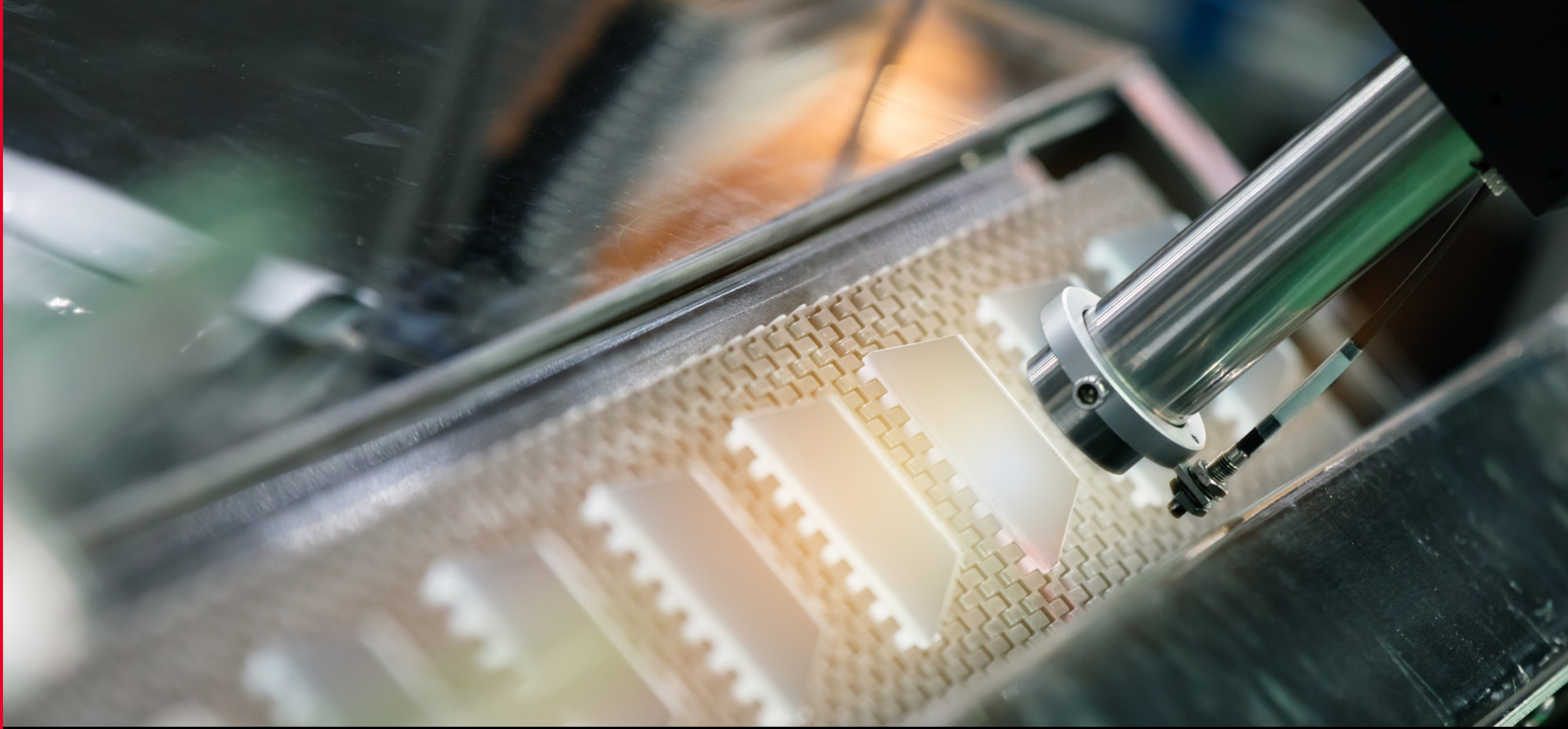

Fundamentals of Sensor Measurements Using a DMM

eBook

KEYSIGHT

Design Accurate and Robust Sensor Products

Sensors permeate everything you touch in your daily life. A mobile phone alone has dozens of sensors, including sensors for audio, touch screens, radio frequency, proximity, gyroscope positioning, and ambient light. Our homes have temperature sensors, security image sensors, biometric door sensors, and more. Sensors are essential to almost everything you use, and their use continues to grow.

Objective:

In this e-book, you will

- Learn more about the types of sensors that are available and how they are transforming our world
- Gain insights into the critical parameters of a sensor, irrespective of its physical measurement types
- Learn about key considerations for choosing the right digital multimeter (DMM) for sensor testing and characterization
- Discover methods for characterizing and troubleshooting a sensor using a DMM

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CHAPTER 1

Essential Sensor Concepts

CHAPTER 1

Sensor Fundamentals

A sensor is a device that measures or detects a physical stimulus and converts it into an electrical signal.

Figure 1 shows a photodiode sensor that detects light. This light sensor is wired to a control system with a cable that may be short or long, depending on the application. The control system has to read the electrical output of the light sensor. In order to make meaningful data out of it, the signal must be pre-processed or signal conditioned.

Signal conditioning amplifies, attenuates, shapes, or isolates signals from transducers before they go to measurement hardware. Signal conditioning converts signals from their raw form into a measurable form, which is quantifiable and accurate.

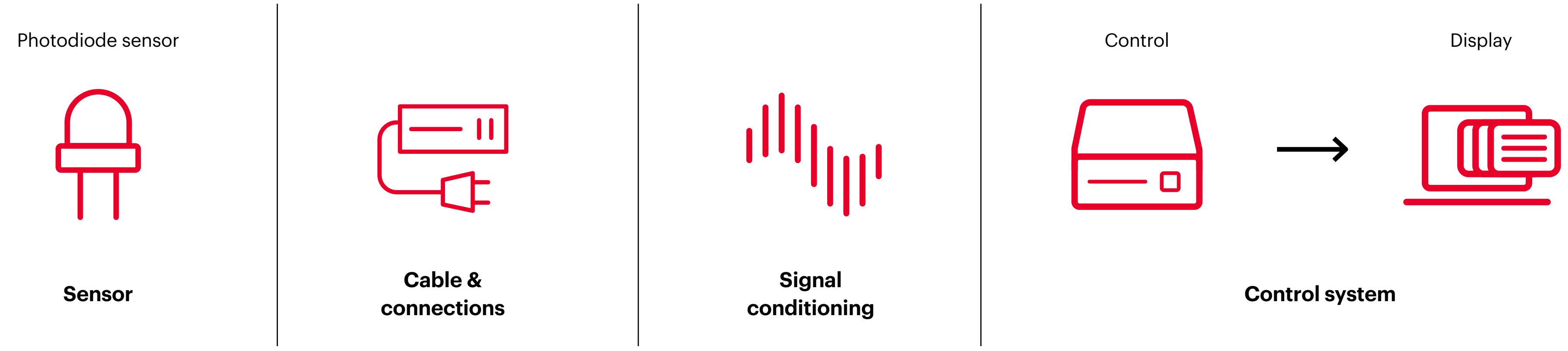


Figure 1. Sensor path in a system

Types of Sensors

Active and passive

Active sensor:
An active sensor requires an external source of excitation

Passive sensor:
A passive sensor generates its own electrical output signal without requiring any external voltage or current.

Table 1 shows examples of sensor types in these two categories. For example, there are active and passive sensors to measure temperature. A thermocouple is a passive sensor for measuring temperature. It uses two dissimilar metal cables to form a electrical junction that produces a temperature-dependent voltage resulting from the thermoelectric effect. This voltage can be displayed as a temperature. Silicon integrated circuit sensors, resistance temperature detectors (RTDs), and thermistors are active sensors that measure temperature. They require external current source excitation to measure the voltage output.

Source: BBC Research LLC, IAS006J Sensors: Technologies and Markets to 2023

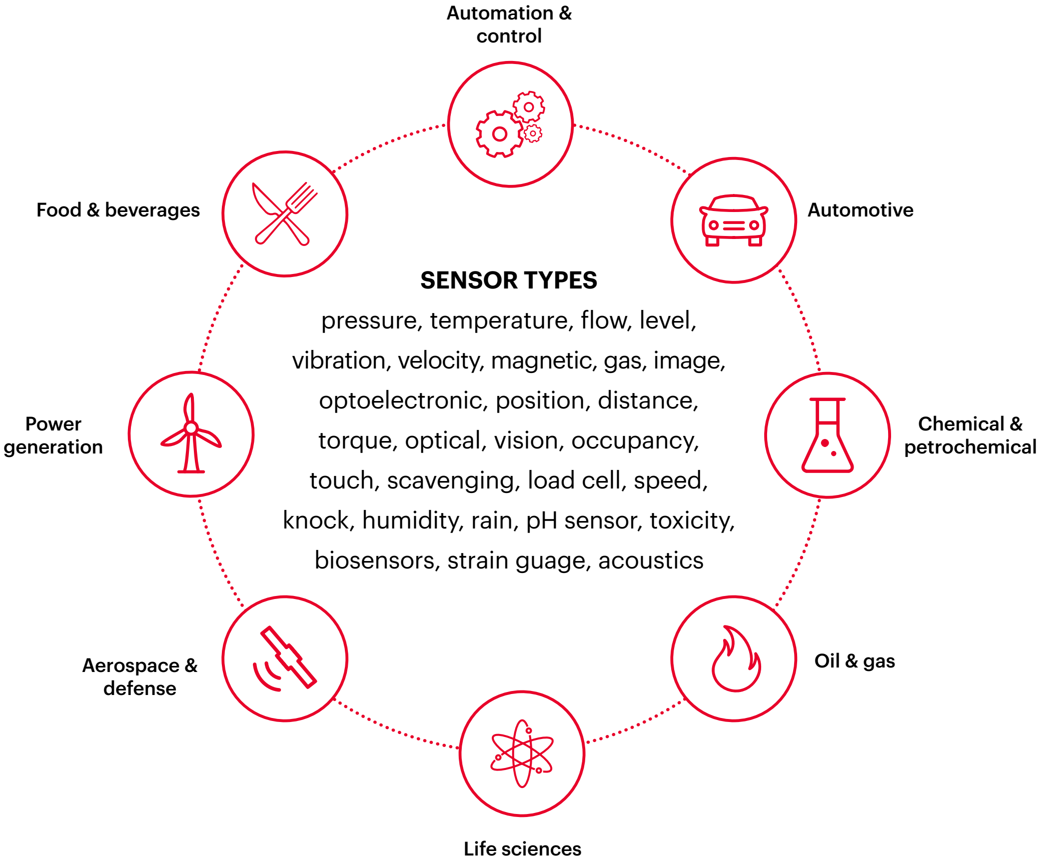
Table 1. Active and passive sensor types and sub-types

Classification	Sensor type	Sensor sub-types
Active	• temperature • force/pressure • acceleration • position • flow	• silicon, RTD, thermistor • strain gauge • accelerometer • linear voltage differential transformer • ultrasonic
Passive	• temperature • force/pressure • light • chemical • flow	• thermocouple • piezoelectric • photodiode • humidity • vortex

Sensors: Market Applications

Sensors had come a long way even before the invention of computers. Humans have the natural sensory perceptions of vision, sound, touch, taste, and smell. We developed artificial sensors as an extension of our sensory perception. These sensors help us automate or regulate the environment, noise, pollution, cleanliness, and so on.

We are now in an era of industrial growth on a global scale unlike anything observed in history. The center of the circle in Figure 4 shows the various sensor types used in multiple industries. The circle itself shows the key industries that are driving the use and growth of sensors.



Sensor Application Examples

We can separate sensor types by the physical parameters they measure, such as temperature, pressure, flow, and light. But, you might be surprised to learn that for each physical parameter, there are highly specialized sensor sub-types (indirect measurements) for specific applications.

Temperature sensor applications

Elements: thermocouple, RTD, thermistor

Direct measurements

- thermostat
- open-ended thermometer

Indirect measurements

- RF & microwave power
- calorimeter
- resistive galvanometer

Source: www.Keysight.com

Pressure sensor applications

Elements: piezoelectric, strain-gauge, capacitive, inductance, resistive, and more

Single pressure gauge

- tire pressure
- pressure cooker
- room pressure

Differential pressure gauge

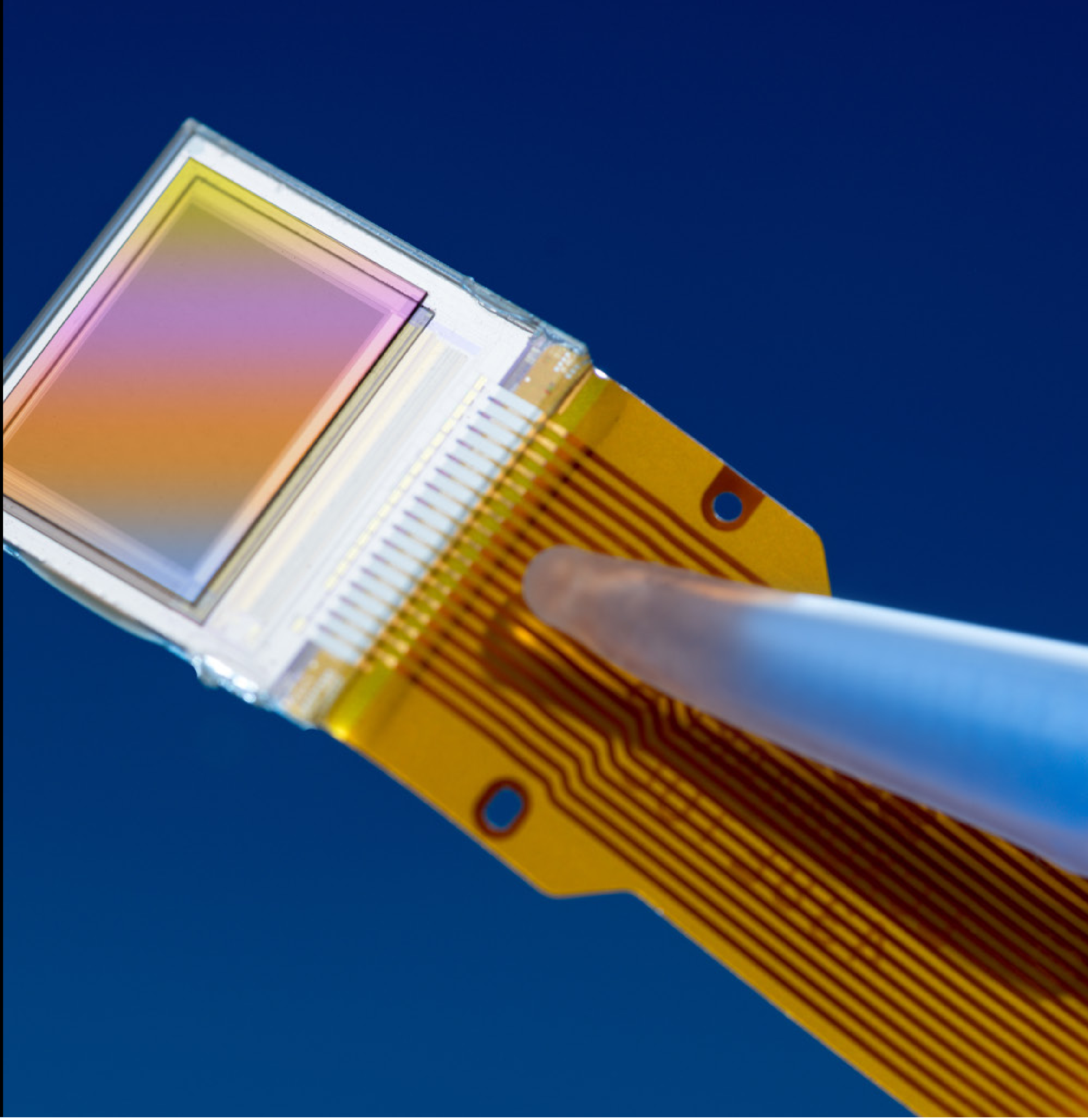
- fan/blower pressure
- fluid flow
- air velocity

Source: www.eurodriveuk.com/tyre-safety-tips

Differential pressure gauge. Source: Davis Instruments

CHAPTER 2

Choosing the Right Sensor



Choosing the Right Sensor

Sensors and measurable outputs

Choosing the right sensor starts with understanding the key parameters and intrinsic characteristics of different sensor types. To make the right selection, you must:

1. Know the physical parameter you need to measure
2. Understand the pros and cons of various types of sensors
3. Evaluate whether the sensor's output meets your requirements for:
    - range
    - linearity
    - 2- or 4-wire output
    - accuracy
    - repeatability
    - response time

Table 2. Types of physical parameter measurements corresponding to the typical sensor types and their sensor output

Measurement	Typical transducer types	Typical transducer output
Temperature	Thermocouple	0 mV to 80 mV
	RTD	2-wire or 4-wire resistance from 5 Ω to 500 Ω
	Thermistor	2-wire resistance from 10 Ω to 1 MΩ
Pressure	Solid state	±10 Vdc
Flow	Rotary type Thermal type	4 mA to 20 mA
Strain	Resistive elements	4-wire resistance from 10 Ω to 10 kΩ
Events	Limit switches	0 V or 5 V pulse train
	Optical counters	
	Rotary encoders	
Digital	System	TTL levels

Key Parameters Across All Sensors

Sensitivity

The sensitivity of a sensor is its ratio of change:

$$\text{Sensitivity} = \frac{\text{Electrical output}}{\text{Physical input}}$$

The **input** represents some form of physical parameter change that you want to measure, such as lumens (light intensity), degrees C/F (temperature), or PSI (pressure). The **output** represents an electrical output, such as voltage, current, resistance, or capacitance change.

The higher the output ratio, the higher the sensitivity.

Figure 5 on the right shows the sensitivity of two sensors. Note that not all sensors have a linear output, but in this case let us assume these two do. The sensor with the red line has higher sensitivity compared to the sensor with the blue line.

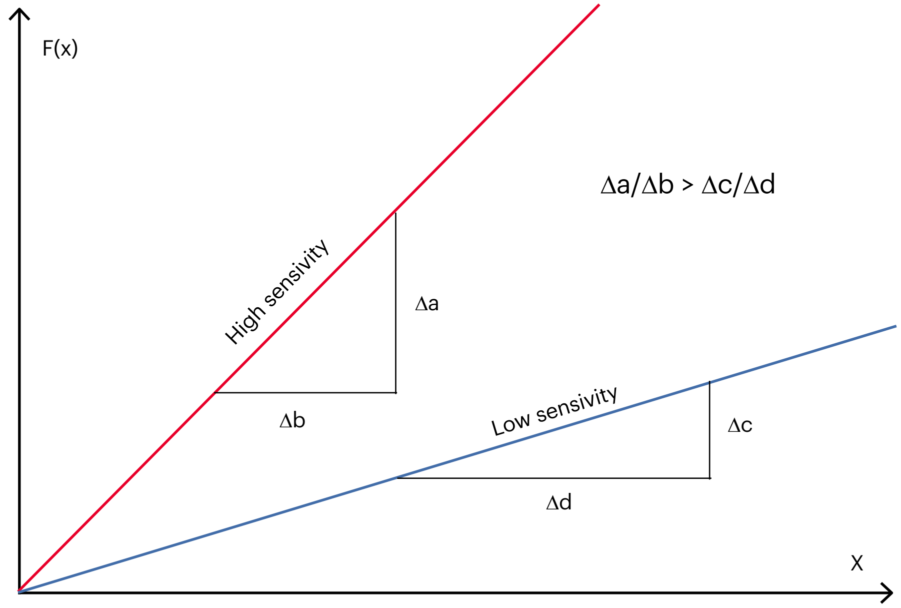


Figure 5. Sensitivity graph

Dynamic range and linearity

Dynamic range is the entire range that the sensor can measure. It is often expressed in decibels (dB). Take, for example, an audio microphone sensor's dynamic range:

$$\text{Audio dB} = 20\mathit{log}\ \frac{\textit{Largest measurable } V_{rms}}{\textit{Smallest measurable } V_{rms}}$$

Figure 6 shows an example of a linear output of a sensor on the red line. The solid line defines the sensor's measurable range, and the dotted line is the possible output that is beyond the measurable capability of the sensor.

Linearity is the difference between an actual curved sensor output and an ideal straight line of a sensor output. Typically, sensors do not produce a straight line or linear output. The blue line in Figure 6 shows an example of a non-linear sensor output. The sensor's output difference as compared to an ideal straight line or theoretical best-fit line determines the extent of its linearity error.

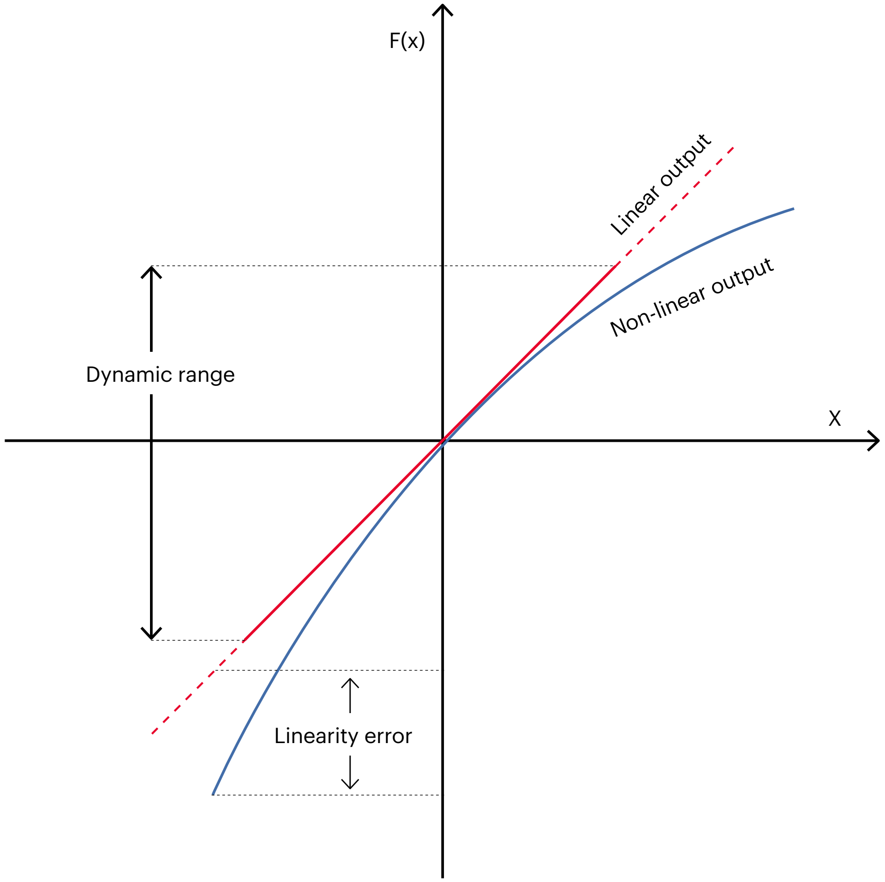


Figure 6. Dynamic range and linearity of sensors

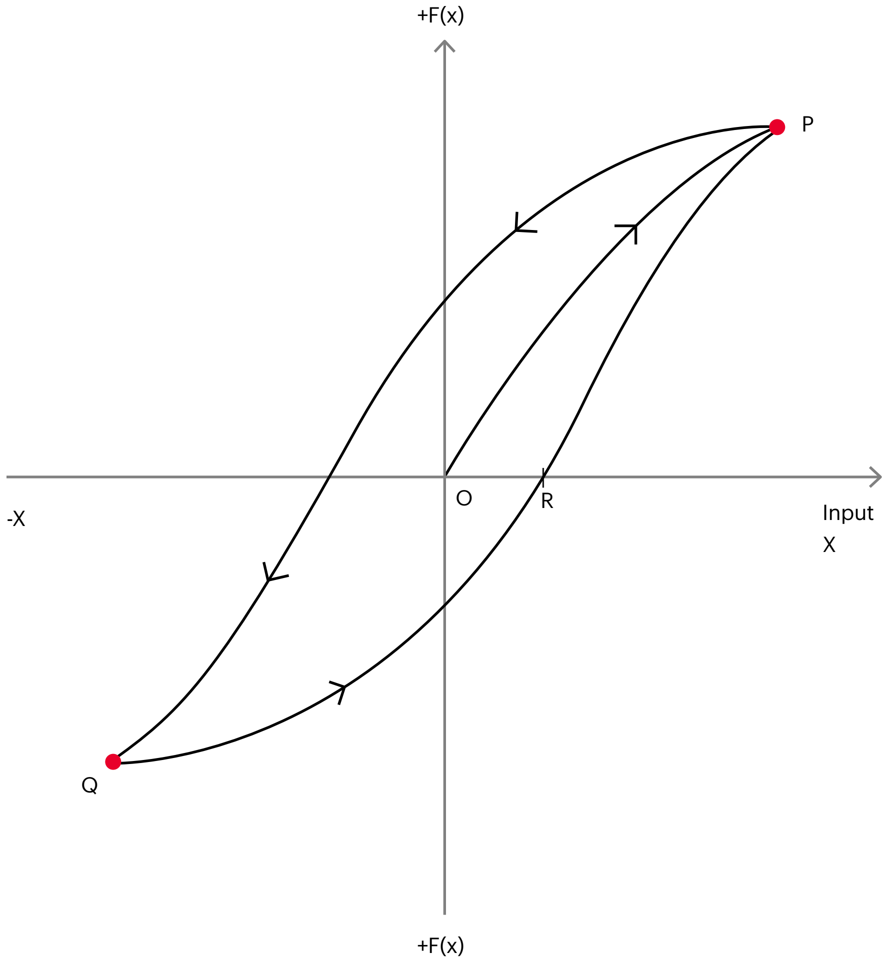


Figure 7. A hysteresis loop observed of a sensor's F(x) output based on which direction the input X changed. The arrows show the path of input X changed (O-P-Q-R)

Hysteresis and repeatability

Some types of sensors, such as temperature sensors, exhibit a hysteresis effect during measurements. If you measure a known temperature point in a controlled oven from cold to hot, and then measure again from hot to cold, the residual difference between the two measurements represents the temperature hysteresis effect error.

A coil-based passive pressure sensor exhibits a similar hysteresis effect when measuring increasing and decreasing pressures.

The hysteresis effect makes it seem as though the sensor is resisting or lagging. This lag depends on the inherent properties of the sensor materials and design of the sensing element.

Hysteresis contributes to non-repeatability of sensor measurements and must be considered when designing and measuring sensor systems.

There are other reasons for non-repeatability besides hysteresis. When measuring at the lowest point of the sensor's dynamic range, the sensor's susceptibility to noise can cause non-repeatability. Other times, electromagnetic interference from proximity to other parts of electronic components can cause non-repeatability.

Response time

One of the most critical sensor characteristics is measurement response time, which is a measure of how fast a sensor reacts to change. It is known as a "time constant" of a sensor, and describes how it responds to a step stimulus.

A product designer should not register a sensor read too early as the information will be inaccurate. Knowing a sensor's response time allows designers to account for appropriate amounts of time before reading a sensor.

T_d **Delay time:** time to reach 50% of steady state for the first time

T_p **Peak time:** time to reach maximum reading for the first time for a given excitement

T_s **Steady-state time:** time to reach wave ripple amplitude within the desired steady-state value

Steady-state error: deviation of the actual steady state value from the desired value

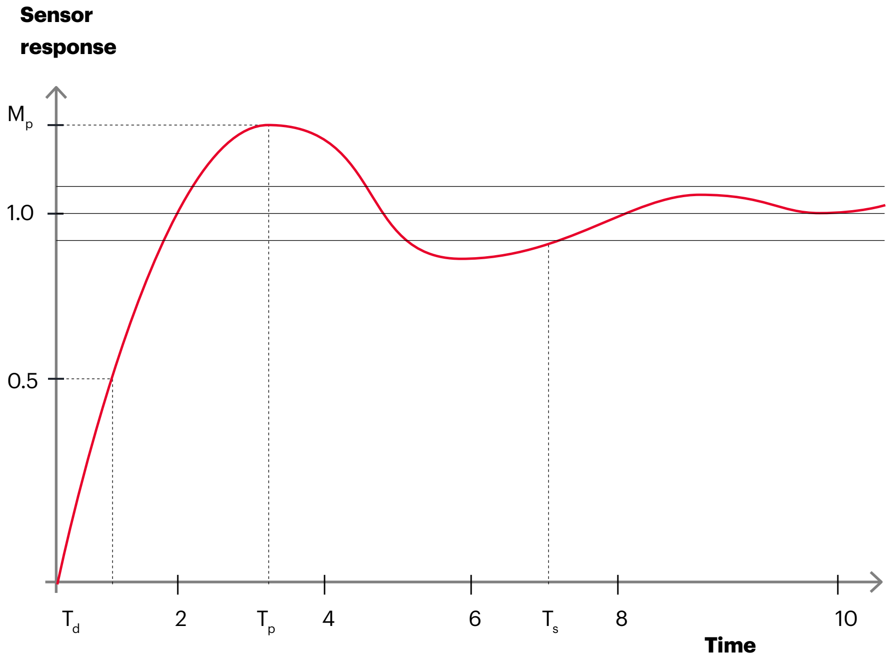


Figure 8. Typical sensor response graph

CHAPTER 3

Selecting the Right DMM: Five Attributes That Impact Sensor Measurements

Selecting the Right DMM: Five Attributes That Impact Sensor Measurements

Key specifications

Consider key specifications such as accuracy, resolution, and speed when choosing the right digital multimeter for sensor measurements. Figure 9 shows how accuracy relates to resolution on a measurement scale. Accuracy is a measure of how good these numbers are, or how much you can trust them. Resolution is the level of detail that is measurable, or the number of significant digits on a DMM.

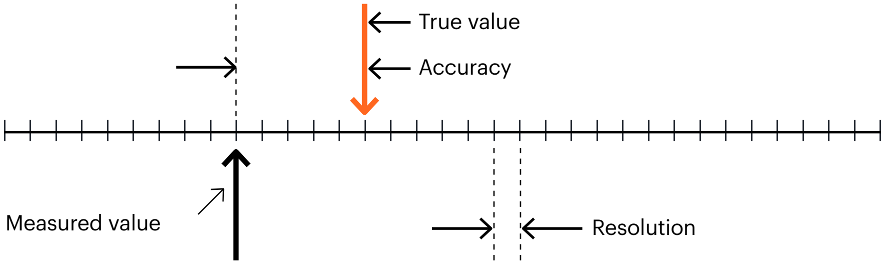
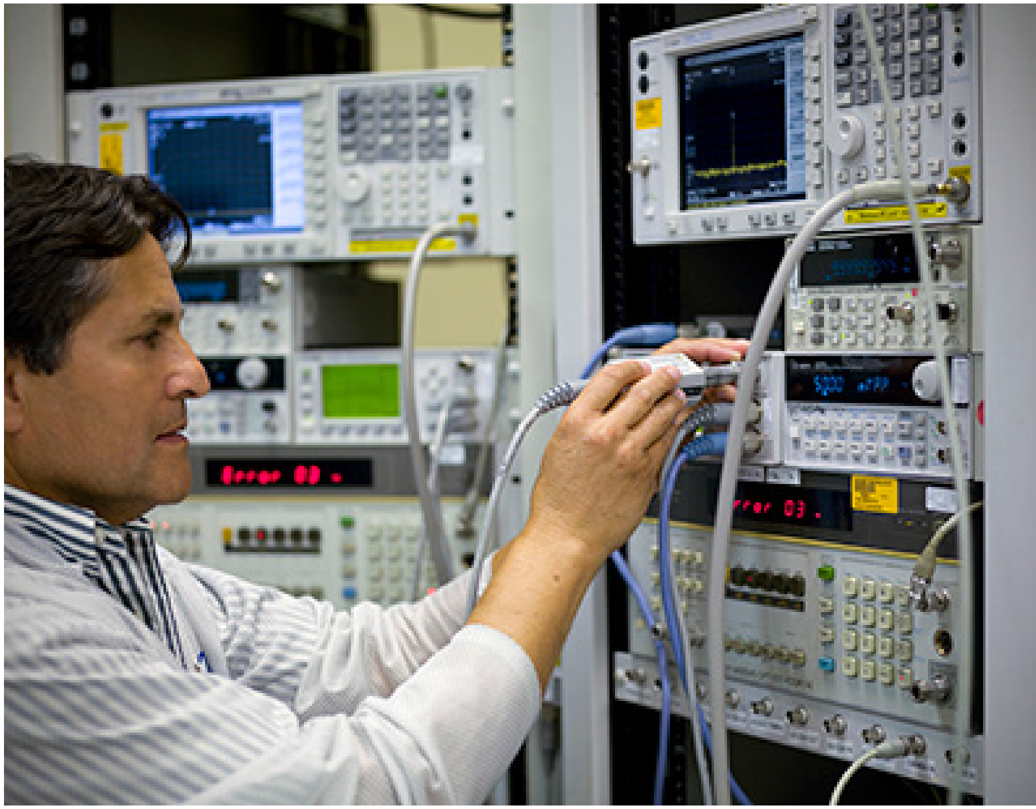


Figure 9. Measurement scale with two arrows pointing to measured value and true value

Accuracy

Accuracy depends on:

- **hardware design** — check your DMM's data sheet
- **hardware stability** — susceptibility to ambient temperature fluctuations, some DMMs have autocalibration



DMM hardware is susceptible to ambient temperature fluctuations. The accuracy of a DMM is usually calibrated at room temperature. As the temperature deviates from room temperature, a DMM's accuracy will worsen.

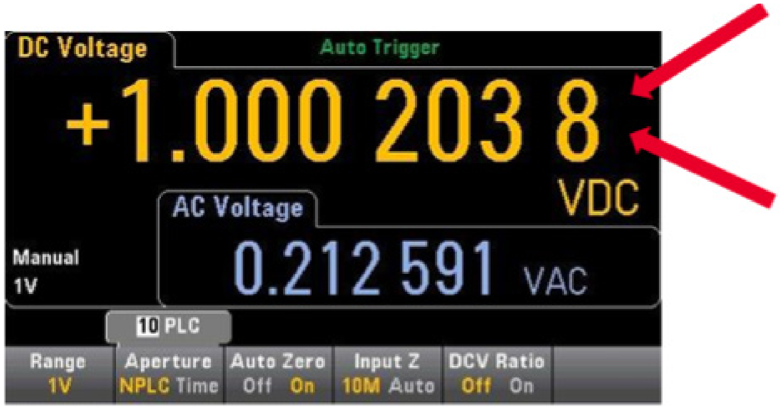
Some DMMs have a built-in autocalibration feature that provides an internal reference for calibrating uncertainties caused by temperature change and drifts over time. This autocalibration feature provides measurement stability while making highly sensitive and accurate measurements in a lab with variable temperatures. It may even calibrate while your DMM is on a system rack full of instruments. While making measurements, a system rack may be 20 °C above room temperature. Higher ambient temperature swings introduce measurement errors. The errors are reducible with the autocalibration feature on some DMMs.

Resolution

When measuring a sensor, set your digital multimeter to the highest resolution possible so it will cover your sensor's dynamic range. To get the highest resolution, choose the range that is closest to your sensor's dynamic range. If possible, avoid auto-ranging to get a seamless measurement without multiple range crossovers.

In Figure 10, the last digit of the DMM display is the number 8. As we are on the 1 V range, 8 represents 800 nV. On the 1 V range, we have the smallest resolution of 100 nV.

As a revision, accuracy is a measure of how good these numbers are, or the closeness of 800 nV to the actual value. Resolution is the level of detail that is measurable or the number of significant digits on a DMM.



DC Voltage

Auto Trigger

+1.000 203 8 VDC

AC Voltage

0.212 591 VAC

Manual 1V

10 PLC

Range 1V

Aperture NPLC Time

Auto Zero Off On

Input Z 10M Auto

DCV Ratio Off On

Finest resolution depends on the range; 100 nV on 1 V range

Is it really 8 nV? Are you sure, or is that value meaningless? Accuracy is measured as a percentage or a number of part per million, and gives you confidence in your measurements.

Figure 10. Typical display of a DMM

Speed

What about measurement speed? What is its relationship to resolution? Speed is essential in manufacturing environments, which value test measurement throughput. Most products come packed with sensors which need to be tested. So, speed is a key factor when purchasing a DMM.

Speed indicates how fast an analog to digital converter (ADC) captures data samples. Put simply, it is the amount of time between samples.

Resolution decreases when ADC sampling speed increases.

Hence, when you look at Figure 11, which comes from the DMM's data sheet, notice that as you decrease the DMM's resolution, measurement speed increases, and vice versa. Check the data sheet to determine the resolution of a DMM across all speeds and that the highest required speed of the DMM meets your resolution requirements.

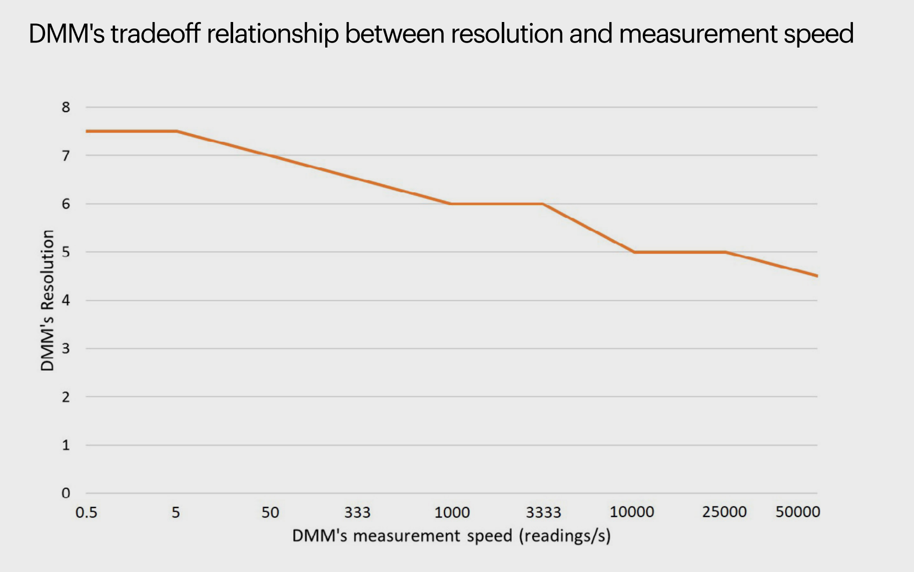


Figure 11. Graph of DMM's resolution versus speed

Measurement intrusiveness

Sensors are delicate. It is essential to select a DMM that provides less measurement intrusiveness to your sensors. In a rack or on a bench, real-world signals are never flat. They have some level of AC signal riding on top from power line noise, other environmental noise, or injected current from the DMM itself. How well your DMM eliminates these extraneous factors from the true measurement makes a significant difference in accuracy.

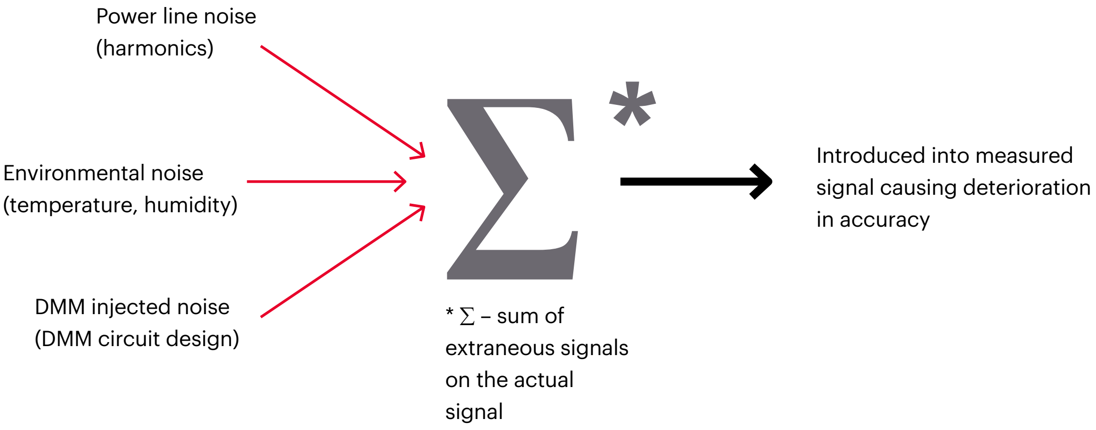
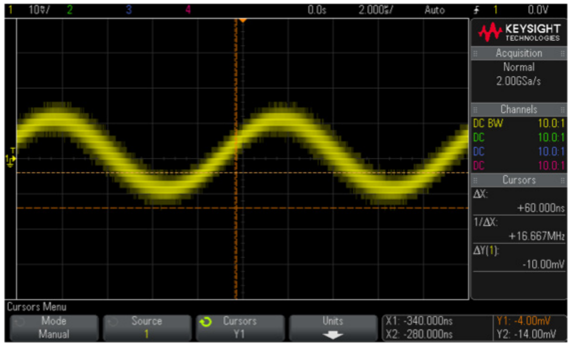


Figure 12. Various types of noise that can affect measurements



A noisy, visibly-digitized AC signal

Trigger automation

Triggering improves throughput by acting as an alternative to inserting delays when you make measurements. Triggers allow you to start measurements based on the detection of a trigger source. Sources include continuous, external triggers such as BNC or BUS, and level triggers, based on the signal crossing a certain threshold. After trigger detection in most advanced DMMs, you can program a trigger delay and capture multiple sample periods. The results are digitized values returned over the BUS or displayed as a trend chart.

Triggering automation is important for measuring transient responses from a sensor. For example, if you want to measure the response time of a sensor, trigger automation is essential.

Trigger source

- auto
- single
- external
- level

→

Trigger options

- samples/trigger
- trigger count
- trigger delay
- trigger slope

→

Data acquisition options

- continuous mode
- digitize mode
- data log mode

CHAPTER 4

Tips for Measuring Sensors with Your New DMM

CHAPTER 4

Five Considerations for Choosing the Right DMM for Sensor Measurements

Tips for Measuring Sensors with Your New DMM

Becoming an expert requires more than just in-depth engineering expertise. You need to master both the technology and the tools. From densely populated PCBs to dynamic ranges of power consumption, modern electronic circuits present challenges for even the most skilled engineer. You need extremely versatile instruments to test sensors in these devices. Master these modern DMM features to make quick work of challenging tests:

- wide test ranges especially for low power ranges
- data logging and digitizer features
- advanced triggering capabilities
- built-in filters and math functions that remove noise in real-time
- auto removal of temperature and drift offset errors

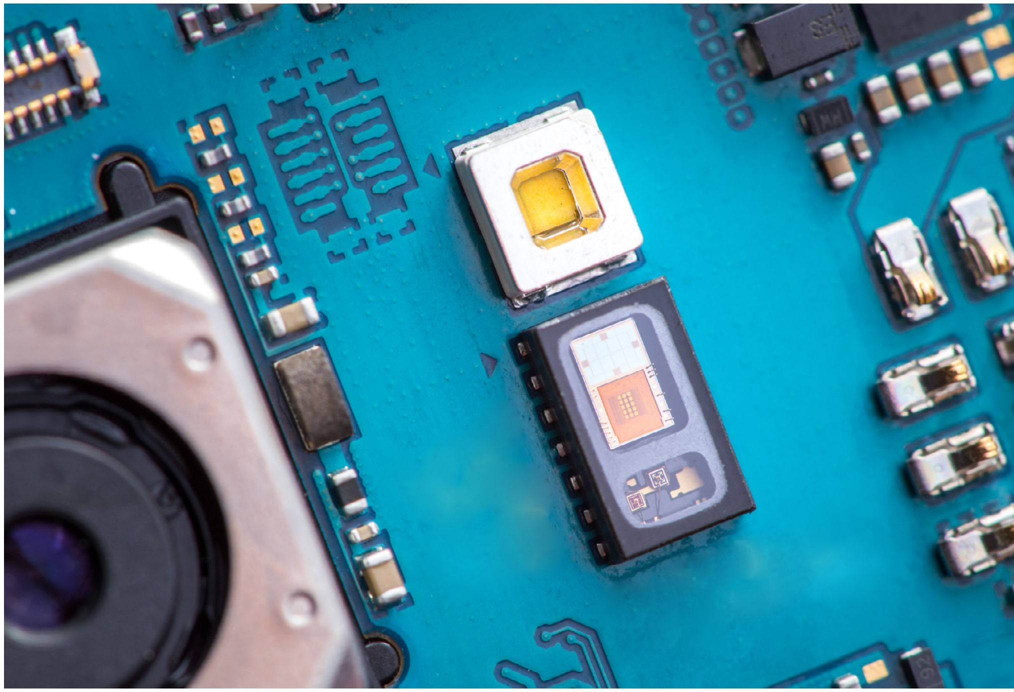


Figure 13. A smartphone with multiple sensors

Reduction of power loss

1. Many portable devices need batteries to operate; such devices conserve energy by reducing power when not in use
2. These intelligent devices can go into hibernation mode when not in use and active mode while in operation
3. To measure this, you need a versatile and capable measuring instrument with the following capabilities:
    - wide dynamic range
    - digitizing feature
    - advanced triggering

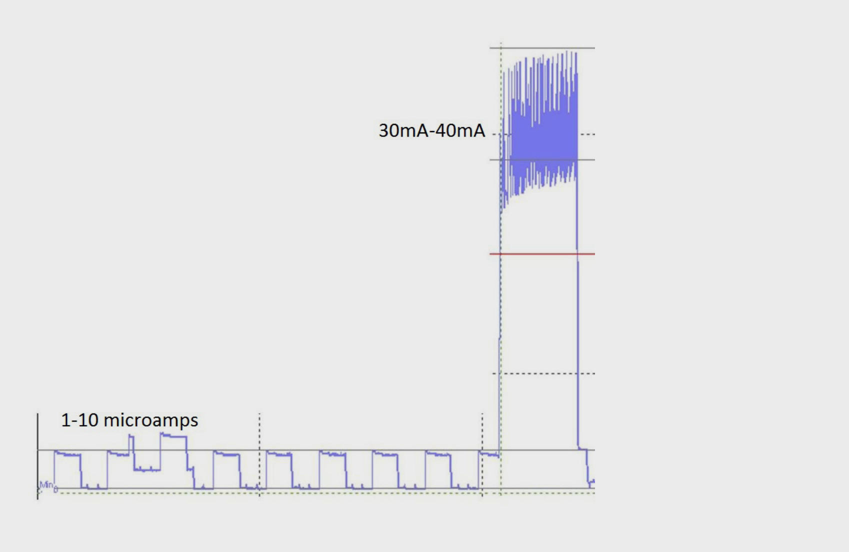


Figure 14. The power consumption of a device at 1-10 micro-amps while in hibernation mode and at 30-40 milli-amps while in active mode.

Understanding sensor failures

When a sensor fails, what can happen?

1. The control system is smart and detects faults and sends a warning
2. An intermittent failure causes inconsistent responses from the control system
3. A complete failure where the control system does not know there was a failure or does not provide feedback

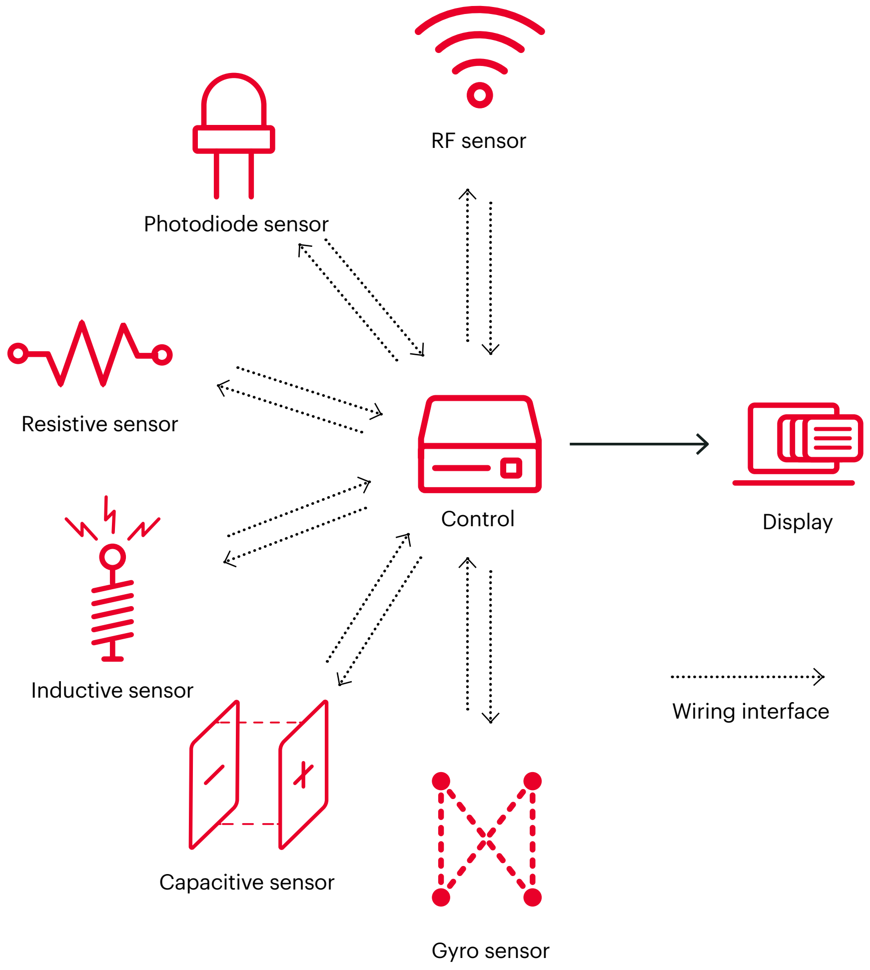


Figure 15. Network of sensors communicating with a control system

Methods for troubleshooting a failed sensor

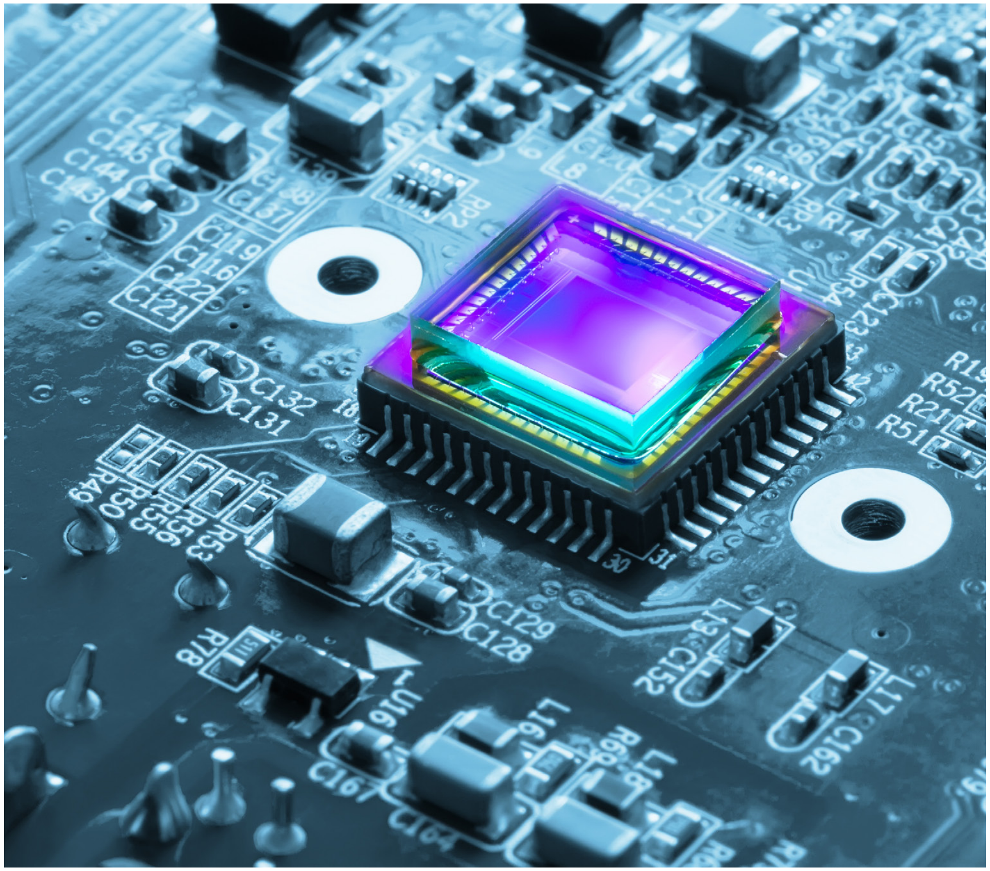
Steps for troubleshooting a sensor:

1. Prepare to troubleshoot the sensor; use tools to reach the failed sensor
2. Assess considerations for troubleshooting the sensor; check the sensor communication path
3. Determine how the sensor failed and what caused the failure
4. Recommend a solution and take corrective actions

For details, read the blog post: Troubleshooting a Sensor with a DMM

How the sensor fails	Potential causes of failure
Catastrophic failure • no measurement or completely out of range	• a short or open circuit in the sensor or the wiring • sensor failure
Offset error • stable measurements with readings slightly above or below the expected value	• poor wiring connections • ground loops • solution contamination on sensor or wire
Unstable readings • erratic measurements	• water damage to wire or sensor • external or non-representative interference • ground loops

Table 3. Examples of how the sensor fails and potential causes



Why sensor characterization is important

Sensor characterization is important:

1. It guarantees readout accuracy
2. Sensors are used in various operating conditions, causing complex interactions
3. Users can analyze readout information and develop error correction algorithms to improve overall accuracy and stability

For more, read the blog post: "How to Achieve Accurate Sensor Characterization Using a Digital Multimeter"

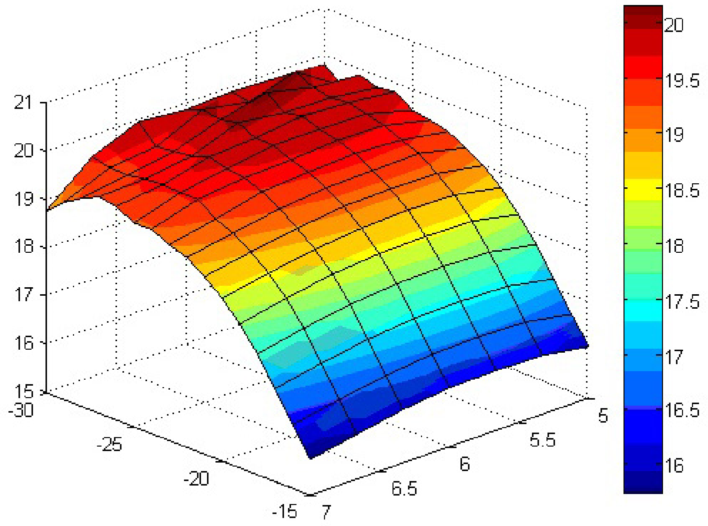


Figure 16. Example of a three-dimensional plot of a characterized sensor. The Z-axis represents the sensor's readout, such as voltage, power, temperature, or force. The X and Y axis are the external conditions the sensor is subjected to, such as input frequency, operating temperature, or pressure.

Optimizing your sensor characterization

Noise affects sensors, especially at the bottom half of their dynamic output range. Measurement environments have temperature noise, audible noise, electromagnetic noise, and more. These affect sensor output signals in their lowest dynamic range. Figure 17 shows an oscilloscope capture of an AC signal with noise riding on the signal.

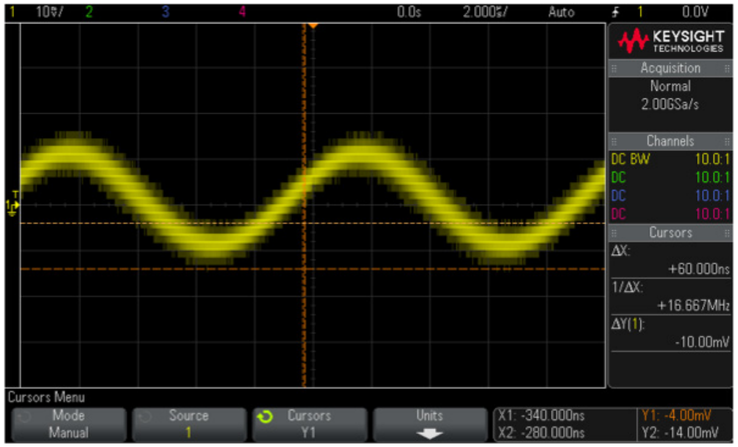


Figure 17. AC signal with noise

To achieve accurate sensor measurements at the sensor's lowest dynamic range, you will need to remove the noise. Robust DMMs have a built-in integrating noise power line cycle function that lets you easily set the integrating time to remove noise from power lines. Some DMMs also have built-in smoothing filters or a moving average filter to reduce random average noise. If you measure AC signals, some DMMs have AC filters to optimize low-frequency accuracy.

Optimizing your sensor characterization

During the sensor characterization process, one area that can affect measurement accuracy is the offset error. The error occurs when a measured value appears when there should not be a value. Figure 18 shows the characteristics of two measurements of a linear sensor.

The red line is an initial measurement; when x = 0, F (x) was also zero. After many measurements, the sensor may indicate "zero-offset" drifted, perhaps because of temperature or circuit component drifts. The blue line shows the subsequent n-th measurement; when x=0, F(x) has an offset value. That offset value indicates an offset error. Most DMMs have a null function to eliminate external offset errors.

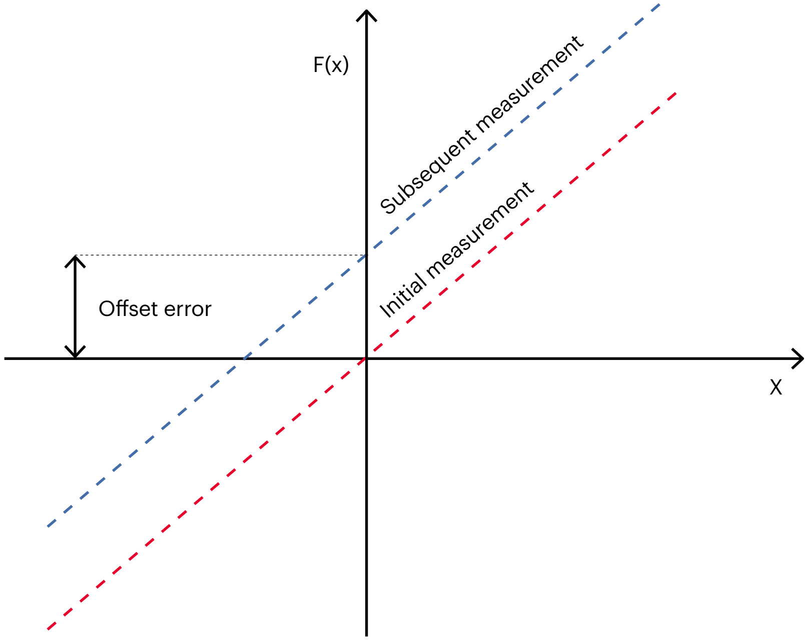


Figure 18. Offset error affecting measurement accuracy

Some DMMs have an Auto Zero function to fix internal DMM's offset error. With Auto Zero, the DMM internally measures the offset following each measurement. It then subtracts that measurement from the preceding reading. This prevents offset voltages present on the DMM's input circuitry from affecting measurement accuracy.

Key learnings

There are many types of sensors; they are embedded in many of the devices and appliances we use every day. The use of sensors will continue to grow and sensor-packed devices will play an even more integral role in our lives. Sensors are now being used to monitor vital health markers in medical patients, prevent car accidents, test the quality of our food, help automate our factories, and more.

With hundreds of types of sensors in the market, you need to choose the right DMM that enables you to design accurate, and robust products. Ensure high integrity sensor measurements by using a DMM that has an autocalibration feature to reduce measurement errors due to ambient temperature fluctuations, broad and linear dynamic ranges, and that minimizes measurement intrusiveness from internal or external noises.

For More Information

Find out more about Keysight's DMM and Data Acquisition System for your sensor testing needs.

www.Keysight.com/find/Truevolt

www.Keysight.com/find/DAQ970A

Keysight enables innovators to push the boundaries of engineering by quickly solving design, emulation, and test challenges to create the best product experiences. Start your innovation journey at www.keysight.com.