Analog Front-End

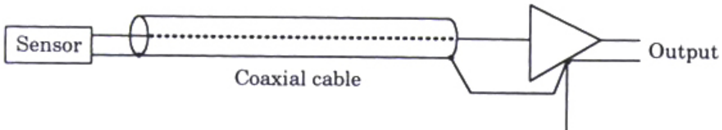
Most data acquisition systems involve obtaining data from various transducers that produce analog signals. Often, the signals from the transducers are low level and require various kinds of signal conditioning. Also, the transducers are frequently located some distance from the data acquisition front-end. Ensuring proper connections to the analog signal of interest and ground are essential to obtaining accurate measurements.

4.1 Proper Connections to the Sensors

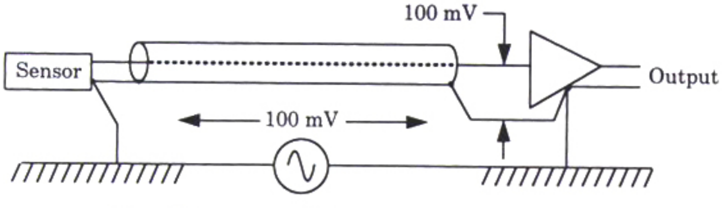
Measuring Data and Not Noise

4.1.1 Differential vs. Single-ended Input Channels

Two very important concepts that affect the performance of a data acquisition system are *single-ended* and *differential.* A single-ended input channel, as shown in Figure 4.1(a), completes the circuit from a sensor to the data acquisition (DAQ) system input circuit via a *signal* wire and a *return* wire. The *return* wire is usually the cable shield and is generally connected to the DAQ system's circuit common—which is generally connected to "ground." In an ideal world, this should not present a problem. *Unfortunately, the world is filled with many noise sources that can interfere with data.* The problem with single-ended input circuits is that the cable shield is part of the signal path—*and any noise voltage developed across the shield adds full-force to the signal!*



(a) with an isolated sensor



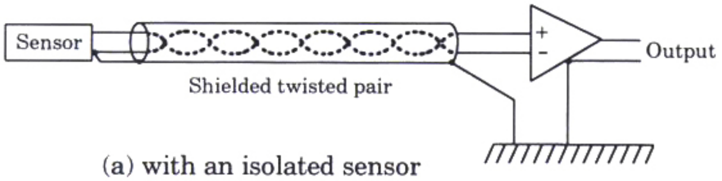
(b) with a grounded sensor

Figure 4.1: A single-ended data acquisition input channel

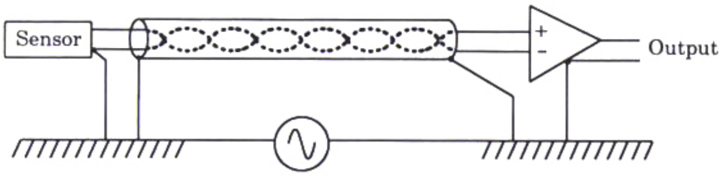
Figure 4.1(b) shows a sensor that is connected to "ground" and is wired to a grounded single-ended input. If there is 100 millivolt ac potential difference between the sensor's "ground" and the DAQ system's "ground," then *all of the 100 millivolt noise* will be superimposed on the signal. If the sensor is a thermocouple, the noise is likely larger than the dc signal voltage. Even if the sensor has no connections to ground, the data acquisition system must be carefully designed so all connection points are very close to the same potential, or errors will be introduced to the received signal of the various channels. Also, if the input wiring is close to sources of electrical noise, interference may be coupled into the signal path.

A differential-input channel—often called a *balanced input*—is generally connected to a sensor as shown in Figure 4.2(a). A *shielded twisted pair* cable is most often used for differential operation. The signal is received by an *instrumentation amplifier*. The primary characteristic of an instrumentation amplifier is that it delivers a signal at its output that is proportional to the *difference* between the voltage on its "+" input and its "-" input.

A real-world example of a differential-input channel is shown in Figure 4.2(b). Note that, in this case, the signal circuit is completed *without any signal passing through the shield*. If a noise voltage is impressed across the shield because of a ground potential difference, the effect on the signal will be greatly attenuated. The characteristic of the cable can cause interference to creep into a differential system with long cable runs. The shielded cable must contain a *twisted pair*. Some single-pair cables have both conductors in the same plane instead of having the pair of wires twisted. If this cable is near a strong source of electrical noise, one signal wire will be nearer to the noise than the other, and the noise will not cancel as well. Also, some two-pair cables with separate shields do not contain pairs that are twisted. Systems using such cables can exhibit unacceptable coupling—called crosstalk—between the channels, even though each pair is shielded.



(a) with an isolated sensor



(b) with a grounded sensor

Figure 4.2: A differential data acquisition input channel

4.1.2 Common Mode and Normal Mode

Common mode rejection ratio—often abbreviated CMRR—describes the effect that unwanted noise between the signal conductors and ground has on the desired input signal. It is called *common* mode because the unwanted signal (often caused by power line noise) is impressed across both conductors of a differential pair and—in the ideal case—is cancelled out by the balanced system. CMRR is generally measured as shown in Figure 4.3. The test voltage is impressed across both conductors of the differential input. Often this test uses a 1000-ohm resistor in one leg to represent the fact that the "real" transducer source may not be perfectly balanced. CMRR is usually expressed in decibels (dB). In this case the dB value represents a logarithmic voltage ratio between the output signal caused by a common-mode voltage and that from a normal-mode voltage. A normal-mode voltage is that impressed across the input conductors. For single-ended systems with the shield conductor connected to ground at the instrumentation front-end, the ratio between common mode and normal mode is 1:1—*no common-mode rejection.*

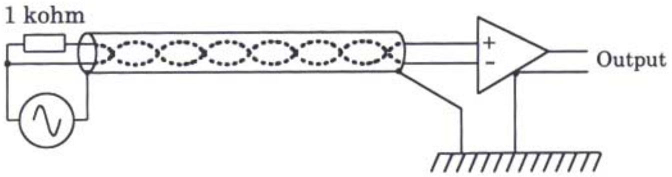


Figure 4.3: Measuring Common Mode Rejection Ratio

Each 20 dB represents an increase in the common mode rejection ratio by a factor of 10. Therefore a CMRR of 80 dB represents an attenuation of common-mode noise equal to 10,000 to 1. Another important parameter here is the maximum linear input swing on the input circuit. This value is often ±10 volts. With a CMRR of 80 dB, a 10 volt RMS (Root Mean Square) common-mode signal should have an effect on the input signal of 2 millivolts (20/10,000). However, if this is a sine wave, the voltage will reach positive and negative peaks of about 14 volts. This will likely be outside the linear range of the instrumentation amplifier and will result in substantial feed-through during portions of each cycle.

As just discussed, the value of CMRR determines how much *common-mode* noise gets converted to *normal-mode* signal. Some amount of noise may also *enter the system as normal-mode signal*, caused by noise pickup at the transducer, etc. For whatever cause, once an unwanted signal becomes a normal-mode voltage, it can be eliminated only by filtering. This is usually accomplished by low-pass filtering. For slowly changing signals, such as thermocouples, this is often accomplished by one- or two-pole passive (resistor-capacitor) filters connected directly to the input pair before any electronics. The cutoff frequency for these filters is often in the range of 2 to 10 Hertz to provide good normal-mode attenuation to power line frequency and its harmonics.

For fast-changing signals, any attempt to attenuate 50 or 60 Hz power line frequencies would prevent these changes from being monitored by the data acquisition system. In this case, sufficient precautions—such as proper grounding and good CMRR—must be taken to prevent noise from becoming normal-mode in the first place.

4.1.3 Isolation

As indicated earlier, most instrumentation front-ends require that each conductor of a differential input—and the signal conductor of a single-ended input—remain within about ±10 volts of the input common ground. This is not satisfactory for input signals with large common-mode voltage present. An example of this is the measurement from a current shunt that is several hundred volts above ground. An isolated input circuit is appropriate for such an application. This isolation can be built into the data acquisition system or consist of an isolation block in front of the DAQ system. In either case, the most common practice is to use an isolation amplifier for this purpose. An isolation amplifier usually uses a dc-to-dc-converter-powered "floating" amplifier that produces a high-frequency signal whose duty cycle is proportional to the input voltage. This high-frequency signal is then coupled across an isolation barrier and filtered. The resulting signal is proportional to the input voltage and is coupled via the output amplifier. An isolated input circuit monitoring a "floating" shunt is shown in Figure 4.4. The advantage of such an input circuit is that it can accommodate high common-mode voltages. Isolated input channels result in a significant increase in per-channel cost. Frequency response is usually limited to about 30 kilohertz. Isolated input circuits are usually specified only when a non-isolated approach cannot be used.

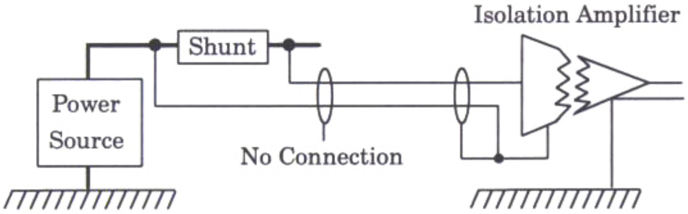


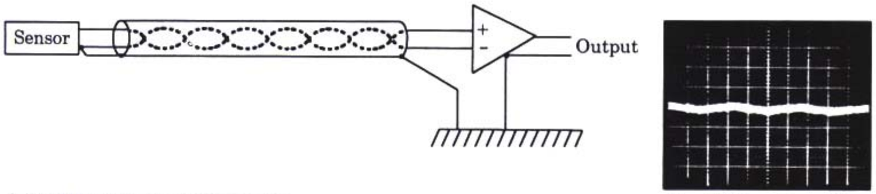
Figure 4.4: An isolated data acquisition input circuit

4.1.4 Grounding—Bad Ground Loops vs. Good Ground Loops

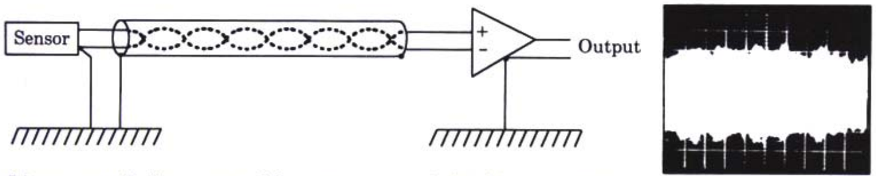
The subject of good grounding practices usually causes more arguments than any other aspects of high-performance data acquisition. Also, it is generally felt that ground loops should be avoided. The purpose of this section is to de-mystify the issue of grounding and show that there are bad *AND* good ground loops!

A good wiring practice for a voltage-input channel is shown in Figure 4.5(a). For this case, the sensor is not grounded and the cable shield is connected to the midpoint of the sensor as well as to the "ground" connection at the data acquisition system. This shield connection also meets the requirement of most instrumentation front-ends—*there must be* *a return path to the instrumentation common so that the input current (as low as it is) will not cause the input pair to "float" outside the common-mode range.* Failure to have this return path is a common cause of DAQ system problems. This will generally cause data to be collected with very poor linearity.

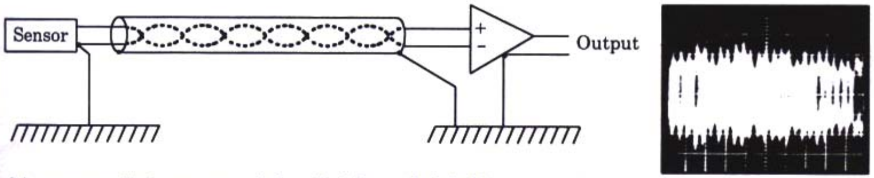
The situation is more complex if the sensor is grounded. The customary recommendation in this case is to connect the shield at the sensor and not at the DAQ system input *to avoid a ground loop,* as is shown in Figure 4.5(b). Another possible method to avoid a ground loop is to leave the shield unconnected at the sensor, as is shown in Figure 4.5(c). For most applications, the circuit shown in Figure 4.5(d) is recommended, with the shield connected at *both ends*, even though this creates a ground loop. This is the first example of a *good* ground loop. In nearly all cases, this double grounding has been shown to give far superior performance than any configuration with the shield "open" at either end.



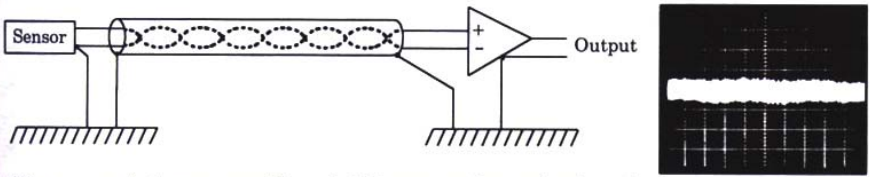
(a) with an isolated sensor



(b) a grounded sensor with a sensor-end shield connection



(c) a grounded sensor with a DAQ-end shield connection



(d) a grounded sensor with a shield connection at both ends

Figure 4.5: Noise levels with various shield grounding methods

The photographs in Figure 4.5 show the results of a test with the sensor ground and the instrumentation front-end ground derived from separate outside ac power drops to increase the noise voltage between these "grounds." A 10-ohm resistor was used to simulate the sensor. The measurements were taken from the output of an instrumentation amplifier with unity gain. For the ungrounded sensor, as shown in Figure 4.5(a), very low noise is present at the instrumentation amplifier output. Figure 4.5(b) shows the result when the shield is connected only at the sensor end. The noise level reached 500 millivolts. Similarly, Figure 4.5(c) shows a peak-to-peak noise level of 550 millivolts with the shield connected only at the amplifier end. Finally, when the shield was connected at *both ends,* creating a good ground loop, the peak-to-peak noise was reduced to 5 millivolts, as shown to Figure 4.5(d). Grounding at *both* ends reduced the noise input by a factor of about *100 to 1.* This configuration contains no filtering. If a single-pole 5 kHz low-pass filter is added, the noise is less than 1 millivolt when both ends are grounded.

How can it be that a ground loop substantially improves performance? A ground loop is generally *bad* if it involves a signal-carrying conductor. An example of this was shown in Figure 4.1(b), where the voltage produced by the ground current translated one-to-one into normal-mode voltage because the shield is a "return" for the signal. A ground loop is often *good* if it does not involve a signal-carrying conductor. The high level of noise was seen when the shield was connected at one end is primarily high-frequency "hash" that entered the system through reduced common-mode rejection and nonlinearities in the instrumentation amplifier at high frequencies. The cable capacitance and other factors greatly reduce the transmission of this noise when the shield is connected to the circuit elements at both ends. Indeed, with a connection to ground at both ends, current flows through the shield, particularly at power-line frequencies, and the signal conductors act as secondary windings of a transformer with the shield as the primary. The effect of this transformer action is greatly reduced because these voltages cancel out in the differential-input instrumentation amplifier. The double grounding cannot be applied if there is a substantial potential difference between the two circuit commons. For this case, an isolated input channel, as shown in Figure 4.4, is appropriate. Generally speaking, if a "grounded" sensor and "grounded" instrumentation input produce a ground potential difference that prevents the grounding of the shield at both ends, input isolation must be provided.

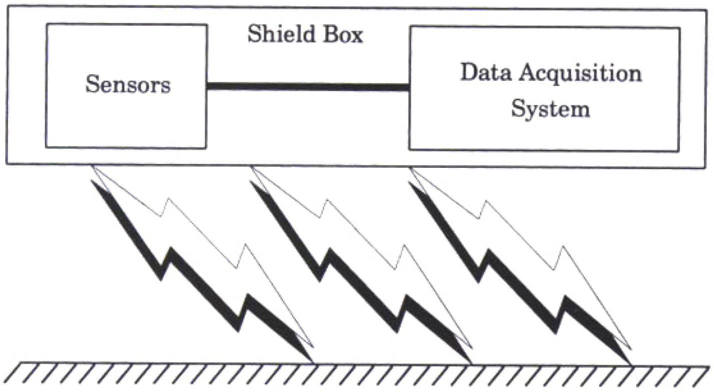


Figure 4.6: A data acquisition system at 1 million volts above ground

Keeping the ground system as unipotential as possible is another very important aspect of reducing noise pickup in a data acquisition system. KineticSystems has supplied data acquisition chassis for research laboratory Van de Graff generators that are operating at 1 million volts above ground and are transmitting digital data to ground-connected hardware via fiber optics. Refer to Figure 4.6. How do these systems operate without excessive noise pickup? Just as people don't notice that the earth's surface is spinning at speeds up to 1,000 miles per hour because all of their surroundings are moving at the same speed, a data front-end and its sensors that are at the same potential and well shielded from a noisy environment can perform quite well. Note that the important factor is that the sensors, the wiring and the instrumentation front-end are at nearly the same potential.

If the data system uses more than one equipment rack, these racks should be bonded to each other directly by screws or by a large conductive strap. The rack system should be connected to a good ground—often electrical conduit. If there are wire ducts or conduit carrying the signal cables, the usual recommendation is that these be bonded to the ground reference for the sensors *and* the racks that contain the data front-end. Note that this creates another ground loop, usually the *good* kind. This approach is controversial when the sensors are in a rather hostile electrical environment. The concern often expressed is that ground bonding at both ends will cause the electrical noise at the sensors to be transmitted to the data system ground and create more interference. Generally, the noise reduction resulting from the sensors and front-end being at nearly the same potential will far outweigh the introduction of noise by the ground loop. An additional benefit of ground bonding is that it will reduce the chance of damage to the electronics in the presence of lightning or other voltage transients. The lower the electrical impedance between the various parts of the circuit, the lower the potential difference in the event of a large voltage transient.

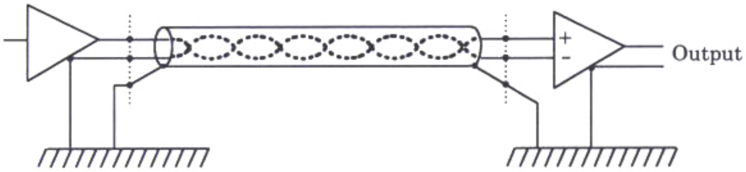


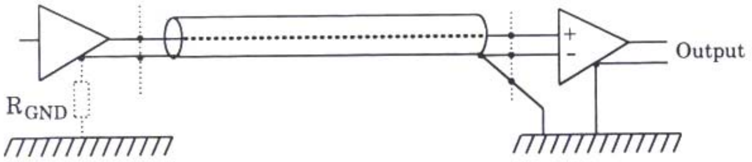
Figure 4.7: Driving a differential input channel from an unbalanced source

Even if the sensors are not connected to any part of an electrical circuit or ground, and the connection is as shown in Figure 4.2(a), the preferred technique is to bond the grounds at the sensors and DAQ front-end, using the input cable conduit, wire tray, or a #8 AWG or heavier wire. This will minimize the effect of any electrostatic coupling of noise to the sensors. Again, this is to keep the entire data acquisition front-end, including the sensors, in as unipotential an environment as possible. A similar approach involves the use of double-shielded cables, where the inner shield is connected as in Figure 4.2(a) and the outer shield is connected to ground at the sensors and to the front-end equipment chassis ground. Again, the guiding principle is to keep *all* parts of the analog subsystem moving at the same potential, just like associated objects are spinning together on the surface of the earth.

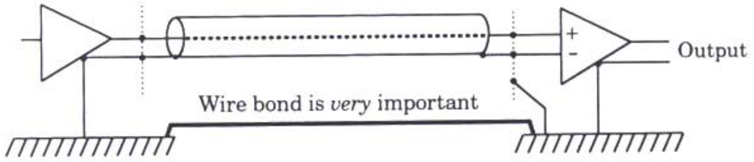
Other approaches can be used if the primary common-mode (signal-to-ground) interference is primarily high frequency in nature. One configuration uses a trifilar transformer, which is a lightly coupled three-winding transformer, with one winding in series with each of the two signal conductors and the third winding in series with the guard connection. This is quite effective in enhancing common-mode rejection at high frequencies. Another approach is to use a capacitor to connect the circuit ground to the shield at the instrumentation front-end. This provides a high-frequency ground while reducing the current caused by power-line frequencies. The effectiveness of the capacitor depends upon the particular situation. Also, some front-ends provide a guard signal for connection to the shield. The guard voltage is derived from a special instrumentation amplifier output that monitors the common-mode voltage and produces a signal to cancel it.

Another question that is often asked involves the correct cabling and ground connection when the signal source is an amplifier output instead of a passive sensor. If properly wired, this output circuit can be single-ended and produce a good signal-to-noise ratio. If the amplifier output circuit drives a two-contact-plus-shield-type connector, the connections are shown in Figure 4.7. This provides a good balance because the output impedance of an instrumentation or operational amplifier is generally less than 1 ohm at low frequencies.

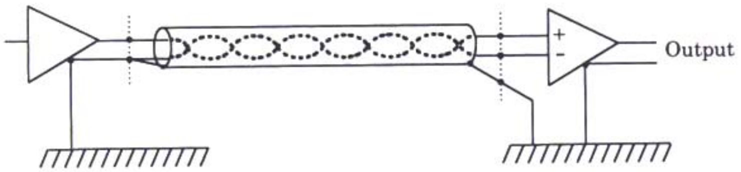
Some signal conditioning chassis contain BNC single-contact connectors at their output and are intended to be used with coaxial cable. This can present problems in correctly wiring a coaxial cable to a differential-input front-end. If the output shield connection on the signal conditioning unit is isolated from ground or has a resistance path to ground of 1000 ohms or greater, then the connections shown in Figure 4.8(a) should be used. If the shield conductor is grounded at the source, then the diagram shown in Figure 4.8(b) can be followed to prevent a ground loop in a signal-carrying conductor. This approach may not be satisfactory unless the data acquisition system contains a high-frequency filter. Also, it is *very* desirable that the ground frames of the chassis associated with the signal transmitter and receiver are mounted in the same rack or nearby racks and are electrically bonded together so that the ground noise between them is minimized. A good wiring alternative, particularly if the two units are not in the same rack, is to convert the cable to a shielded-twisted-pair type *as close to the source as possible* as shown in Figure 4.8(c).



(a) The source is "floating" or has a high resistsnce path to ground



(b) The source is grounded



(c) Using paired cable

Figure 4.8: Connecting drivers with coaxial outputs to differential inputs

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