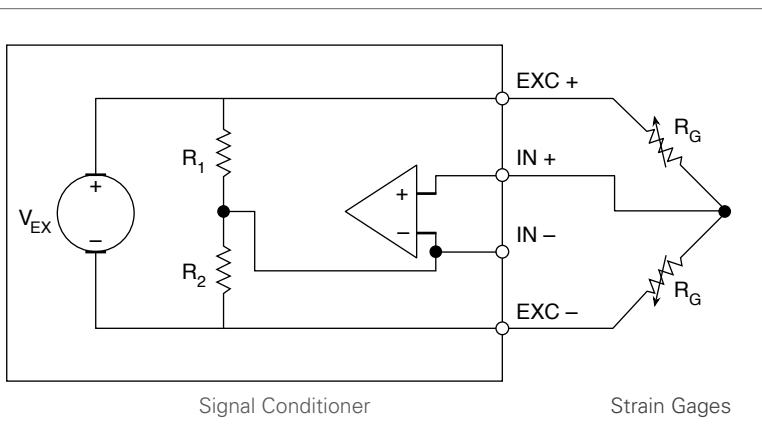


Figure 2.
Connection of a Half-Bridge Strain Gage Circuit

Bridge Completion

Bridge completion is needed for quarter- and half-bridge sensors to form a four-resistor Wheatstone bridge. Strain gage signal conditioners typically provide half-bridge completion networks consisting of high-precision resistors. The completion resistors offer a fixed reference for detecting small voltage changes across the active sensor(s).

Sampling Method

Typically, the digitizer is the most expensive part of a data acquisition system. Multiplexing can sequentially route a number of signals into a single digitizer, thus achieving a cost-effective way to greatly expand the signal count of a system. When it is critical to measure two or more signals at the same instant in time, such as in-structure characterization, simultaneous sampling is recommended.

Sensor-Specific Signal Conditioning

To achieve the best measurements, understanding the signal conditioning needs for each measurement type is paramount. Based on the sensors you require to perform an application, certain types of signal conditioning you need to consider certain types of signal conditioning to ensure the best measurements possible. Table 1 provides a summary of signal conditioning types for the different sensors and measurements.

	Amplification	Attenuation	Isolation	Filtering	Excitation	Linearization	CJC	Bridge Completion
Thermocouple	✓	–	✓	✓		✓	✓	–
Thermistor	✓	–	✓	✓	✓	✓	–	–
RTD	✓	–	✓	✓	✓	✓	–	–
Strain Gage	✓	–	✓	✓	✓	✓	–	✓
Load, Pressure, Torque	✓	–	✓	✓	✓	✓	–	–
Accelerometer	✓	–	✓	✓	✓	✓	–	–
Microphone	✓	–		✓	✓	✓	–	–
LVDT/RVDT	✓	–	✓	✓	✓	✓	–	–
High Voltage	–	✓	✓	–	–	–	–	–

Table 1.
Unique Requirements for Sensor-Based Measurements

Temperature Sensors

The most common sensors used to measure temperature are thermocouples, RTDs, and thermistors. These sensors typically emit a low-output voltage measured in the millivolt range. The output of these sensors is too small for measurement devices with a large input range to measure accurately. For example, a typical signal range for a thermocouple is ± 80 mV. If you have a 16-bit digitizer with a range of ± 10 V, you can use only 0.8 percent of the range of the ADC. To solve this problem, use amplification to increase the size of your output signal to match the range of the ADC.

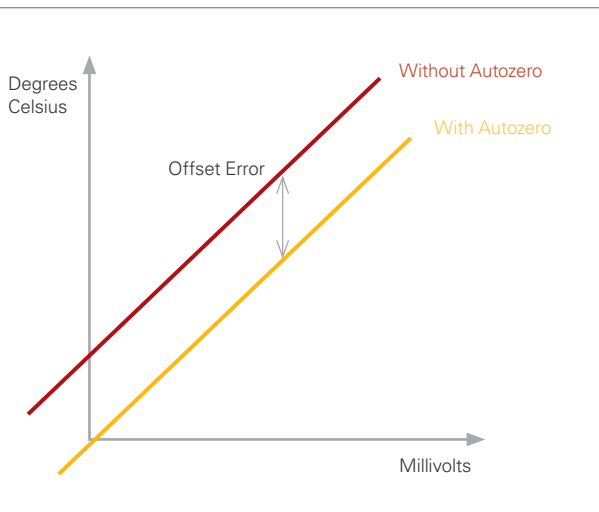


Figure 3.
Autozero compensates for offset error in the measurement device.

As discussed previously, thermistors, RTDs, and thermocouples often output signals very close to 0 V; therefore, offset errors from the measurement device can be a large factor in overall accuracy. Offset error is the deviation in measured temperature relative to the reference temperature. Many devices support a built-in autozero function that automatically measures the internal offset before you acquire temperature data and compensates for offset error in the measurement device. If the measurement device does not support autozero, ensure that the device is regularly calibrated and use the specification document to identify how offset error affects the overall accuracy.

Since temperature measurements are usually sampled at a slow rate, these measurements are susceptible to high-frequency noise. Lowpass filters are commonly used to

eliminate high-frequency noise and 50 Hz and 60 Hz power line noise, which is prevalent in most laboratory or industrial environments.

Thermocouple

Thermocouples have specific signal conditioning requirements. Because cold junctions are formed by the connection of the thermocouple to wires or terminals of the data acquisition device, they generate voltages that add to your net measurement. For example, in the system shown in Figure 4, instead of measuring AB, which is desired, the actual measurement is $AB+AC+BC$. The additional voltages generated by the extra junctions are cold-junction error. To eliminate this error, the known temperatures of AC and BC are subtracted from the total measurement to obtain the true temperature. This adjustment is known as cold junction compensation (CJC). Most thermocouple measurement devices include built-in CJC and automatic scaling in software. If the data acquisition device does not have built-in CJC, the temperature must be measured externally to account for this difference in software.

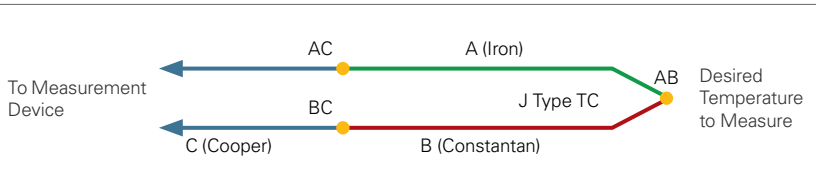


Figure 4.
Cold-junction error adds more voltage to the thermocouple measurement.

Although a CJC helps account for errors induced from cold junctions, the CJC itself and how it is implemented can cause errors as well. The overall CJC error includes the error from the CJC sensor, the error from the device measuring the CJC sensor, and the gradient between the cold junction and the CJC sensor. The temperature gradient between the cold junction and the

CJC sensor is the largest factor. Placing the CJCs as close as possible to the thermocouple terminals helps reduce this type of CJC error. To reduce errors from the CJC sensor, use an accurate temperature sensor such as an RTD, a thermistor, or an IC temperature sensor designed for the temperature range the cold junctions will be subjected to. To reduce errors from the measurement device, invest in a device that offers the accuracy specifications you need for the application, calibrate the device as required, and use the device only within the conditions specified by the manufacturer.

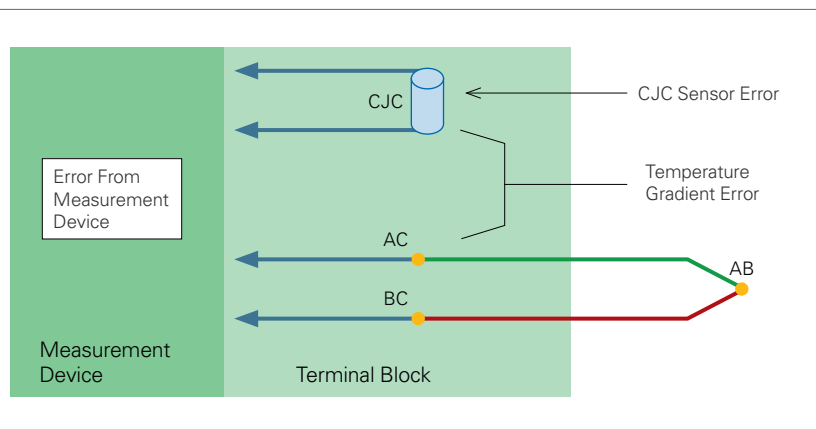


Figure 5.
Thermocouple Measurement System

Another source of noise that can affect thermocouples is directly mounting or soldering them to conductive materials or submersing them in water. When a thermocouple is connected to a conductive material, it is susceptible to common-mode noise and ground loops. Isolation helps prevent ground loops and can significantly improve the rejection of common mode noise. Conductive materials with large common-mode voltages require isolation to effectively measure large common-mode voltages.

Thermistors and RTDs

Thermistors and RTDs are active temperature sensors that require voltage or current excitation. It is important to note that sending a large excitation current results in self-heating, which affects the accuracy of your measurement. If you cannot dissipate this extra heat, consider lowering the excitation current. When using RTDs or thermistors, be sure to implement amplification and lowpass filters as discussed earlier to help eliminate the effect of noise.

Strain Gage

Strain gage measurement involves sensing extremely small changes in resistance. The proper selection and use of the bridge and signal conditioning are required for reliable measurements. The three main types of strain gages are quarter, half, and full bridge. The name refers to how many legs of the Wheatstone bridge are made up of actively sensing strain gages. Therefore, you need bridge-completion circuitry for quarter- and half-bridge strain gages. Typically signal conditioning circuitry strain gages are designed for half-bridge completion networks. If you

are using a quarter-bridge sensor, you need a third resistor commonly referred to as the quarter-bridge completion resistor. Similar to temperature sensors, most strain gages require amplification because they have relatively low output levels (less than 100 mV) which makes them vulnerable to noise. Using lowpass filters can help remove noise from unwanted high-frequency components.

Strain gages require voltage excitation levels between 2.5 V and 10 V. The change in output voltage for a given level of strain increases in direct proportion to the excitation voltage. Although a higher voltage excitation generates a proportionately higher output voltage and thus improves signal-to-noise ratio, the higher voltage can also cause errors because of self-heating. Self-heating changes a strain gage's resistivity and sensitivity, affects the adhesive's ability to transfer strain, and introduces temperature effects between lead wires and the foil gage. This has a large impact on measurements when the structure does not provide good heat dissipation, such as plastic. You can reduce self-

heating by either selecting a strain gage with a larger surface area for better heat dissipation or reducing the excitation level.

If the strain gage circuit is far from the signal conditioning circuitry and excitation source, the resistance of long lead wires and small gage wires can result in a lower excitation voltage delivered to the bridge. Compensate for this error by using remote sense. Remote sense measures the amount of excitation actually delivered to the sensor and regulates the excitation supply through negative feedback to compensate for lead losses and deliver the needed voltage at the bridge.

When a strain gage is installed and connected to a Wheatstone bridge, it is unlikely that zero volts are read when no strain is applied. Strain gage imperfections, lead wire resistance, and prestrained installation condition generate some nonzero initial voltage offset. In this case perform offset nulling or null calibration in hardware or software to compensate for the inherent bridge imbalance. In software, take an initial measurement before applying strain and use this

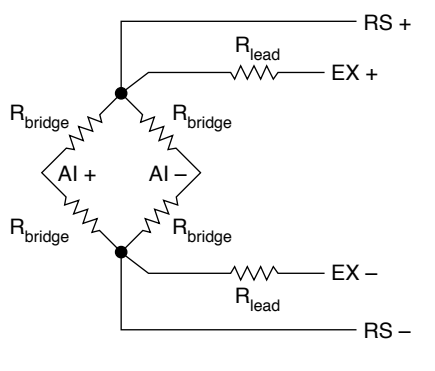


Figure 6.
Remote sense measures the actual excitation level delivered to the sensor.

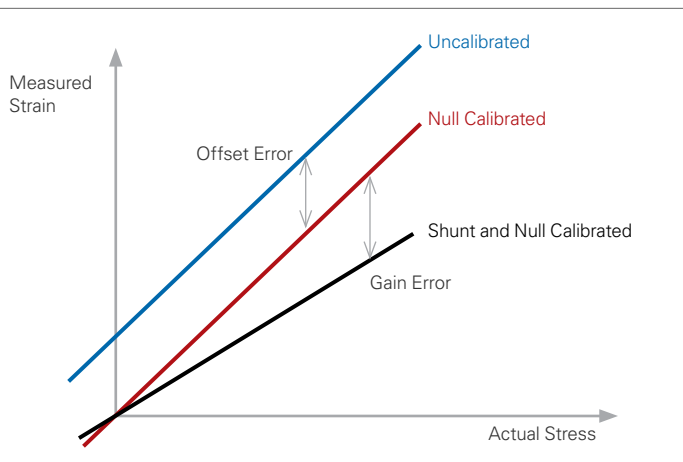


Figure 7.
Null and shunt calibration adjust the offset and gain error of the measurement device.

initial voltage in the strain calculations to calculate strain offset. Simple and fast, this method requires no manual adjustments. The disadvantage of software compensation with traditional measurements is a loss in effective measurement range due to large offsets. Another method uses hardware to balance the bridge. Measure the initial strain and then fine-tune a potentiometer as a leg of the Wheatstone bridge to physically adjust the output of the bridge to zero. By varying the resistance of the potentiometer, you can control the level of the bridge output and set the initial output to 0 V.

Load, Pressure, and Torque

The most common tool for measuring load, pressure, and torque is a full-bridge strain-gage-based sensor. In a full-bridge setup, all four of the Wheatstone bridge legs are actually strain gages; therefore, you do not

need additional resistors or bridge-completion circuitry. Load, pressure, and torque sensors can output low or high voltages, depending on the excitation requirements of the sensor. Typically powered by a measurement device, low-excitation-level sensors output millivolt- and volt-range signals, but high-excitation-level sensors require higher external power sources to operate and output ± 5 V, ± 10 V, or 4–20 mA. Since this is a full-bridge strain measurement, the signal conditioning discussed previously for strain measurements such as remote sensing and shunt calibration also applies.

Accelerometers and Microphones

Sound and vibration measurements are closely related. Accelerometers and microphones both measure oscillations but in different media; therefore, the theory of sound and vibration measurements and their necessary signal conditioning techniques are similar. The type of signal conditioning implemented for accelerometers and microphones depends on whether they have built-in amplifiers. Because the charge produced by an accelerometer is very small, the electrical signal produced by the sensor is susceptible to noise, and you must use sensitive electronics to amplify and condition the signal.

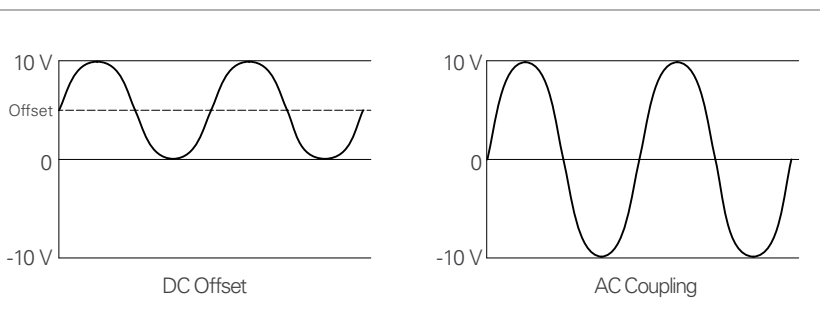


Figure 8.
AC coupling filters out the DC component from a signal to increase measurement resolution.

Integrated Electronic Piezoelectric (IEPE) sensors integrate the charge amplifier or voltage amplifier close to the sensor to ensure better noise immunity and more convenient packaging. This signal conditioning provides a constant current source to power the circuitry inside the sensors. Since piezoelectric accelerometers are high-impedance sources, you must design a charge-sensitive amplifier with low noise, high input impedance, and low output

impedance. Like accelerometers, microphones can be powered externally or internally. Externally polarized condenser microphones require 200 V from an external power supply. Prepolarized condenser microphones are powered by IEPE preamplifiers that require a constant current source.

When IEPE signal conditioning is enabled, a DC voltage offset is generated equal to the product of the excitation current and sensor impedance. The signal acquired from the sensor consists of both AC and DC components, where the DC component offsets the AC component from zero. This can lower the resolution of the measurement because the signal amplification is limited by the range of the ADC. You can solve this problem by implementing AC coupling. Also known as capacitive coupling, AC coupling uses a capacitor in series with the signal to filter out the DC component from a signal.

LVDTs

Linear variable differential transformers (LVDTs) and rotary variable differential transformers (RVDTs) are popular sensors for measuring position. LVDTs operate like transformers and consist of a stationary coil assembly and moveable core. An LVDT measures displacement by associating a specific signal value for any given position of the core. Signal conditioning circuitry is essential for the proper operation of an LVDT.

You must generate a sinusoidal signal to provide excitation for the primary coil. This signal is typically between 400 Hz and 10 kHz, and the frequency of the signal should be at least 10 times greater than the highest expected frequency of the core motion. You should apply the same sine wave used for excitation to demodulate the secondary output signal. You should also include a lowpass filter to remove high-frequency ripple. The resulting output is a DC voltage that is proportional to the core displacement.

Key Considerations When Building a Signal Conditioning System

When you are designing any new conditioned measurement system, keep in mind that some of the variables that contribute to its success are directly related to the conditioning circuitry as detailed above, while others are more practical and relate to the implementation, system integration, and maintenance of your design. Overlooking these can have a significant impact on the time, money, and resources you devote to the project as a whole.

Integration

The ability of the signal conditioning system to integrate easily with the rest of the system is important. Understanding the interaction between different components of the measurement chain helps characterize expected results and troubleshoot unexpected ones. From the sensor to each stage of the conditioning, the ADC, and the communications bus, every link in the chain adds more sources of error and can degrade system specifications. Where possible, reduce this risk of error by combining measurement chains into a single system such as integrating the conditioning and ADC within a single module.

Connectivity

Connecting signals to a signal conditioning system can be a major issue if not considered carefully beforehand. A best-in-class signal conditioning system should offer a wide range of connectivity options, including thermocouple plugs, screw terminals, and BNC connectors. As the application changes, so does the need for different connectivity, such as D-SUB, RJ45/50, mini-XLR, and LEMO. Creating new connectivity devices for changing test requirements can become unmanageable over time as technology requirements change. Using an approach that has connectivity options limits concerns for proper connection and maintenance.

Expandability

By architecting your system in a modular way, you have more flexibility to change and expand both channel count and signal mix. Architectures with high levels of cross-functional reliance can require a massive overhaul to make even relatively minor alterations. Consider logging temperature data to evaluate the design limits of an engine in a test cell. You originally implemented a thermocouple because of its large operating range, but now you need a more accurate sensor such as an RTD to fine-tune the temperature that causes a component to fail. Since RTDs are active sensors, you must now incorporate current excitation into your system. If you design in a modular fashion, you can swap out your thermocouple module with relative ease. But if you combine the thermocouple module with other thermocouple modules on a PCB, you are bound to either compromise your measurement and stick with the thermocouple or invest heavily in a full redesign.

Isolation

When the measured signal is either a high voltage or a voltage subject to spikes, you should isolate those signals from the rest of the system. Inadequate isolation compromises the safety of the operator as well as the integrity of the entire data acquisition system. When determining system isolation requirements, you must have reliable and accurate isolation specifications, including a safe working voltage rating and an installation rating. Vendors routinely work with isolation specifications and certifications to ensure a product

meets industry standards. If you have a complete understanding of these requirements, then you can successfully produce an isolated system.

Bandwidth

When designing or specifying data acquisition systems, make sure the systems' bandwidth is high enough to handle the data throughput you need and accommodate future channel-count growth. System bandwidth is typically expressed in samples per second (hertz). To determine the necessary minimum bandwidth of the system, multiply the total number of expected channels by the per channel maximum sample rate.

When designing or specifying products for signal conditioning; consider external factors that could affect the system's bandwidth. For example, many pressure sensors have high output values and therefore do not need amplification. However, the high output impedance of these sensors causes the settling time of channels on multiplexed or scanned data acquisition devices to increase. This can cause ghosting to occur if the sample rate is too high because the capacitor does not have time to charge or discharge to the correct voltage. If you did not design a voltage follower or buffer circuit into your signal conditioner, then you would have to place limits on maximum allowed sample rate.

Software

A large portion of the total cost of a test and measurement system is application development when you account for the necessary engineering and time resources for setup, development, and testing. You can minimize this cost by developing within an environment designed specifically for this kind of engineering application. For example, even though it is possible to use hardware to perform a null calibration for a strain gage, you may not want to leave this task or responsibility up to your operator or technician. Therefore, you should compensate for the initial strain offset in software to ensure that the calibration is completed correctly before every acquisition. Development environments such as LabVIEW are optimized for this kind of task so you can be more productive and spend time where it matters.

Configuration and Installation

Any signal conditioning system should be easy to use. No one can afford to lose time because of overly complex installation or configuration issues. An ideal signal conditioning system polls the hardware, reports which equipment is present, and provides a software interface for assigning all settings. You should be able to use your software environment to configure and scale your channels.

Calibration

To make the most accurate measurements possible, you must periodically calibrate the entire data acquisition system. Most measurement devices are calibrated at the factory, but the accuracy drifts over time. Many commercial off-the-shelf (COTS) systems have precision onboard voltage references; this allows the measurement system to be adjusted to compensate for temperature changes. Ideal for short-term environmental changes, this method is often used as an easy performance check to confirm a fully operation system before performing test sequences. Keep in mind that even these onboard references drift, so this is not a replacement

for external calibration services that keep the system performing up to published specifications year after year.

If a metrology lab is available, you can easily follow documented calibration procedures. However, if the documentation is out of date, a metrology lab is not available, or the engineer who implemented the system is not accessible, maintaining the calibration standards can be a costly challenge. A good COTS signal conditioning system comes with up-to-date, published specifications and calibration services that can mitigate these challenges.

Maintenance

Once you have finalized your signal conditioning design, you need to compile all of the system information into a formal document. Troubleshooting the system, adding new functionality, or duplicating the system can be nearly impossible without detailed documentation. You want to be prepared in case the engineer who designed the system moves to a different company or project. Taking the time to properly develop and document the test procedures used also helps minimize time and cost when you need to make repairs or modifications. Many COTS providers of integrated conditioning and ADC hardware offer most of this documentation, but it is still important to check and document wiring and connectivity diagrams.

Implementing a Signal Conditioning System

When considering whether to build and incorporate your own custom signal conditioning system or purchase an integrated signal conditioning solution, you should evaluate the application requirements, resources available, and key considerations to determine the right path forward. Use the following table as a guide to choose the best approach for your application.

Use cases for integrated and custom-built signal conditioning:

Integrated Signal Conditioning	Custom-Built Signal Conditioning
<p>Best for:</p> <ul style="list-style-type: none"> ▪ Mixed-measurement systems ▪ Flexible systems or systems exposed to potential expansion ▪ Short project timeframes/deadlines ▪ Systems that may be reproduced ▪ Systems that must be maintained for a long time 	<p>Best for:</p> <ul style="list-style-type: none"> ▪ Smaller, fixed functionality; fixed-channel-count systems ▪ Low hardware budget projects with team proficiency in analog design ▪ Long project timeframes ▪ Extreme specialization on signal input

You should consider a signal conditioning system as a platform that defines the measurement capabilities of a data acquisition system. With the wide range of accurate conditioning provided off the shelf, you do not need to invest time in custom conditioning.



NI offers two platforms featuring signal conditioning data acquisition systems: CompactDAQ and PXI. These systems consist of multichannel signal conditioning modules that offer analog input, analog output, digital I/O, counter/timer, and switching installed in one or more chassis.

The CompactDAQ and PXI platforms are designed to give you confidence in the accuracy of your measurements whatever your custom conditioning needs. The combination of conditioning circuitry with high-resolution ADCs and communications buses reduces your risk of error from disparate components and drastically decreases your hardware design investment compared with custom circuitry.

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