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Guide to Sensors for Manufacturing and Machine Control

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Sensors are the first entry point of all feedback data into the control system. Without sensors, many simple tasks would be impossible, such as tracking products on an assembly line, monitoring the temperature of a heat-treating oven, or determining the presence of a package for intralogistics distribution. Sensors are a critical piece of all industrial infrastructure.

It's important for engineers to understand the differences between sensor technologies. The wide variety of sensor signals, specifications, and limitations must all be considered when designing new systems or troubleshooting existing machines.

Our team has compiled this sensor ebook in partnership with contributions from our friends at Carlo Gavazzi, a leader in control systems and sensor devices. Carlo Gavazzi generously provided devices for physical bench tests and product images for a wide range of sensor applications.

The content was written and edited by our engineering content team at Control.com, with special thanks to authors Antonio Armenta and Damond Goodwin. We hope you will find the content practical as you continue your journey of understanding electrical control systems.

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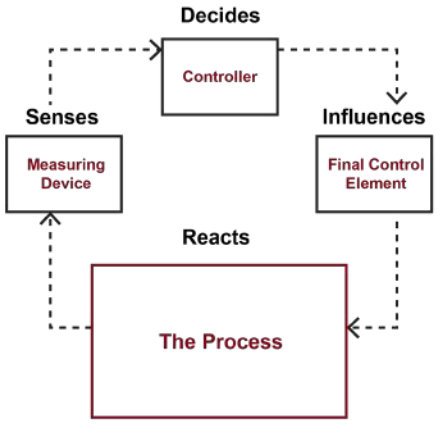
Guide to Sensors for Manufacturing and Machine Control

Modern manufacturing processes are complex, requiring multiple steps that must work together to create a final product. These steps may be simple, or they may be complex sub-processes in themselves. In most cases, complexity raises the necessity for automation. When any process runs automatically, sensors become extremely important.

Sensors perceive a physical quantity at the input and send a corresponding electrical signal to the output. Sensors are transducer devices because they convert energy from one form to another. As the name suggests, sensors can sense the world around them and convert that input into something that a computer or a process controller can understand. Imagine sensors to be like human nerve terminals. Without them, the industrial process is open-loop, meaning it's essentially blind to itself and the environment. The system operates with the hope that it is responding as expected.

In the more common closed-loop control model, sensors are the key devices that provide information about the process. This closed-loop model allows the system to correct errors and update the output signals to account for the inevitable variations in the surrounding environment.



The traditional process control loop.

Industrial sensors can be found in nearly every modern manufacturing process, regardless of complexity. As a result, it is nearly impossible to develop an automated system without sensors.

The History of Sensor Technology

The earliest examples of sensing technology can be found as far back as the nineteenth century with Warren Johnson's invention of the bimetal thermostat. The next several decades saw the arrival of some of the first forms of discrete sensors, including limit switches, photoelectric sensors, and magnetic devices.

The first analog sensors originated in the mid-twentieth century when American inventor Samuel Bagno created the motion sensor in the 1940s based on technology developed during World War II. The first infrared sensors were developed around the same time. Other sensors, such as ultrasonic, humidity, gas, and vibration, were created in the following decades.

Fast forward to today. The industrial world has now gone through several major disruptions and is in the middle of what many consider the fourth revolution, each with its own impact on the world of sensors. The first revolution brought mechanical sensors, the second brought electrical sensors, and the third introduced computers and digital systems. Finally, this fourth revolution, Industry 4.0, has given birth to what many call smart industrial sensors.

Connectivity and communication are key to all modern so-called smart sensors.

Smart sensors include network connectivity for data transfer, diagnostics, and ease of integration. Smart sensors can share measurement data with a centralized system and the cloud. This networking ability enables far more advanced analytics, instant insights into a live manufacturing process, and access from anywhere in the world.

Industrial Sensor Classifications

Fundamentally, every industrial sensor is designed to detect some measurable value exhibited by a physical quantity. Physical quantities can be magnetic fields, temperature, pressure, frequency, or light conditions. Any measurable changes to the process are captured by the sensor and converted to an output. Outputs can be simple signals or complex data signals with the addition of embedded digital signal processing circuits.

Sensors must be highly reliable since feedback systems must be able to depend on repeatable, accurate process data. Ideally, a sensor should always produce the same output when subjected to the same physical input value, time after time.

Analog sensors require a reliable, linear relationship between input and output, characterized by the slope-intercept mathematical model with both a slope (gain value) and intercept (zero offset) to ensure both linear consistency and a carefully calibrated output.

There are different ways to classify industrial sensors. At a very high level, sensors are designed to serve two distinct branches of industrial automation. First, there are sensors that measure continuous values for ongoing processes that often work with fluids and varying temperatures. These sensors are used for **monitoring control, also known as process control.**

There are also many sensors devoted to detecting objects as they are created, modified, shipped, and delivered across the global manufacturing and supply chain network. This category of sensors is used for **manufacturing control, also known as machine control.**

This guide will examine these machine control sensors found throughout manufacturing operations. Most commonly, these sensors include the following types of operating theory:

- Mechanical
- Photoelectric
- Magnetic and inductive
- Capacitive
- Ultrasonic

Different types of industrial sensors.

Some sensors are needed only to provide an on/off signal, simply measuring the presence of an object within a field of view. These discrete sensors provide an output voltage that will land at either 0 V or at the control system's full voltage. Other types of sensors can provide a varying range of values between a minimum and a maximum, providing more insight than their discrete sensor counterparts. These analog sensor output ranges include, most commonly, 0-10 V or 4-20 mA. To provide meaning, these analog outputs must be processed and converted to the desired engineering unit of measurement inside the programmable controller.

Sensors could also be categorized according to how they are placed. Online sensors are those where the material or process flows in front of or through the sensor. Offline sensors are used for sampling and quality control and are found inside many measurement tools and meters.

New sensors are being developed continuously; however, only a few have become successful marketable products. The expected characteristics of reliability and simplicity offered by well-established sensor types and brands usually outweigh the benefits of new sensing technologies that have yet to be proven in the market.

Mechanical Sensors

The oldest types of sensors pre-date any sort of digital processing. Much like a light switch, the presence and position of objects can be detected when a force is applied to a lever. Due to the simplicity and reliability of such methods, mechanical sensors are still very common.

Limit Switches

The electromechanical limit switch is, perhaps, the most common example of object presence detection by input force. A set of metal contacts engages when the torque (the applied force against a rotating spring arm) exceeds a pre-set value. Depending on the size of the limit switch, the torque required can vary but is usually less than 1.0 N-m, even for the largest switches. The sensitivity can be adjusted by changing the placement of the lever arm on the actuator.

Limit switches come in many shapes and sizes with various operator mechanisms.

A similar actuation is the plunger type of limit switch, which operates using a direct force rather than a rotational force against a torsional spring. This direct force often exceeds the 10 N required to activate the internal switching contacts.

Connecting a limit switch is relatively simple. One wire supplies the incoming voltage, and the other supplies the outgoing voltage as a signal to the controller. Electromechanical limit switches are easy to identify from the distinct clicking sound as they change between energized states. These switches are a form of discrete sensor with only on/off status indication.

Potentiometer Position Sensors

Potentiometers are variable resistors that can be used to provide position sensing. The variable resistance can be used to generate a variable voltage based on the current position around a resistive disk or along a linear strip of resistance. The mechanical motion is thereby translated into a variable analog voltage.

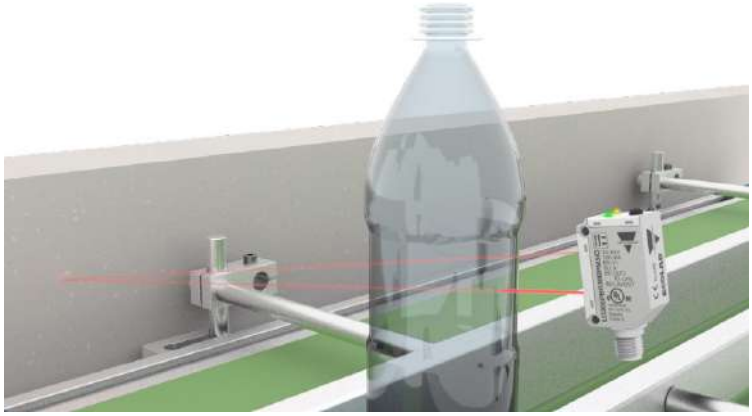
The most common use of industrial potentiometers is position sensing for motion control. Some small servo motors use a set of gears to attach the drive shaft to a rotating potentiometer shaft, creating a continuous feedback loop. As the drive shaft approaches the target positional angle, the potentiometer's voltage equals the input voltage signal, verifying the correct position back to the control circuit.

A potentiometer is linked to the DC motor in many small servo mechanisms.

Linear potentiometers can be similarly used to provide a position for the axis of a linear motion assembly. As the target item slides along the axis, the voltage changes and provides a feedback signal to the controller.

Photoelectric Sensors

In the basic configuration, photoelectric sensors (or optical sensors) consist of a light emitter and a receiver. Normally, the emitters employ light-emitting diodes (LEDs) that can produce modulated pulses. The receivers consist of photodiodes or phototransistors that can convert light at the sensor element into electrical signals. The modulated light is filtered out from any background interference, and the conditioned signals are then amplified and sent to the controller.

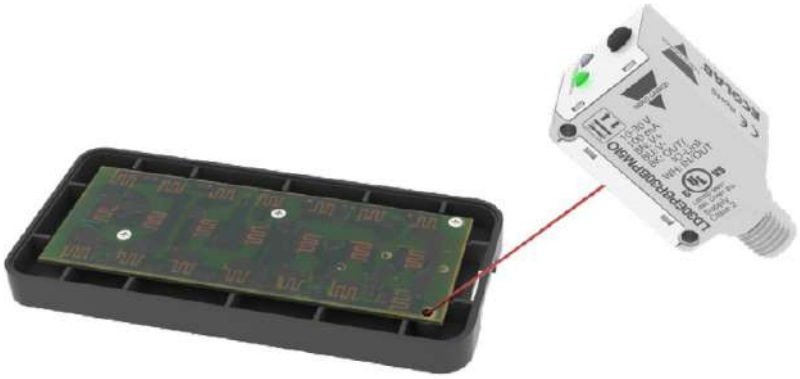


Optical sensors often operate in the visible light spectrum, but they can also be IR or even UV.

Light exists in different ranges of frequency in the electromagnetic spectrum. Specifically, infrared, visible, and ultraviolet light make up individual bands at the lower frequency end of the spectrum. This chapter focuses on optical sensors that operate in the infrared (IR) and visible light spectrums.

Together with mechanical sensors, optical sensors are the most popular sensing category in industrial automation. This popularity is because optical sensors are relatively simple to set up and calibrate and do not receive much influence from outside interferences. Also, they can operate over long distances.

Discrete presence sensing and analog position detection are both extremely common optical sensor signal types. Some sensors even provide both analog and discrete outputs simultaneously for flexible installation.



A diffuse reflective sensor can be used for small part or feature detection.

The three most common types of photoelectric sensors are the through-beam, retro-reflective, and diffuse reflective sensors.

Through-Beam Sensors

With through-beam sensors, the transmitter and the receiver are housed in separate enclosures. The two components are placed opposite each other, with the light beam from the transmitter directly hitting the receiver. As soon as something obstructs the light beam, a detection event occurs. Common examples of this type of sensor include garage door monitors or safety light curtains guarding a machine cell. With a high-power laser emitter, the sensing distance can easily be tens of meters.

Retro-Reflective Sensors

Retro-reflective sensors consist of an emitter and receiver in the same housing, while a reflector is placed opposite the emitter/receiver pair. This reflector is mounted at an angle that perfectly bounces the light beam directly back to the receiver. These sensors also offer a long range, while any added complexity of installing reflectors is usually fairly minimal.

Diffuse Reflective Sensors

In a diffuse reflective sensor, the emitter and receiver are once again housed together. Detection occurs when the light beam from the emitter reaches the receiver, but only after it has bounced from the surface of the object itself. These sensors are more cost-effective and generally easier to mount than the previous two types since they do not depend on the perfect alignment of a receiver or reflector. However, they have a relatively short detecting range since much of the light is scattered when it reflects off of the object's surface.

Fiber Optic Sensors

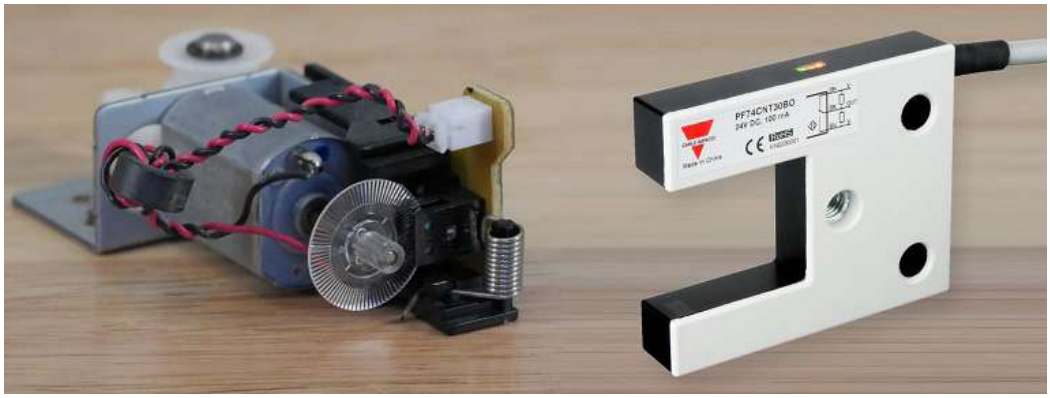
In the vernacular of industrial automation, this category is not technically a unique type of sensor but rather a specialized form factor of the previously discussed sensors. Optical fiber is a flexible medium that can transmit a signal using light.

A fiber optic amplifier sensor.

The metal or plastic-jacketed fiber cables are fixed to the front of fiber optic sensors (also commonly known as fiber optic amplifiers) using special built-in ports. The light passes through the optical fibers from the sensor body to the target location, allowing the electronics inside the main sensor body to be installed safely away from a hazardous or inconvenient location.

Fork Sensors

Optical encoders employ a type of through-beam technology referred to as a fork sensor. These sensors are designed exclusively to use light for motion detection. These sensors consist of a light source and receiver in a forked configuration that surrounds an encoded disk. As the disk rotates, light is alternately passed through or blocked by the openings in the disk. These forks are also found as non-contact limit stops for CNC machines, and larger versions can be used as detectors for the presence of objects like elevator carriages in a moving system.



On the left, a small fork sensor surrounds the optical encoder disk on a moving carriage assembly. On the right is an industrial fork sensor that may be used in larger position detection applications.

Magnetic and Inductive Sensors

The physical principle of magnetism has been known for centuries, but it was only first studied by British philosopher William Gilbert at the end of the sixteenth century.

There are strong similarities between magnetic and electric properties. Magnetic fields are produced by moving electric charges. This phenomenon was first discovered by physicist Hans Oersted in 1820. He observed that compasses worked differently in the vicinity of electric currents.

Induction is based on the well-known Faraday's law of induction. It states that an induced voltage is equal to the rate of change of the magnetic field. This principle is behind most inductive sensors used today.

Inductive proximity switches depend on the interaction of high-frequency magnetic fields and metal objects.

Inductive Proximity Sensors

Inductive proximity sensors (also called prox sensors) are the most common way to detect the presence of ferrous metallic objects in an industrial process. These sensors include an oscillator, a small circuit that produces a high-frequency magnetic field. When a ferrous metallic object (primarily steel) enters the sensing field, current is induced inside the object, which causes a load on the oscillator circuit. This load decreases the amplitude of the oscillation, and if the amplitude becomes low enough, the sensing circuit produces an output signal.

The inductive proximity sensor can also detect some non-ferrous metals, like copper and aluminum, but a specific derating factor for each material decreases the sensing distance. Even with the most dense, iron-laden targets, the sensing distance is no more than a few mm for most models. Some amplifiers can increase the distance to several centimeters, but this is still less than the distance range of optical sensors.

This inductive proximity sensor has an extended range, allowing measurements of up to 40 mm.

Due to the limited detection range of inductive proximity sensors, they are not practical for measuring the distance between the sensor and the object, so it is very unusual to find inductive proximity sensors with analog outputs. Instead, they will provide on/off detection only with discrete outputs.

Reed Switches

Magnetic reed switches consist of two small and thin ferromagnetic reeds in a special encasing. Their purpose is to manage the flow of electricity by opening or closing an electric circuit based on an induced magnetic field.

Like electric sensors, reed switches can be built for normally open (NO) and normally closed (NC) operation. An NO reed switch would close the electric circuit upon the presence of a magnetic field. An NC switch opens in the presence of a magnetic field.

Reed switches have numerous applications in home appliances, cars, and the medical sector. They can also be found in many manufacturing environments. A common use of reed switches is for safety in machine cell door open/close detection, where the magnetic switching signal can also include a unique key to prevent unauthorized access or intentional overriding with a simple magnet.

Safety-rated magnetic sensors for door applications. This pair includes both emitter and receiver devices.

Position Switches

Magnetic sensors are also commonly found as the pivotal technology inside pneumatic position sensors, which are called switches when they only provide a discrete on/off output. The small sensors are usually shaped for round or t-slot actuator bodies, and they can detect the end-stop or intermediate positions of cylinders that are constructed with magnetic pistons.

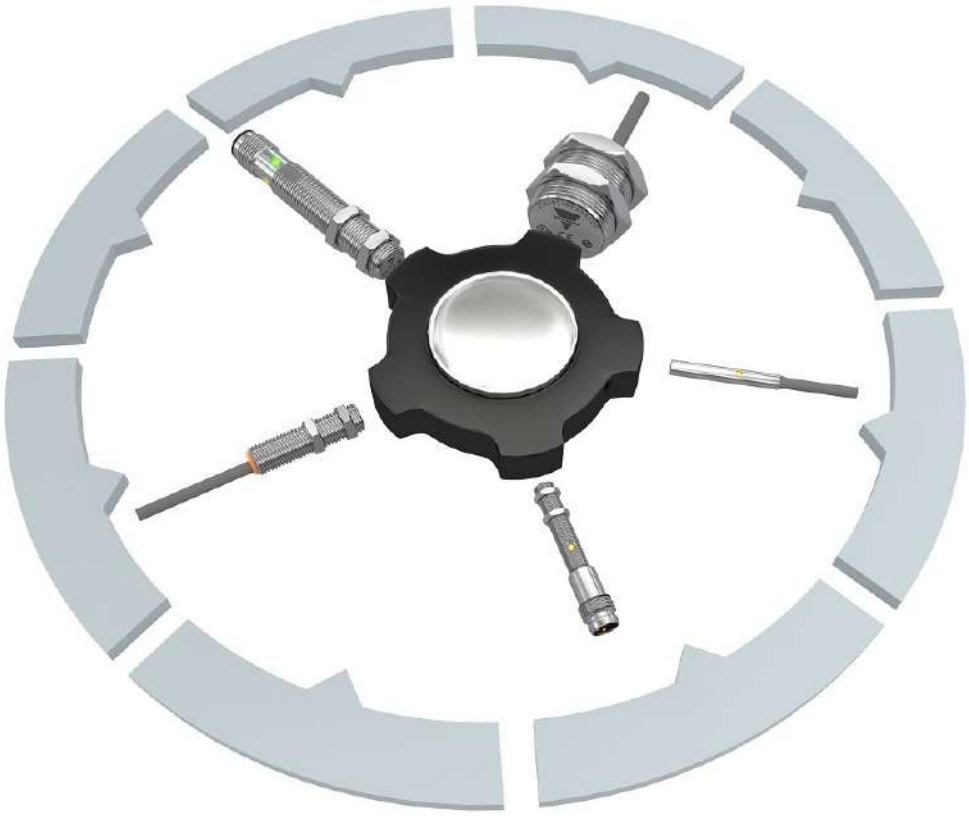
Installing a sensor to provide positional feedback can allow the system to come to a stop more gently than hard-stop control and prevent damage inside the actuator. Positional feedback is critical to ensuring that the piston has actually accomplished its motion task before the next process step can begin.

In addition to the standard linear actuators, these position sensors are found on rotary actuators and virtually all robot pneumatic grippers.

Hall Effect Sensor

The Hall effect was discovered by American physicist Edwin Hall in 1879. The operating theory states that a voltage (called the Hall voltage) is produced perpendicularly across a conductor when that conductor is subjected to current in the presence of a magnetic field. The great advantage of Hall effect sensors is that they can detect magnetic fields even when no changes exist, making them very useful for measuring current in DC applications.

Common industrial applications of Hall effect sensors include DC transformers and position sensing in DC motors. Any noncontact DC clamp meter (ammeter) also uses the Hall effect for operation, while AC clamp meters rely on inductance.



Inductive and Hall effect sensors are commonly used to determine the position (and rpm) of rotating gears and cams.

Capacitive Sensors

Capacitive proximity sensors are remarkably versatile in terms of the acceptable variety of detectable materials. Unlike their inductive and magnetic counterparts, capacitive proximity sensors emit an electrostatic field rather than electromagnetic.

An electrical capacitor consists of two plates separated by an insulative (also known as a dielectric) layer. In the case of these industrial sensors, the object to be sensed acts as one plate, while the sensor itself is the other plate.

The capacitive proximity sensor uses an internal circuit to generate oscillations in the electrostatic field. As the sensed object moves closer, the oscillations gain amplitude until they trip the detection circuit, and the output signal energizes.

Capacitive proximity sensors can detect most liquids, wood, metal, and plastic. While they might work best in clean environments, these noncontact sensors are designed for industrial use and are quite reliable, even in vibration-heavy environments. They have limitations in extreme conditions such as heavy dirt, dust, temperature changes, or humidity, as these will change the electrostatic properties of the environment. These sensors are very susceptible to interference from radio frequencies and electromagnetic fields from other devices.

Typical capacitive proximity sensors.

Despite their versatility, capacitive sensors share similar constraints in detection range as inductive proximity sensors. The range of most of these capacitive sensors is relatively short, typically less than 50 mm. Sensors with the largest face diameters (that is, a larger capacitance plate) provided the greatest sensing range.

Due to their limited detection range, capacitive sensors are usually found with discrete outputs only, not analog.

Ultrasonic Sensors

As indicated by the term sonic, these sensors use sound waves to determine the distance between the sensor and the object being measured.

Ultrasonic sensors contain both an emitter and a receiver. The emitter component, like a small speaker, sends out a sound wave with a specific frequency. This pulse of sound bounces off an object's surface and returns to the receiver element of the sensor. The time it takes for the sound wave to travel to the object and back is used to calculate the distance.

Ultrasonic sensor with a variable (analog) output signal.

Ultrasonic sensors are well-suited for applications where the material is not conductive or has a low dielectric constant, which make the material a poor candidate forinductive and capacitive sensors. Additionally, ultrasonic pulses can bounce off transparent objects. They can sense sheets of glass and clear plastic, which is impossible for photoelectric sensors that rely on light.

On the other hand, ultrasonic is not the best choice for sensing soft or foamy objects or shapes with odd angles and curved surfaces, which reflect the sound waves away from the sensing element.

Ultrasonic sensors can be purchased with adjustable set points to trigger the output signal when the object passes a certain distance in front of the sensor. This is a discrete signal output with either positive or negative signal polarity. These sensors can also output an analog voltage or current signal that rises proportionally across the entire sensing range, which may vary from just a few millimeters up to many meters in front of the sensor.

Sensor Specification Sheets

Specification datasheets for sensors give specific information that includes voltage ratings for the sensor, operating range, minimum (min) value, maximum (max) value, voltage drop, and others. Some information is displayed for all types of sensors, but other specifications are unique to the type of sensor being used. For example, a pressure sensor will not have any specifications for light wavelength like some laser sensors might.

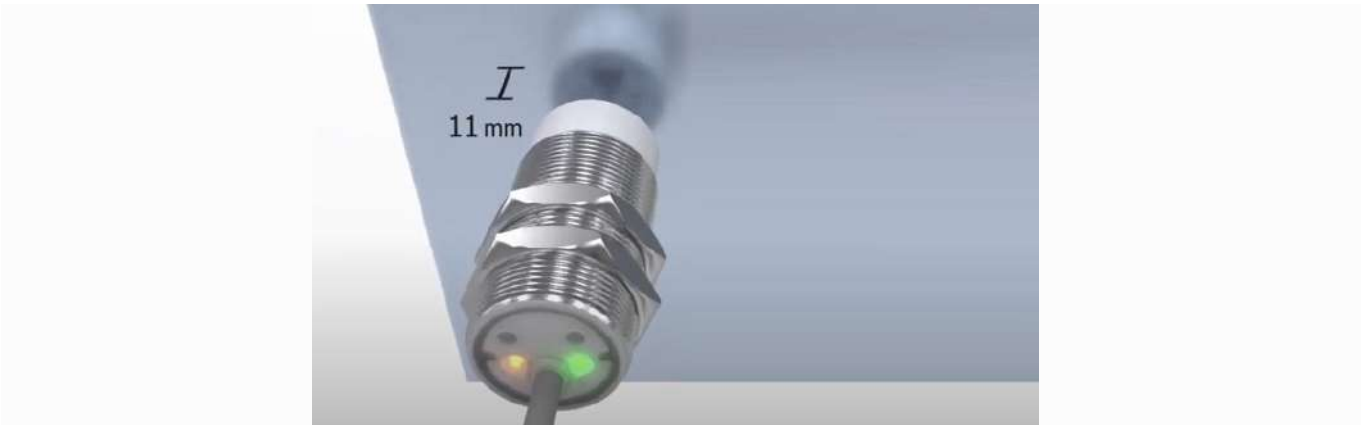
Every sensor includes various physical and electrical limits based on the physical sensor enclosure and the electronics contained inside of the sensor. These limits are found in specification sheets and are critical in determining the accuracy and application of certain sensors.

In the following sections, we will explain the most common terms you will find in sensor datasheets.

Sensor Range and Span

The range defines the min and max physical quantity that the sensor can detect. For example, a laser distance or proximity sensor might have a range of 0.2 to 10 m. This means that the laser can be used to measure the distance or the presence of an item within the range of 0.2 m at a minimum to a maximum of 10 m. The values 0.2 m and 10 m are this particular sensor's min and max values, respectively.

For object detection sensors, range usually refers to a physical distance. For other sensors outside the scope of this book, range might refer to temperature, pressure, or flow rate.



A sensor's range determines the value of inputs a sensor can process.

A specification related to the range is one called span. The span of a sensor is simply the total of the range. For the laser distance sensor example, the span would be 9.8 m because (10 m) - (0.2 m) = 9.8 m. Range and span are often primary determining factors when choosing a sensor since the sensor is useless outside of its operating range.

Electrical Specifications

Every sensor has a unique combination of power supply, consumption, and protection specs. Looking at the electrical specifications is necessary to ensure the sensor will have the correct operating voltage, current, and protective measures. The following are typical examples of useful electrical specifications and their meanings:

- **Operating Voltage:** This is the voltage range the sensor can operate normally without damage, for example, 10-30 VDC or 90-130 VAC.
- **Current Consumption:** This is the maximum amount of current the sensor will use. For example, <100 mA means the sensor will not exceed a current usage of 100 mA. The current consumption is important for determining a total power budget from a supply.
- **Current Output:** Sensors must provide current to a load device, which may be a controller. The specification shows the largest allowable current for the load device, and most sensors cannot drive a load like a large contactor or solenoid.
- **Reverse Polarity Protection:** This tells you whether or not a sensor is protected if it is wired incorrectly (with reverse polarity) during installation.
- **Short-Circuit Protection:** This protects the sensor from damage if the output is short-circuited. Without this, the sensor would become permanently damaged from a shorted output.

General Specifications

These specifications are useful for the physical constraints of the sensor. These include temperature ranges, physical size, and weight.

- **Temperature Range:** Temperature range can be split into the operating temperature range and storage temperature range. Operating temperature is the maximum range in which the sensor can function normally, while storage temperature is the temperature range in which the sensor can safely be stored without causing damage.
- **Dimensions:** Dimensions are often given in length, width, and height.
- **Weight:** The weight of the sensor without any added components. For these last two specifications, it's very important to look closely at the datasheet for the desired part number since many vendors use stock images to represent an entire product line.
- **Typical Lifetime:** The amount of time the sensor can be expected to function correctly under normal circumstances, for example, 50,000 hours. This equates to just over five years of continuous use. For electromechanical devices, lifetime might be measured in switching cycles.
- **Nonlinearity:** Expressed as a percentage that the sensor reading deviates from the actual measurement curve. It is often represented graphically as an ideal curve with the measurement curve transposed over it. The maximum difference between the two is the maximum nonlinearity. This is important because nonlinearity may create a data difference larger than the maximum error that the system can tolerate, making the sensor unusable for certain applications.

Sensor Accuracy and Deviations

Accuracy and deviations are determining factors in how precisely a sensor can operate. These specifications are highly dependent on the type of sensor being used. For example, a laser distance sensor may have a large list of specifications that determine accuracy based on the measured color or material. Yet a fluid flow meter may have only a few accuracy specifications based on temperature and material measured.

I/O Specifications

I/O specifications define the amount, type, and specifics of input and output signals for a sensor. Many different types of information can be displayed in this section of a datasheet, but here are a few of the most common:

- **Inputs:** These are the number and type of inputs available for the sensor to use and whether they are analog or digital. Sometimes, an input signal can be used to program or "teach" a sensor.
- **Discrete Outputs:** The output specification will state properties including NO or NC, NPN or PNP, and, in the case of optical sensors, light-on or dark-on, which are a reference to whether the sensor will output a signal in the presence or absence of reflected light. Sensors may provide more than one discrete output.
- **Analog Output:** Often expressed as a range of available voltage or current for analog outputs. The most common industrial voltage range is 0-10 V, and the most common current is 4-20 mA, but there are other standards that may exist.
- **Protocol Output:** Many modern sensors are also equipped with digital protocols like IO-Link, which can provide process data, setpoints, and operational data for the sensor itself.

Device-level protocols require more infrastructure, such as these network components, but the extra operational data can be invaluable.

While some of this information is sensor-specific, much of the information on one spec sheet, such as operating temperature or operating voltage, will be found on all. Understanding these specifications can save time and money from incorrect sensor applications and the downtime they can create.

Conclusion

Integrating sensors into any automated process is no simple task. The sensing type, the specifications for each machine, and the intended future use of the data are all very important factors to consider. Engineers should never hesitate to dive into technical datasheets and application notes for guidance, and they should also be willing to contact the manufacturer for advice on unique situations.

Our team would again like to express our thanks to the writing team and to the contributions of Carlo Gavazzi in illustrating and explaining the intricacies of sensor technology. We hope you are now better equipped to select, install, and troubleshoot sensors, helping drive the future of modern manufacturing and machine control.

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