# How to Choose the Right Sensor for Your Measurement System

## Overview

You can choose from many different sensors on the market today to measure all types of natural phenomena. This white paper categorizes and compares the most common sensors for measuring seven of these phenomena to help you choose the best option for your application.

## Temperature

The most common sensors for measuring temperature are thermocouples, thermistors, and resistance temperature detectors (RTDs). Fiber-optic sensors, while more specialized, are growing in popularity for temperature measurements.

| Temp. Sensor | Signal Conditioning Required | Accuracy | Sensitivity | Comparison |
|---|---|---|---|---|
| Thermocouple | ▪ Amplification<br>▪ Filtering<br>▪ Cold-Junction Compensation | Good | Good | ▪ Self-Powered<br>▪ Inexpensive<br>▪ Rugged<br>▪ Large Temperature Range |
| RTD | ▪ Amplification<br>▪ Filtering<br>▪ Current Excitation | Best | Better | ▪ Very Accurate<br>▪ Very Stable |
| Thermistor | ▪ Amplification<br>▪ Filtering<br>▪ Voltage Excitation | Better | Best | ▪ High Resistance<br>▪ Low Thermal Mass |
| Fiber Optics | ▪ Little or No Amplification<br>▪ Filtering | Best | Best | ▪ Good for Hazardous Environments<br>▪ Good for Long Distances<br>▪ Immune to Electromagnetic Interference (EMI)-Induced Noise<br>▪ Small, Lightweight |

Table 1.
*Comparison of Common Temperature Sensors*

### Thermocouples

Thermocouples, the most popular temperature sensors, are effective in applications that require a large temperature range. They are inexpensive ($1 to $50 USD) and have a response time of fractions of a second. Due to material properties and other factors, temperature accuracy of less than 1 °C can be hard to achieve.

### RTDs

RTDs are nearly as popular as thermocouples and can maintain a stable temperature reading for years. In contrast to thermocouples, RTDs have a smaller temperature range (-200 to 500 °C), require current excitation, and have a slower response time (2.5 to 10 s). RTDs are primarily used for accurate temperature measurements (±1.9 percent) in applications that are not time critical. RTDs can cost between $25 and $1,000 USD.

### Thermistors

Thermistors have a smaller temperature range (-90 to 130 °C) than previously mentioned sensors. They have the best accuracy (±.05 °C), but they are more fragile than thermocouples or RTDs. Thermistors involve excitation like the RTD; however, the thermistor requires voltage excitation rather than current excitation. A thermistor typically ranges between $2 and $10 USD in price.

### Fiber Optics

Another alternative is the use of fiber optics to measure temperature. Fiber-optic temperature sensors are effective for environments that are hazardous or where there could be regular electromagnetic interference. They are nonconductive, electrically passive, immune to electromagnetic interference (EMI)-induced noise, and able to transmit data over long distances with little or no loss in signal integrity.

## Strain

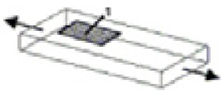
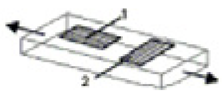
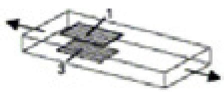
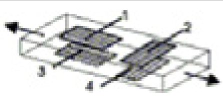
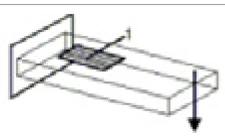
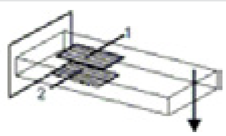
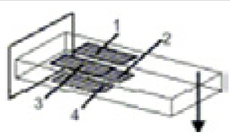
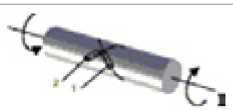
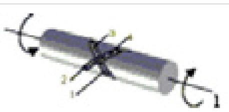
| Strain | Gage Setup | Bridge Type | Sensitivity MV/V @100 uE | Details |
|---|---|---|---|---|
| Axial |  | ¼ | 0.5 | Good: Simplest to implement, but must use a dummy gage if compensating for temperature. Responds equally to axial strain. |
| |  | ½ | 0.65 | Better: Temperature compensated, but it is sensitive to bending strain. |
| |  | ½ | 1.0 | Better: Rejects bending strain, but not temperature. Must use dummy gages if compensating for temperature. |
| |  | Full | 1.3 | Best: More sensitive and compensates for both temperature and bending strain. |
| Bending |  | ¼ | 0.5 | Good: Simplest to implement, but must use a dummy gage if compensating for temperature. Responds equally to axial strain. |
| |  | ½ | 1.0 | Better: Rejects axial strain and is temperature compensated. |
| |  | Full | 2.0 | Best: Rejects axial strain and is temperature compensated. Most sensitive to bending strain. |
| Torsional and Shear |  | ½ | 1.0 | Good: Gages must be mounted at 45 degrees from centerline. |
| |  | Full | 2.0 | Best: Most sensitive full-bridge version of previous setup. Rejects both axial and bending strains. |

Table 2.
*Comparison of Common Strain Gage Configurations*

Strain is typically measured by a resistive strain gage. These flat resistors are usually attached to a surface that is expected to flex or bend. One use case for resistive strain gages is structural testing of airplane wings. Strain gages can measure very small twists, bends, and pulls on surfaces. When more than one resistive strain gage is wired together, a bridge is created.

A more sensitive measurement is available with the purchase of more strain gages. You can use up to four active strain gages to build a Wheatstone bridge circuit; this is called a full-bridge configuration. There are also half-bridge (two active strain gages) and quarter-bridge (one active strain gage) configurations. The more active strain gages you use, the more accurate your readings will be.

Strain gages require current or voltage excitation and are susceptible to temperature drift, bending strain, and axial strain, which can give false readings without the use of additional resistive strain gages.

- Axial bridges measure stretching or the pulling apart of a material.
- Bending bridges measure a stretch on one side of a material and a contraction on its opposing side.
- Torsional and shear bridges measure the twist of a material.

Strain is measured with a dimensionless unit (e or ε), which is equivalent to a small change in length divided by the full length of an object under measure.

Similar to temperature systems, fiber-optic sensors can be used to measure strain in hazardous environments, where a regular electrical measurement could be altered by electromagnetic interference. Fiber-optic strain sensors are nonconductive, electrically passive, immune to EMI-induced noise, and able to transmit data over long distances with little or no loss in signal integrity.

## Sound

| Microphones | Price | Environment | Impedance Level | Sensitivity | Comparison |
|---|---|---|---|---|---|
| Prepolarized Condenser | Medium | Tough | Medium | Best | ▪ Condenser designs are most used<br>▪ Best in humid environments |
| Externally Polarized Condenser | High | Tough | Better | Good | ▪ Condenser designs are most used<br>▪ Best in high-temperature environments |
| Carbon Microphone | Low | Average | High | Good | ▪ Low quality<br>▪ Used in early basic design of telephone handset |
| Electret | Low | Average | Low | Better | ▪ Better with high frequencies |
| Piezoelectric | Medium | Tough | High | Good | ▪ Suitable for shock and blast pressure measurement applications |
| Dynamic/Magnetic | High | Tough | Medium | Better | ▪ Resistant to moisture<br>▪ Not good in highly magnetic environment |

Table 3.
*Comparison of Common Sound Sensors*

Microphones are used to measure sound, but you have many different types of microphones to consider when choosing a sensor for an application.

### Condenser Microphones
The most common are condenser microphones. These may come either prepolarized (meaning that a power source is included within the microphone) or externally polarized. Externally polarized condenser microphones require an additional power source, which adds cost to projects. Prepolarized microphones are preferred in humid environments where a power supply's components could be damaged, and externally polarized condenser microphones are preferred in high-temperature environments.

### Piezoelectric Microphones
Robust piezoelectric microphones are used in shock and blast pressure measurement applications. These durable microphones can measure high-amplitude (decibels) pressure ranges. Their disadvantage is the high noise levels they also pick up.

### Dynamic/Magnetic Microphones
In addition to the piezoelectric microphone, dynamic or magnetic microphones function in tough environments. They rely on movement to magnetically induce an electric charge in a way that makes them resistant to water, but obviously these microphones are not very useful in highly magnetic environments.

### Electret Microphones
Electret microphones are small and effective at detecting high-frequency sound. They are used in millions of computers and electronic devices around the globe. They are relatively cheap, and their only drawback is the lack of bass they provide. In addition, carbon microphones, which are less commonplace today, can be used in applications in which the quality of sound is not an issue.

## Vibration

| Vibration Sensors | Natural Frequency | Number of Axes | Damping Coefficient | Scale Factor | Comparison |
|---|---|---|---|---|---|
| Ceramic Piezoelectric (accelerometer) | >5 kHz | Up to 3 | Small | Requires High Output | ▪ Used in vibration and shock measurements |
| Linear Variable Differential Transformer (LVDT) | <80 Hz | Up to 3 | Medium | Varies | ▪ Limited to steady-state acceleration or low-frequency vibration measurement |
| Proximity Probe | <30 Hz | Up to 3 | Medium | Varies | ▪ Limited to steady-state acceleration or low-frequency vibration measurement<br>▪ Spring mass attached to wiper of potentiometer |
| Variable Reluctance | <100 Hz | Up to 3 | Medium | Varies | ▪ Output exists only when mass is in motion<br>▪ Used in shock studies and oil exploration |

Table 4.
*Comparison of Common Vibration Sensors*

### Ceramic Piezoelectric Sensor or Accelerometer

Vibration or acceleration is most commonly measured using a ceramic piezoelectric sensor or accelerometer.

Three major factors differentiate vibration sensors: the natural frequency, the damping coefficient, and a scale factor. The scale factor relates the output to an acceleration input and is linked to sensitivity. Together, the natural frequency and damping coefficient determine the accuracy level of a vibration sensor. In a system consisting of a spring and attached mass, if you were to pull the mass back away from equilibrium and release the mass, the mass would vibrate forward (past the equilibrium) and backward until it came to rest. The friction that brings the mass to rest is defined by the damping coefficient, and the rate at which the mass vibrates forward and backward is its natural frequency.

Ceramic piezoelectric vibration sensors are the most commonly used sensors because they are the most versatile sensors. These vibration sensors can be used in shock measurements (explosions and failure tests), high-frequency measurements, and slower low-frequency vibration measurements. This is shown by their higher than average natural frequency. However, this sensor typically has outputs in the millivolt range and requires a high-input-impedance, low-noise detector to interpret voltages from its piezoelectric crystal.

### Proximity Probes and Linear Variable Differential Transformers (LVDTs)

Proximity probes and LVDTs are similar. Both are limited to steady-state acceleration or low-frequency vibration measurement; however, the LVDT vibration sensor has a slightly higher natural frequency, meaning that it can handle/detect more vibration. The proximity probe is simply a spring mass attached to the wiper of a potentiometer.

### Variable Reluctance Vibration Sensor

A variable reluctance vibration sensor uses permanent magnets and movement through coils to measure motion and vibration. This is a special vibration sensor because it registers output only when the mass it is measuring is in motion. This makes it particularly useful in earthquake shock studies and oil exploration to pick up vibrations reflected from underground rock strata.

## Position and Displacement

| Position Sensor | Price | Environment | Accuracy | Sensitivity | Comparison |
|---|---|---|---|---|---|
| Hall Effect Sensor | Low | Standard | On or off | On or off | ▪ Only certain that target is nearby when depressing sensor |
| Optical Encoders – Linear and Rotary | Varies | Standard | Varies | High | ▪ Accuracy determined by number of counts per revolution |
| Potentiometers | Low | Standard | High | High | ▪ Required to be physically attached to moving target |
| Linear and Rotary Variable Differential Transformers (LVDT) or (RVDT) | High | Known for tolerance of dirty industrial environments and precision | High | High | ▪ Handles a high degree of power<br>▪ Requires signal conditioning<br>▪ RVDTs typically operate over any angular range of ±30 to 70 °C |
| Eddy-Current Proximity Probe | Medium | ▪ Noncontacting<br>▪ Tolerance of dirty environments<br>▪ Not sensitive to material between sensor and target | Medium | Varies | ▪ Not good where high resolution is required<br>▪ Not good for use when a large gap exists between sensor and target (optical and laser sensors are better)<br>▪ Good when mounted on a reasonably stationary mechanical structure to measure nearby moving machinery |
| Reflective Light Proximity Sensor | Varies | Standard | Varies | High | ▪ Line of sight to target required for measurement<br>▪ Good for use when large gap exists between sensor and target<br>▪ Accuracy determined by quality of sensor |

Table 5.
*Comparison of Common Position Sensors*

You can choose from many different types of position sensors. The driving factors in selecting a position sensor are excitation, filtering, environment, and whether line of sight or a direct, physical connection is required to measure distance. There is not one universally preferred sensor type as with pressure or force. Position has been measured with sensors for a long time, so both preference and application play a role in making this decision.

### Hall Effect Sensors

With Hall effect sensors, the presence of an object is determined when that object depresses a button. It is either "on" and the object is touching the button or "off" and the target could be anywhere. Hall effect sensors have been used in keyboards and even in robot boxing battle competitions to determine when a blow was delivered. This sensor provides no scale for how far away an object is from the sensor when the button is "off," but it is effective for applications that do not require highly detailed position information.

### Potentiometers

Potentiometers are sensors that use a sliding contact to create an adjustable voltage divider. This adjustable voltage measures position. Potentiometers provide a slight drag to the system that they are physically connected to. While this is required for their use, potentiometers are cheap compared to other position sensors and can offer great accuracy.

### Optical Encoders

Another position sensor commonly used is the optical encoder, which can be either linear or rotary. These devices can determine speed, direction, and position with fast, high accuracy. As the name suggests, optical encoders use light to determine position. A series of striped bars divide up the distance to be measured by counts. The more counts, the higher the accuracy. Some rotary optical encoders can have up to 30,000 counts to offer tremendous accuracy. Also, because of their fast response time, they are ideal for many motion control applications.

Sensors with physical components that attach to a system, like the potentiometer, add a small amount of resistance to the movement of the system's parts. However, encoders hardly produce any friction when they move and are very lightweight, but they must have seals to operate within a harsh or dusty environment, which adds to cost. An additional cost is also typically incurred in high-accuracy applications because optical encoders require their own bearings to avoid misalignment when incorporated into products.

### Linear Variable Differential Transformers (LVDTs)

Linear variable differential transformers (LVDTs) and their rotary counterpart (RVDTs) use magnetic induction to determine position. They are both effective for industrial and aerospace applications because of their robustness. Both require signal conditioning, which can add to cost. Also, these sensors must be accurately aligned inside heavy, expensive packaging and contain wound coils that are expensive to manufacture. In addition to their cost, they are known for their high precision.

### Eddy-Current Sensors

Eddy-current sensors use magnetic fields to determine position and are moderately priced. They are used less in applications that require highly detailed positioning information or where large gaps exist between the sensor and the target. These sensors are better used on assembly lines when mounted on a reasonably stationary mechanical structure to measure nearby moving machinery or products. For more precise positioning information, use a light proximity sensor instead.

### Reflective Light Proximity Sensors

Reflective light proximity sensors use a beam's travel time to and from a reflective target to determine distance. They have a quick response time and are excellent in applications where large gaps exist between the sensor and target. Line of sight is required when using this sensor, and the accuracy and quality of this sensor is directly related to its price.

## Pressure

High or low pressure is all relative – like heat. It can be "hot" in a room, but the temperature in that room is nothing compared to the temperature on the surface of the sun. With pressure, the comparison makes the measurement.

There are five common pressure measurement types: absolute, gauge, vacuum, differential, and sealed. Consider the following example of measuring the pressure within a tire, and note how each major type is relative to a different reference pressure.

| Pressure Relative Measurement Types | Tire Example | Comparison |
|---|---|---|
| Absolute | Absolute pressure = standard atmospheric pressure + gauge pressure | Relative to 0 Pa, the pressure in a vacuum |
| Gauge | Reading from tire pressure gauge | Relative to local atmospheric pressure |
| Vacuum | Typically negative value when relative to local atmospheric pressure. Flat tire = 0 kPa on vacuum gauge | Relative to either absolute vacuum (0 Pa) or local atmospheric pressure |
| Differential | Differential pressure = pressure difference between two different tires | Relative to another pressurized container |
| Sealed | Sealed pressure = gauge pressure + difference between local atmospheric pressure and sea level pressure | Relative to sea level pressure |

Table 6.
*Comparison of Relative Pressure Measurement Types*

- An absolute pressure measurement includes the standard pressure from the weight of the atmosphere (101.325 kPa) and the additional pressure within the tire. The typical tire pressure is 34 PSI or about 234 kPa. The absolute pressure is 234 kPa plus 101.325 kPa or 331.325 kPa.
- A gauge pressure measurement is relative to the local atmospheric pressure and is equal to 234 kPa or 34 PSI.
- Vacuum pressure is relative to either an absolute vacuum or local atmospheric pressure. A flat tire could have the same pressure as the local atmosphere or 0 kPa (relative to atmospheric pressure). This same vacuum pressure measurement could equal 234 kPa (relative to an absolute vacuum).
- Differential pressure is just the difference between any two pressure levels. In the tire example, this means the difference in pressure between two tires. It could also mean the difference between atmospheric pressure and the pressure inside a single tire.
- Sealed pressure measurements are differential pressure measurements taken with a known comparison pressure. Typically this pressure is sea level, but it could be any pressure depending on the application.

Each of these measurement types could alter your pressure values, so you need to know which type of measurement your sensors are acquiring.

Bridge-based (strain gages), or piezoresistive sensors, are the most commonly used pressure sensors. This is due to their simple construction and durability. These characteristics allow for lower cost and make them ideal for higher channel systems.

These common pressure sensors can be either conditioned or nonconditioned. Typically conditioned sensors are more expensive because they contain components for filtering and signal amplification, as well as excitation leads and the regular circuitry for measurement. If you are working with nonconditioned pressure bridge-based sensors, your hardware needs signal conditioning. Check the sensor's documentation so that you know whether you need additional components for amplification or filtering.

## Force

| Load Cell Sensors | Price | Weight Range | Accuracy | Sensitivity | Comparison |
|---|---|---|---|---|---|
| Beam Style | Low | 10 – 5k lb | High | Medium | ▪ Used with tanks, platform scales<br>▪ Strain gages are exposed and require protection |
| S Beam | Low | 10 – 5k lb | High | Medium | ▪ Used with tanks, platform scales<br>▪ Better sealing and protection than bending beam |
| Canister | Medium | Up to 500k lb | Medium | High | ▪ Used for truck, tank, and hopper scales<br>▪ Handles load movements<br>▪ No horizontal load protection |
| Pancake/Low Profile | Low | 5 – 500k lb | Medium | Medium | ▪ All stainless steel<br>▪ Used with tanks, bins, and scales<br>▪ No load movement allowed |
| Button and Washer | Low | Either<br>0 – 50k lb or<br>0 – 200 lb typically | Low | Medium | ▪ Loads must be centered<br>▪ No load movement allowed |

Table 7.
*Comparison of Common Load Cell Sensors*

At one time, mechanical lever scales were primarily used to measure force. Today, strain gage based load cells are the most common because they do not require the amount of calibration and maintenance that scales need.

Load cells can be either conditioned or nonconditioned. Typically conditioned sensors are more expensive because they contain components for filtering, signal amplification, as well as excitation leads, and the regular circuitry for measurement. If you are working with nonconditioned bridge-based sensors, your hardware needs signal conditioning. Check the sensor's documentation so that you know whether you need additional components for amplification or filtering.

Beam style load cells are useful when a linear force is expected and are typically used in weighing applications of both small and large items (10 lb up to 5k lb). They have an average sensitivity, but are highly accurate. This load cell has simple construction and a low cost.

The S beam load cell is similar to the beam style with the exception of its design. Because of this design difference (the load cell's characteristic S shape), the sensor is effective for high side load rejection and measuring the weight of a load that is not centered. This low-cost load cell's design is also simple.

The canister load cell can handle larger loads than both S and beam style load cells. It can also handle load movement easily and is highly sensitive; however, the sensor requires horizontal load protection.

Pancake or low-profile load cells are designed in such a way that they require absolutely no movement to achieve an accurate reading. If your application has time constraints or requires quick measurements, you may consider using the canister load cell instead.

Button and washer load cells are typically used to measure the weights of smaller objects (up to 200 lb). Like pancake or low-profile load cells, the object being weighed must not be moving to obtain an accurate measurement. The load must also be centered on what is usually a small scale. The benefit to these load cells is that they are inexpensive.