Signal Conditioning Tutorial

Introduction

PC-based data acquisition (DAQ) systems and plug-in boards are used in a very wide range of applications in the laboratory, in the field, and on the manufacturing plant floor. Typically, DAQ plug-in boards are general-purpose data acquisition instruments that are well suited for measuring voltage signals.

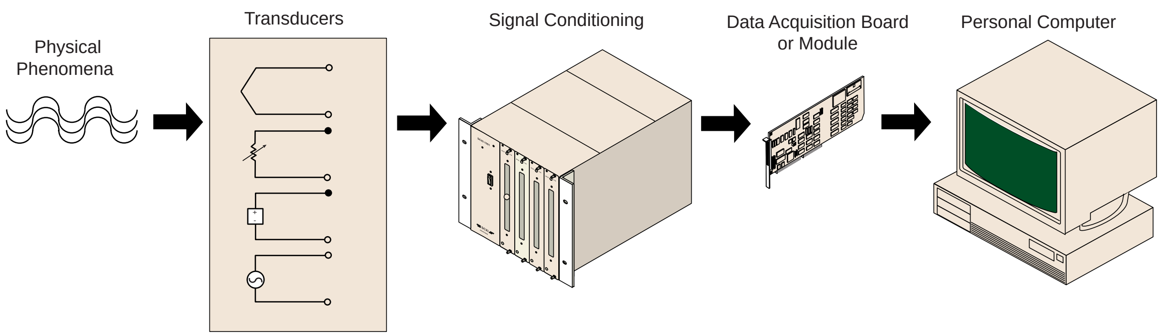

Figure 1. Signal conditioning is an important component of a PC-based DAQ system.

However, most real-world sensors and transducers generate signals that must be conditioned before a DAQ device can reliably and accurately acquire the signal. This front-end processing, referred to as signal conditioning, includes functions such as signal amplification, filtering, electrical isolation, and multiplexing. Therefore, most PC-based DAQ systems include some form of signal conditioning in addition to the plug-in DAQ board and personal computer, as shown in Figure 1.

Front-end switching systems also increase the functionality of your measurement and automation system General-purpose switching delivers digital control of the presence or absence of a signal in your system, such as power to a motor. Multiplexer/matrix relay configurations control source and signal routing for your system, or act as a multiplexing front end for devices such as digital multimeters (DMMs).

Transducer Conditioning

Transducers are devices that convert physical phenomena, such as temperature, strain, pressure, or light, into electrical properties, such as voltage or resistance. Transducer characteristics define many of the signal conditioning requirements of a DAQ system.

Thermocouples

The most popular transducer for measuring temperature is the thermocouple. Although the thermocouple is inexpensive, rugged, and can operate over a very wide range of temperatures, the thermocouple has some unique signal conditioning requirements.

A thermocouple operates on the principle that the junction of two dissimilar metals generates a voltage that varies with temperature. However, connecting the thermocouple wire to the wire that connects it to the measurement device creates an additional thermoelectric junction, referred to as the cold junction. The actual measured voltage, V_{MEAS}, therefore includes both the thermocouple voltage and the cold-junction voltages (V_{CJ}) (see Figure 2). The method of compensating for these unwanted cold-junction voltages is called cold-junction compensation.

Most of the National Instruments signal conditioning products compensate for cold-junctions by using an additional sensor, such as thermistor or IC sensor, placed on the signal connector or terminal block to measure the ambient temperature at the cold junction directly. Software can then compute the appropriate compensation for the unwanted thermoelectric voltages.

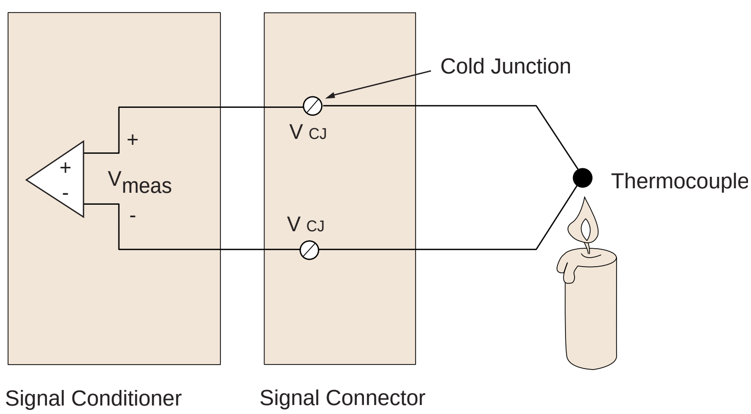

Figure 2. The connection of thermocouple wires to a measurement system creates an additional thermoelectric junction, called the cold junction, which must be compensated for with signal conditioning.

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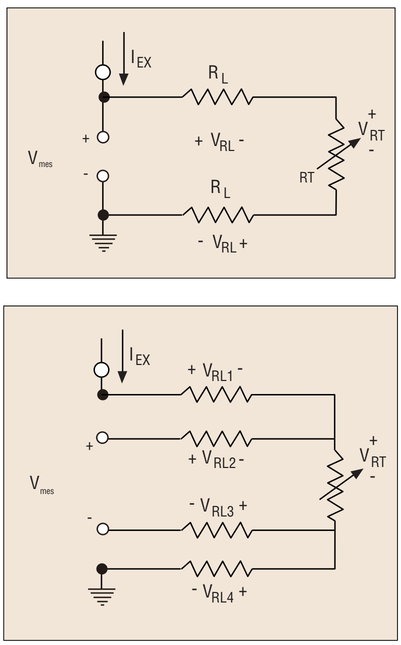
Sensitivity and noise are also important measurement issues with thermocouples. Thermocouple outputs are very low in level and change only 7 to 50 µV for every 1 ˚C change in temperature, making the signals are very susceptible to the effects of electrical noise. Therefore, thermocouple conditioners include lowpass noise filters for suppressing 50 and 60 Hz noise and high-gain instrumentation amplifiers to boost the level of the signal. Amplifying the thermocouple signal also increases the resolution, or sensitivity, of the measurement. For example, a typical DAQ board with an ADC input range of ±10 V and an onboard gain of 50 has a resolution of 98 µV. This corresponds to about 2 ˚C for a type J or K thermocouple. However, by adding a signal conditioner with an additional gain of 100 to the system, the measurement resolution increases to 1 µV, which corresponds to a fraction of a degree Celsius.

RTDs

Another popular temperature-sensing device is the resistance-temperature detector (RTD), a device whose resistance increases with temperature. The most popular type of RTD is made of platinum and has a nominal resistance of 100 Ω at 0 ˚C. Because an RTD is a resistive device, you must pass a current through the RTD to produce a voltage that a DAQ device can measure. With relatively low resistance (100 Ω) that changes only slightly with temperature (less than 0.4 Ω/°C), RTDs require signal conditioners with high-precision excitation current sources, high-gain amplifiers, and provisions for four-wire and three-wire measurements that minimize lead error effects.

For example, a two-wire RTD measurement, shown in Figure 3a, will include voltage drop errors caused by the excitation current passing through lead resistance, R_L. These errors, which can be significant, are removed by using a four-wire RTD measurement, shown in Figure 3b . The four-wire configuration uses a second pair of wires to carry the excitation current to the RTD. Therefore, only negligible current flows through the sensing wires, so the lead resistance error is very small.

RTDs are also available in three-wire configurations. The three-wire RTD is most effective in a Wheatstone bridge configuration. In this configuration, the lead resistances are located in opposite arms of the bridge, so their errors cancel each other out.



3a

3b

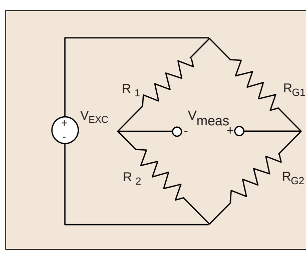
Figure 3. Errors cause by lead wire resistance, R_L, are minimized by using a four-wire measurement for RTDs.

Strain Gauges

The strain gauge is a device commonly used in mechanical testing and measurement. The most common gauge, the bonded-resistance strain gauge, consists of a grid of very fine foil or wire whose electrical resistance varies linearly with the strain applied to the device. When using a strain gauge, you bond the strain gauge to the device under test, apply force, and measure the strain by detecting changes in resistance. Strain gauges are also used in sensors that detect force or other derived parameters, such as acceleration, pressure, and vibration.

Because strain measurement requires detecting very small changes in resistance, the Wheatstone bridge circuit is used predominantly. The Wheatstone bridge circuit consists of four resistive elements with a voltage excitation supply applied to the ends of the bridge. Strain gauges can occupy one, two, or four arms of the bridge, with any remaining positions filled with fixed resistors. Figure 4 shows a configuration with a half-bridge strain gauge consisting of two strain elements, R_{G1} and R_{G2}, combined with two fixed resistors, R_1 and R_2.

With a voltage V_{EXC} powering the bridge, the measurement system measures the voltage V_{MEAS} across the bridge. In the unstrained state, when the ratio of R_{G1} to R_{G2} equals the ratio of R_1 to R_2 , the measured voltage V_{MEAS} is 0 V. This condition is referred to as a balanced bridge. As strain is applied to the



$$V_{meas} = \left(\frac{R_{G2}}{R_{G1} + R_{G2}} - \frac{R_2}{R_1 + R_2} \right) V_{EXC}$$

Figure 4. Strain gauges are measured in a Wheatstone bridge configuration.

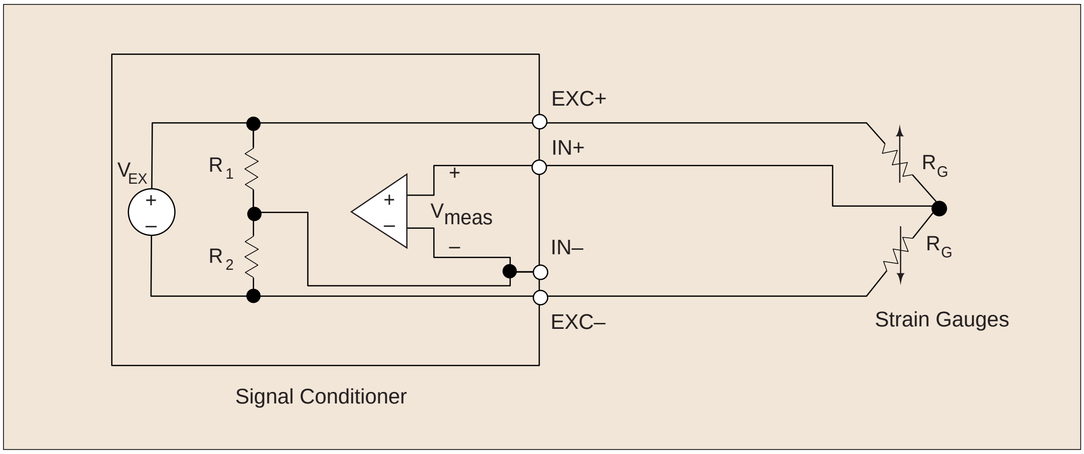


Figure 5. Connection of Half-Bridge Strain Gauge Circuit.

gauges, their resistance values change, causing a change in the voltage at V_{MEAS}.

Strain-gauge conditioning products have voltage excitation sources, gain amplifiers, and provisions for bridge-completion resistors (see Figure 5), which should be very precise and stable. Because strain-gauge bridges are rarely balanced perfectly, some signal conditioners also use offset nulling, a process in which you adjust the resistance ratio of the unstrained bridge to balance the bridge and remove any initial DC offset voltage. Alternatively, you can measure this initial offset voltage and use this measurement in your conversion routines to compensate for the unbalanced initial condition.

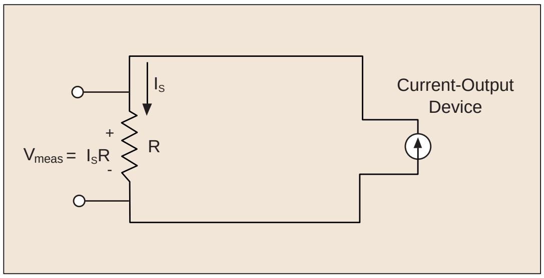


Figure 6. Process current signals, usually 0-20 mA or 4-20 mA, are converted to voltage signals using precision resistors.

Current Signals

Many devices or transmitters used in process control and monitoring applications output a current signal, usually 4 to 20 mA or 0 to 20 mA. Current signals are used because they are more immune to errors such as radiated noise and voltage drops on long wire runs. Signal conditioners convert current signals to a voltage signal by passing the input current signal through a precision resistor, as shown in Figure 6. The resulting voltage, $V_{MEAS} = I_S R$, can then be further conditioned and digitized.

General Signal Conditioning Functions

In addition to handling specific transducers, signal conditioners perform a variety of general-purpose conditioning functions to improve the quality, flexibility and reliability of your measurement system.

Signal Amplification

Because real-world signals are often very small in magnitude, signal conditioning can improve the accuracy of your data.

Signal Conditioning	Function
Transducer Interfacing	Interfaces DAQ equipment to specific transducers
	Cold-junction compensation for thermocouples
	Excitation for RTDs, thermistors, strain gauges
	Bridge measurements for strain gauges
	Current-to-voltage conversion for 4-20 mA device
Signal Amplification	Increases resolution of measurement
	Improves signal-to-noise ratio (when located near sensor)
Filtering	Removal of unwanted 50/60 Hz power noise
	Antialiasing
Isolation	Breaks ground loops
	Rejects large common-mode voltages
	Protection from damaging high voltages
Channel Multiplexing	Economically expands the channel capacity of DAQ system
Miscellaneous Conditioning	Attenuation of high voltages (down to 10 V or less)
	Simultaneous sample and hold
	Frequency-to-voltage conversion
Digital I/O Conditioning	Optical isolation
	Level conversion (120/240 VAC to TTL)
	Relay switching

Table 1. Basic Signal Conditioning Functions

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Amplifiers boost the level of the input signal to better match the range of the analog-to-digital converter (ADC), thus increasing the resolution and sensitivity of the measurement. While many DAQ boards include onboard amplifiers for this reason, many transducers, such as thermocouples, require even additional amplification.

In addition, using external signal conditioners located closer to the signal source, or transducer, improves the signal-to-noise ratio of the measurement by boosting the signal level before it is affected by environmental noise.

Filtering

Additionally, signal conditioners can include filters to reject unwanted noise within a certain frequency range. Almost all DAQ applications are subject to some degree of 50 Hz or 60 Hz noise picked up from power lines or machinery. Therefore, most conditioners include lowpass filters designed specifically to provide maximum rejection of 50 Hz or 60 Hz noise. For example, the SCXI-1120/21 modules include a a lowpass filter with a cutoff bandwidth of 4 Hz so that rejection of 50/60 Hz noise is maximized (90 dB).

Another common use of filters are used to prevent signal aliasing – a phenomenon that arises when a signal is undersampled (sampled too slowly). The Nyquist theorem states that when you sample an analog signal, any signal components with a frequency greater than one-half the sampling frequency will appear in the sampled data as a lower frequency signal. This signal distortion can be avoided only by removing any signal components above one-half the sampling frequency with lowpass filters before the signal is sampled. Some signal conditioners, such as the SCXI-1141, that are used for vibration monitoring and other more dynamic measurements include special antialiasing filters that feature programmable bandwidth (variable according to the sampling rate) and very sharp filter rolloff.

Isolation

Improper grounding of the system is one of the most common causes of measurement problems, noise, and damaged DAQ boards. Signal conditioners with isolation can prevent most of these problems. Such devices pass the signal from its source to the measurement device without a galvanic or physical connection by using transformer, optical, or capacitive coupling techniques. Besides breaking ground loops, isolation blocks high-voltage surges and reject high common-mode voltage, protecting expensive DAQ instrumentation and operators.

For example, suppose you are to monitor temperature using thermocouples soldered to a high-voltage machine. Although the thermocouples output a differential voltage of less than 50 mV, this output voltage can be at a high potential with respect to ground. This potential between both leads of a differential signal and ground is called the common-mode voltage; ideally, it should be completely ignored by the DAQ measurement system. Connecting the thermocouple leads directly to a nonisolated DAQ board, which can typically handle about 12 V of common-mode voltage, would probably damage the board. However, you can connect the thermocouple leads to an isolated signal conditioner, which rejects the high common-mode voltage, safely passing the 50 mV differential signal on to the DAQ device for accurate measurement. (See Figure 7.)

Manufacturers specify isolation levels differently, and you should ensure that your signal conditioning is designed to operate safely at high voltage levels. Agencies such as UL and CE designate compliance requirements for safe design of high-voltage instrumentation. For example, all SCXI modules are compliant with the EU Low Voltage Directive, adhering to IEC-1010 for Installation Category II, and are double insulated for a continuous working voltage of 250 Vrms. Devices that are not compliant to Installation Category II may not be safe for use with power line voltages.

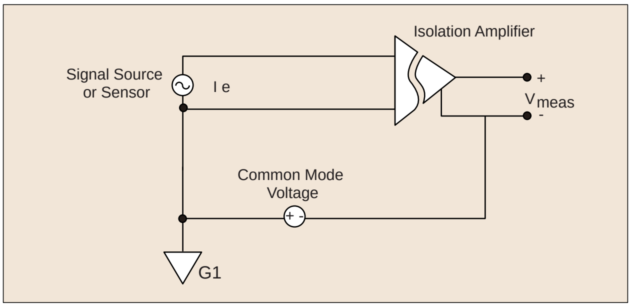

Figure 7. Isolation removes common-mode voltage errors, typically caused by differences in ground potentials.

Multiplexer/Matrix Expansion

Most plug-in DAQ boards or modules include eight differential or 16 single-ended analog input channels, with some options as high as 64 single-ended channels. External signal conditioners with multiplexing can economically expand the capacity of the DAQ device to handle large numbers of channels. For example, SCXI modules multiplex conditioned signals onto the SCXIbus in the backplane of the chassis for connection to a digitizing DAQ device. (See Figure 8.) In this way, you can condition and multiplex up to 3,072 analog input channels and digitize them with a single plug-in DAQ board.

Matrix switching offers greater flexibility by programmatically routing signals and sources to and from different test units. A matrix device is described in terms of columns and rows. Test I/O lines are typically connected to the columns and test equipment

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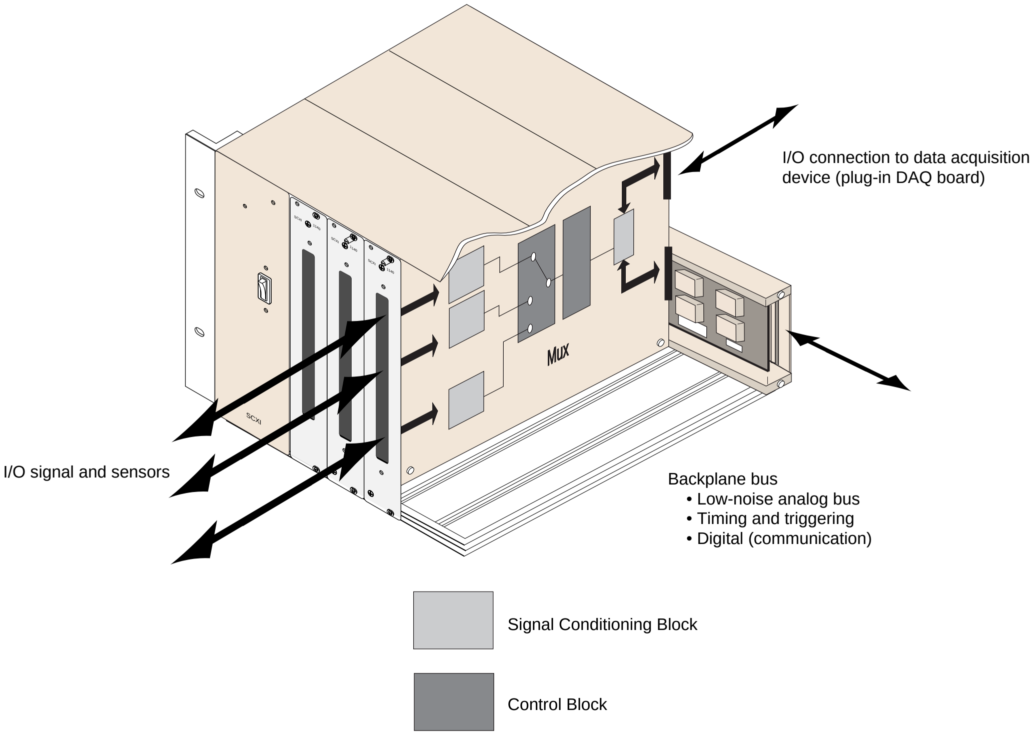

Figure 8. Multiplexing signal conditioners, such as SCXI, combine conditioning and multiplexing to handle very large numbers of channels in an efficient and economical manner.

is typically connected to the rows. Any row or rows can be programmatically routed to any column or columns by closing the corresponding relays. A single row can be routed to several columns or a single column can be routed to a group of rows. With such a configuration you can drive or sense any I/O signal connected to the system without reconnecting any wires.

A typical matrix-oriented test system has a DMM, oscilloscope, function generator, and power source connected to the rows, and various I/O signals connected to the columns. This configuration can drive or sense any combination of signals or waveforms on any of the I/O lines, greatly increasing the flexibility and usability of your test equipment.

A multiplexer/matrix unit can also operate purely in multiplexer mode, acting as a multiplexing front-end to a single device such as a DMM. This is a low-cost solution that increases the number of channels a DMM can read.

Digital Signal Conditioning/General Purpose Conditioning

Digital, or discrete, signals also have conditioning needs. Most commonly, digital I/O devices either drive or sense TTL and CMOS-compatible 5 V logic levels. Relays of some sort are required to interface with real-world switching levels. General-purpose switching means controlling the state of an electromechanical or solid-state relay with a digital output signal from a DAQ device (Figure 9.) The relay, which is equipped to handle higher power than the DAQ board, also isolates these power signals from your computer. With general-purpose switching, you can control external motors, valves, solenoids, and lamps. The National Instruments product lines with general-purpose switching solutions include SCXI, SC-206x, FieldPoint, SSR Series, and the ER-8/16.

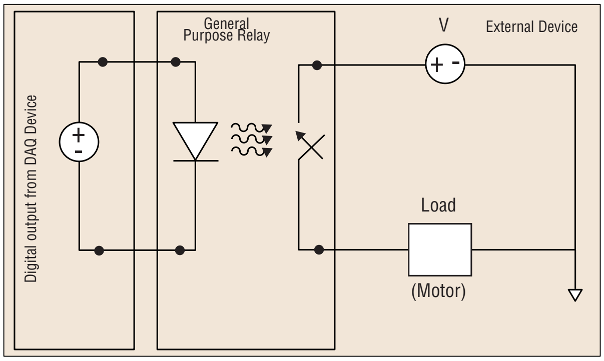

Figure 9. General Purpose Switching.