1. Point B is ground. Therefore, point A is also ground. (Rule 2)
2. Since the current flowing from V_{in} to V_{out} is constant (Rule 1), $V_{out}/R_2 = -V_{in}/R_1$
3. Therefore, voltage gain = $V_{out}/V_{in} = -R_2/R_1$

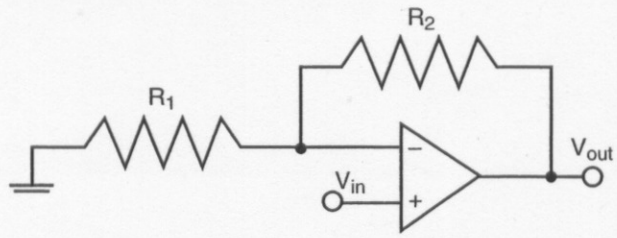

Figure 1.1.9: Non-inverting amplifier.

Figure 1.1.9 illustrates another useful configuration of an op-amp. This is a non-inverting amplifier, which is a slightly different expression than the inverting amplifier. Taking it step-by-step,

1. $V_a = V_{in}$ (Rule 2)
2. Since V_a comes from a voltage divider, $V_a = (R_1/(R_1 + R_2))\ V_{out}$
3. Therefore, $V_{in} = (R_1/(R_1 + R_2))\ V_{out}$
4. $V_{out}/V_{in} = (R_1 + R_2)/R_1 = 1 + R_2/R_1$

The following section provides more details on sensor systems and signal conditioning.

1.2 Sensor Systems

Analog Devices Technical Staff
Walt Kester, Editor

This section deals with sensors and associated signal conditioning circuits. The topic is broad, but the focus here is to concentrate on the sensors with just enough coverage of signal conditioning to introduce it and to at least imply its importance in the overall system.

Strictly speaking, a *sensor* is a device that receives a signal or stimulus and responds with an electrical signal, while a *transducer* is a converter of one type of energy into another. In practice, however, the terms are often used interchangeably.

Sensors and their associated circuits are used to measure various physical properties such as temperature, force, pressure, flow, position, light intensity, etc. These properties act as the stimulus to the sensor, and the sensor output is conditioned and processed to provide the corresponding measurement of the physical property. We will not cover all possible types of sensors here, only the most popular ones, and specifically, those that lend themselves to process control and data acquisition systems.

Excerpted from *Practical Design Techniques for Sensor Signal Conditioning*, Analog Devices, Inc., www.analog.com.

Sensors do not operate by themselves. They are generally part of a larger system consisting of signal conditioners and various analog or digital signal processing circuits. The *system* could be a measurement system, data acquisition system, or process control system, for example.

Sensors may be classified in a number of ways. From a signal conditioning viewpoint it is useful to classify sensors as either *active* or *passive*. An *active* sensor requires an external source of excitation. Resistor-based sensors such as thermistors, RTDs (Resistance Temperature Detectors), and strain gages are examples of active sensors, because a current must be passed through them and the corresponding voltage measured in order to determine the resistance value. An alternative would be to place the devices in a bridge circuit; however, in either case, an external current or voltage is required.

On the other hand, *passive* (or *self-generating*) sensors generate their own electrical output signal without requiring external voltages or currents. Examples of passive sensors are thermocouples and photodiodes which generate thermoelectric voltages and photocurrents, respectively, which are independent of external circuits. It should be noted that these definitions (*active* vs. *passive*) refer to the need (or lack thereof) of external active circuitry to produce the electrical output signal from the sensor. It would seem equally logical to consider a thermocouple to be active in the sense that it produces an output voltage with no external circuitry. However, the convention in the industry is to classify the sensor with respect to the external circuit requirement as defined above.

SENSORS:

Convert a Signal or Stimulus (Representing a Physical Property) into an Electrical Output

TRANSDUCERS:

Convert One Type of Energy into Another

The Terms are often Interchanged

Active Sensors Require an External Source of Excitation: RTDs, Strain-Gages

Passive (Self-Generating) Sensors do not: Thermocouples, Photodiodes, Piezoelectrics

Figure 1.2.1: Sensor overview.

PROPERTY	SENSOR	ACTIVE/PASSIVE	OUTPUT
Temperature	Thermocouple	Passive	Voltage
	Silicon	Active	Voltage/Current
	RTD	Active	Resistance
	Thermistor	Active	Resistance
Force/Pressure	Strain Gage	Active	Resistance
	Piezoelectric	Passive	Voltage
Acceleration	Accelerometer	Active	Capacitance
Position	LVDT	Active	AC Voltage
Light Intensity	Photodiode	Passive	Current

Figure 1.2.2: Typical sensors and their outputs

A logical way to classify sensors—and the method used throughout the remainder of this book—is with respect to the physical property the sensor is designed to measure. Thus, we have temperature sensors, force sensors, pressure sensors, motion sensors, etc. However, sensors which measure different properties may have the same type of electrical output. For instance, a resistance temperature detector (RTD) is a variable resistance, as is a resistive strain gage. Both RTDs and strain gages are often placed in bridge circuits, and the conditioning circuits are therefore quite similar. In fact, bridges and their conditioning circuits deserve a detailed discussion.

The full-scale outputs of most sensors (passive or active) are relatively small voltages, currents, or resistance changes, and therefore their outputs must be properly conditioned before further analog or digital processing can occur. Because of this, an entire class of circuits have evolved, generally referred to as *signal conditioning* circuits. Amplification, level translation, galvanic isolation, impedance transformation, linearization, and filtering are fundamental signal conditioning functions that may be required.

Whatever form the conditioning takes, however, the circuitry and performance will be governed by the electrical character of the sensor and its output. Accurate characterization of the sensor in terms of parameters appropriate to the application, e.g., sensitivity, voltage and current levels, linearity, impedances, gain, offset, drift, time constants, maximum electrical ratings, and stray impedances and other important considerations can spell the difference between substandard and successful application of the device, especially in cases where high resolution and precision, or low-level measurements are involved.

Higher levels of integration now allow ICs to play a significant role in both analog and digital signal conditioning. ADCs (analog-to-digital converters) specifically designed for measurement applications often contain on-chip programmable-gain amplifiers (PGAs) and other useful circuits, such as current sources for driving RTDs, thereby minimizing the external conditioning circuit requirements.

Most sensor outputs are nonlinear with respect to the stimulus, and their outputs must be linearized in order to yield correct measurements. Analog techniques may be used to perform this function. However, the recent introduction of high performance ADCs now allows linearization to be done much more efficiently and accurately in software and eliminates the need for tedious manual calibration using multiple and sometimes interactive trimpots.

The application of sensors in a typical process control system is shown in Figure 1.2.3. Assume the physical property to be controlled is the temperature. The output of the temperature sensor is conditioned and then digitized by an ADC. The microcontroller or host computer determines if the temperature is above or below the desired value, and outputs a digital word to the digital-to-analog converter (DAC). The DAC output is conditioned and drives the *actuator*, in this case a heater. Notice that the interface between the control center and the remote process is via the industry-standard 4–20mA loop.

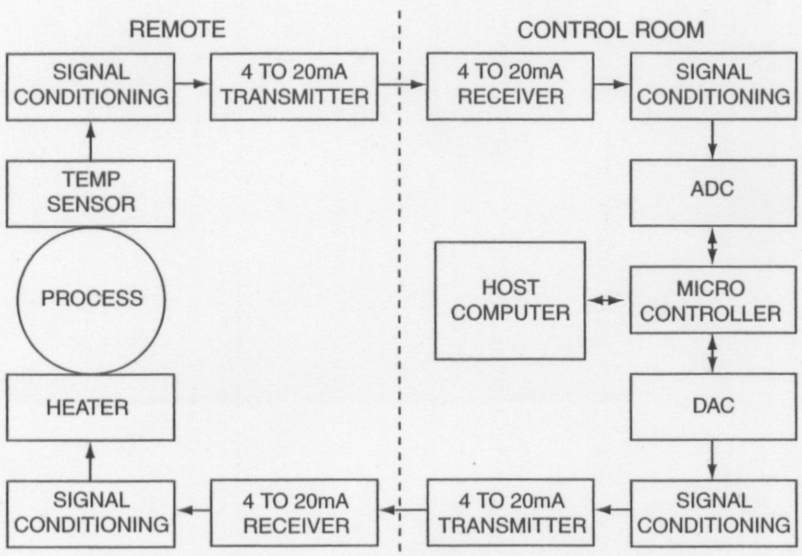

Figure 1.2.3: Typical industrial process control loop.

Digital techniques have become increasingly popular in processing sensor outputs in data acquisition, process control, and measurement. Generally, 8-bit microcontrollers (8051-based, for example) have sufficient speed and processing capability for most applications. By including the A/D conversion and the microcontroller programmability on the sensor itself, a "smart sensor" can be implemented with self-contained calibration and linearization features, among others. A smart sensor can then interface directly to an industrial network as shown in Figure 1.2.4.

The basic building blocks of a "smart sensor" are shown in Figure 1.2.5, constructed with multiple ICs. The Analog Devices MicroConverter™-series of products includes on-chip high performance multiplexers, analog-to-digital converters (ADCs) and digital-to-analog converters (DACs), coupled with Flash memory and an industry-standard 8052 microcontroller core, as well as support circuitry and several standard serial port configurations. These are the first integrated circuits which are truly smart sensor data acquisition systems (high-performance data conversion circuits, microcontroller, Flash memory) on a single chip (see Figure 1.2.6).

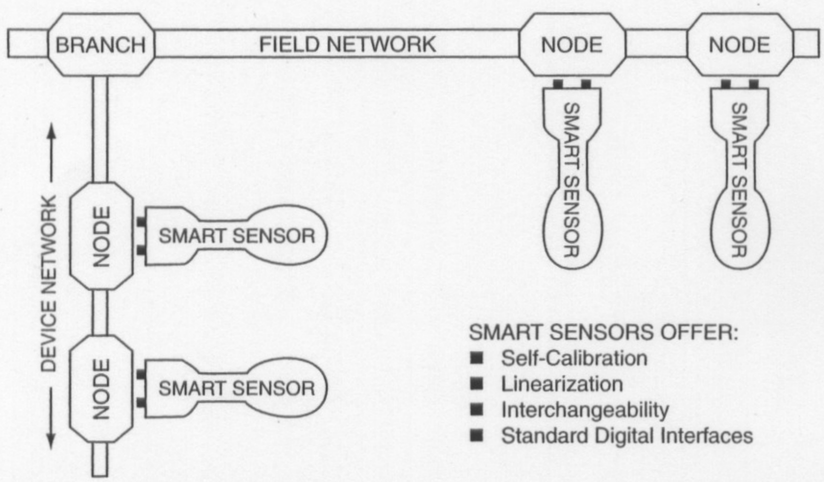

Figure 1.2.4: Standardization at the digital interface using smart sensors.

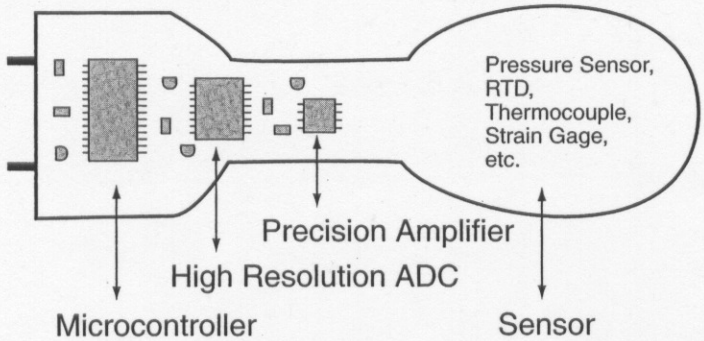

Figure 1.2.5: Basic elements in a smart sensor.

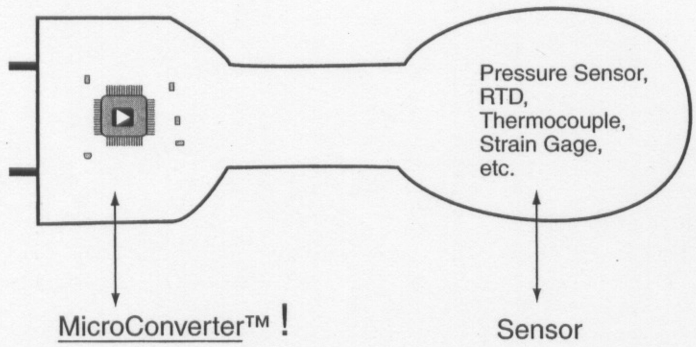

Figure 1.2.6: The even smarter sensor.

CHAPTER 2

Application Considerations

Jon Wilson, Technical Editor

The highest quality, most up-to-date, most accurately calibrated and most carefully selected sensor can still give totally erroneous data if it is not correctly applied. This section will address some of the issues that need to be considered to assure correct application of any sensor.

The following check list is derived from a list originally assembled by Applications Engineering at Endevco® in the late 1970s. It has been sporadically updated as additional issues were encountered. It is generally applicable to all sensor applications, but many of the items mentioned will not apply to any given specific application. However, it provides a reminder of questions that need to be asked and answered during selection and application of any sensor.

Often one of the most difficult tasks facing an instrumentation engineer is the selection of the proper measuring system. Economic realities and the pressing need for safe, properly functioning hardware create an ever-increasing demand to obtain accurate, reliable data on each and every measurement.

On the other hand, each application will have different characteristics from the next and will probably be subjected to different environments with different data requirements. As test or measurement programs progress, data are usually subjected to increasing manipulation, analysis and scrutiny. In this environment, the instrumentation engineer can no longer depend on his general-purpose measurement systems and expect to obtain acceptable data. Indeed, he must carefully analyze every aspect of the test to be performed, the test article, the environmental conditions, and, if available, the analytical predictions. In most cases, this process will indicate a clear choice of acceptable system components. In some cases, this analysis will identify unavoidable compromises or trade-offs and alert the instrumentation engineer and his customer to possible deficiencies in the results.

The intent of this chapter is to assist in the process of selecting an acceptable measuring system. While we hope it will be an aid, we understand it cannot totally address the wide variety of situations likely to arise.

Let's look at a few hypothetical cases where instrument selection was made with care, but where the tests were failures.

1. A test requires that low *g*, low-frequency information be measured on the axle bearings of railroad cars to assess the state of the roadbed. After considerable evaluation of the range of conditions to be measured, a high-sensitivity, low-resonance piezoelectric accelerometer is selected. The shocks generated when the wheels hit the gaps between track sections saturate the amplifier, making it impossible to gather any meaningful data.
2. A test article must be exposed to a combined environment of vibration and a rapidly changing temperature. The engineer selects an accelerometer for its high temperature rating without consulting the manufacturer. Thermal transient output swamps the vibration data.
3. Concern over ground loops prompts the selection of an isolated accelerometer. The test structure is made partially from lightweight composites, and the cases of some accelerometers are not referenced to ground. Capacitive coupling of radiated interference to the signal line overwhelms the data.

From these examples, we hope to make the point that, for all measurement systems, it is not adequate to consider only that which we wish to measure. In fact, every physical and electrical phenomenon that is present needs to be considered lest it overwhelm or, perhaps worse, subtly contaminate our data. The user must remember that every measurement system responds to its total environment.

2.1 Sensor Characteristics

The prospective user is generally forced to make a selection based on the characteristics available on the product data sheet. Many performance characteristics are shown on a typical data sheet. Many manufacturers feel that the data sheet should provide as much information as possible. Unfortunately, this abundance of data may create some confusion for a potential user, particularly the new user. Therefore the instrumentation engineer must be sure he or she understands the pertinent characteristics and how they will affect the measurement. If there is any doubt, the manufacturer should be contacted for clarification.

2.2 System Characteristics

The sensor and signal conditioners must be selected to work together as a system. Moreover, the system must be selected to perform well in the intended applications. Overall system accuracy is usually affected most by sensor characteristics such as environmental effects and dynamic characteristics. Amplifier characteristics such as nonlinearity, harmonic distortion and flatness of the frequency response curve are usually negligible when compared to sensor errors.

2.3 Instrument Selection

Selecting a sensor/signal conditioner system for highly accurate measurements requires very skillful and careful measurement engineering. All environmental, mechanical, and measurement conditions must be considered. Installation must be carefully planned and carried out. The following guidelines are offered as an aid to selecting and installing measurement systems for the best possible accuracy.

Sensor

The most important element in a measurement system is the sensor. If the data is distorted or corrupted by the sensor, there is often little that can be done to correct it.

Will the sensor operate satisfactorily in the measurement environment?

Check:
- Temperature Range
- Maximum Shock and Vibration
- Humidity
- Pressure
- Acoustic Level
- Corrosive Gases
- Magnetic and RF Fields
- Nuclear Radiation
- Salt Spray
- Transient Temperatures
- Strain in the Mounting Surface

Will the sensor characteristics provide the desired data accuracy?

Check:
- Sensitivity
- Frequency Response
  - Resonance Frequency
    - Minor Resonances
- Internal Capacitance
- Transverse Sensitivity
- Amplitude Linearity and Hysteresis
- Temperature Deviation
- Weight and size
- Internal Resistance at Maximum Temperature

Calibration Accuracy
Strain Sensitivity
Damping at Temperature Extremes
Zero Measurand Output
Thermal Zero Shift
Thermal Transient Response

Is the proper mounting being used for this application?

Check:

Is Insulating Stud Required?
Ground Loops
Calibration Simulation
Is Adhesive Mounting Required?
Thread Size, Depth and Class

Cable

Cables and connectors are usually the weakest link in the measurement system chain.

Will the cable operate satisfactorily in the measurement environment?

Check:

Temperature Range
Humidity Conditions

Will the cable characteristics provide the desired data accuracy?

Check:

Low Noise
Size and Weight
Flexibility
Is Sealed Connection Required?

Power Supply

Will the power supply operate satisfactorily in the measurement environment?

Check:

Temperature Range
Maximum Shock and Vibration
Humidity
Pressure
Acoustic Level
Corrosive Gases
Magnetic and RF Fields
Nuclear Radiation
Salt Spray

Is this the proper power supply for the application?

Check:
- Voltage Regulation
- Current Regulation

Compliance Voltage
- Output Voltage Adjustable?
- Output Current Adjustable?
- Long Output Lines?
  - Need for External Sensing
- Isolation
- Mode Card, if Required

Will the power supply characteristics provide the desired data accuracy?

Check:
- Load Regulation
- Line Regulation
- Temperature Stability
- Time Stability
- Ripple and Noise
- Output Impedance
- Line-Transient Response
- Noise to Ground
- DC Isolation

Amplifier

The amplifier must provide gain, impedance matching, output drive current, and other signal processing.

Will the amplifier operate satisfactorily in the measurement environment?

Check:
- Temperature Range
- Maximum Shock and Vibration
- Humidity
- Pressure
- Acoustic Level
- Corrosive Gases
- Magnetic and RF Fields
- Nuclear Radiation
- Salt Spray

Is this the proper amplifier for the application?

Check:

- Long Input Lines?
  - Need for Charge Amplifier
  - Need for Remote Charge Amplifier
- Long Output Lines
  - Need for Power Amplifier
- Airborne
  - Size, Weight, Power Limitations

Will the amplifier characteristics provide the desired data accuracy?

Check:

- Gain and Gain Stability
- Frequency Response
- Linearity
- Stability
- Phase Shift
- Output Current and Voltage
- Residual Noise
- Input Impedance
- Transient Response
- Overload Capability
- Common Mode Rejection
- Zero-Temperature Coefficient
- Gain-Temperature Coefficient

2.4 Data Acquisition and Readout

Does the remainder of the system, including any additional amplifiers, filters, data acquisition and readout devices, introduce any limitation that will tend to degrade the sensor-amplifier characteristics?

Check: ALL of previous check items, plus Adequate Resolution.

2.5 Installation

Even the most carefully and thoughtfully selected and calibrated system can produce bad data if carelessly or ignorantly installed.

Sensor

Is the unit in good condition and ready to use?

- Check:
  - Up-to-Date Calibration
  - Physical Condition
    - Case
    - Mounting Surface
    - Connector
    - Mounting Hardware
  - Inspect for Clean Connector
  - Internal Resistance

Is the mounting hardware in good condition and ready to use?

- Check:
  - Mounting Surface Condition
  - Thread Condition
  - Burred End Slots
  - Insulated Stud
    - Insulation Resistance
    - Stud Damage by Over Torquing
  - Mounting Surface Clean and Flat
  - Sensor Base Surface Clean and Flat
  - Hole Drilled and Tapped Deep Enough
  - Correct Tap Size
  - Hole Properly Aligned Perpendicular to Mounting Surface
  - Stud Threads Lubricated
  - Sensor Mounted with Recommended Torque

Cement Mounting

- Check:
  - Mounting Surface Clean and Flat
  - Dental Cement for Uneven Surfaces
  - Cement Cured Properly
  - Sensor Mounted to Cementing Stud with Recommended Torque

Cable

Is the cable in good condition and ready for use?

- Check:
  - Physical Condition
    - Cable Kinked, Crushed
    - Connector Threads, Pins
  - Inspect for Clean Connectors
  - Continuity
  - Insulation Resistance
  - Capacitance
  - All Cable Connections Secure
  - Cable Properly restrained
  - Excess Cable Coiled and Tied Down
  - Drip Loop Provided
  - Connectors Sealed and Potted, if Required

Power Supply, Amplifier, and Readout

Are the units in good condition and ready to use?

- Check:
  - Up-to-Date Calibration
  - Physical Condition
    - Connectors
    - Case
    - Output Cables
  - Inspect for Clean Connectors
  - Mounted Securely
  - All Cable Connections Secure
  - Gain Hole Cover Sealed, if Required
  - Recommended Grounding in Use

When the above questions have been answered to the user's satisfaction, the measurement system has a high probability of providing accurate data.

CHAPTER 3

Measurement Issues and Criteria

Jon Wilson, Technical Editor

Sensors are most commonly used to make quantifiable measurements, as opposed to qualitative detection or presence sensing. Therefore, it should be obvious that the requirements of the measurement will determine the selection and application of the sensor. How then can we quantify the requirements of the measurement?

First, we must consider what it is we want to measure. Sensors are available to measure almost anything you can think of, and many things you would never think of (but someone has!). Pressure, temperature and flow are probably the most common measurements as they are involved in monitoring and controlling many industrial processes and material transfers. A brief tour of a Sensors Expo exhibition or a quick look at the internet will yield hundreds, if not thousands, of quantities, characteristics or phenomena that can be measured with sensors.

Second, we must consider the environment of the sensor. Environmental effects are perhaps the biggest contributor to measurement errors in most measurement systems. Sensors, and indeed whole measurement systems, respond to their total environment, not just to the measurand. In extreme cases, the response to the combination of environments may be greater than the response to the desired measurand. One of the sensor designer's greatest challenges is to minimize the response to the environment and maximize the response to the desired measurand. Assessing the environment and estimating its effect on the measurement system is an extremely important part of the selection and application process.

The environment includes not only such parameters as temperature, pressure and vibration, but also the mounting or attachment of the sensor, electromagnetic and electrostatic effects, and the rates of change of the various environments. For example, a sensor may be little affected by extreme temperatures, but may produce huge errors in a rapidly changing temperature ("thermal transient sensitivity").

Third, we must consider the requirements for accuracy (uncertainty) of the measurement. Often, we would like to achieve the lowest possible uncertainty, but that may not be economically feasible, or even necessary. How will the information derived from the measurement be used? Will it really make a difference, in the long run, whether the uncertainty is 1% or 1½%? Will highly accurate sensor data be obscured by inaccuracies in the signal conditioning or recording processes? On the other hand, many modern data acquisition systems are capable of much greater accuracy than the sensors making the measurement. A user must not be misled by thinking that high resolution in a data acquisition system will produce high accuracy data from a low accuracy sensor.

Last, but not least, the user must assure that the whole system is calibrated and traceable to a national standards organization (such as National Institute of Standards and Technology [NIST] in the United States). Without documented traceability, the uncertainty of any measurement is unknown. Either each part of the measurement system must be calibrated and an overall uncertainty calculated, or the total system must be calibrated as it will be used ("system calibration" or "end-to-end calibration").

Since most sensors do not have any adjustment capability for conventional "calibration", a characterization or evaluation of sensor parameters is most often required. For the lowest uncertainty in the measurement, the characterization should be done with mounting and environment as similar as possible to the actual measurement conditions.

While this handbook concentrates on sensor technology, a properly selected, calibrated, and applied sensor is necessary but not sufficient to assure accurate measurements. The sensor must be carefully matched with, and integrated into, the total measurement system and its environment.