Sensor basics: Types, functions and applications

Martin Rowe - September 12, 2013

The Apple iPhone brought the benefits of integrated multi-sensor technology to the masses, and while the application of sensors and their associated algorithms has multiplied and changed the world forever, the fundamentals of the main sensor types and how they work has not. If you've forgotten those fundamentals, are new to sensor applications, or just need a handy list for reference, this article offers a review of major sensor types and applications.

Editor's note: *Classifying anything is a challenge, and sensors are no exception. We did our best to group the following sections in a way that makes sense, but of course, we were working with something that's more of a matrix. For example, we discuss capacitive sensors in terms of how they're used in touch screens. Then, we discuss inductive sensors as they're used to detect proximity. But some proximity sensors are capacitive. So we chose to highlight inductive proximity sensors because they're more widely used.*

We also chose to focus on photoresistors and photodiodes when discussing optical sensors. We could have written an entire section on CCD and CMOS optical sensors used in cameras. They were worth mentioning, but we felt that photoresistors and photodiodes was a better fit.
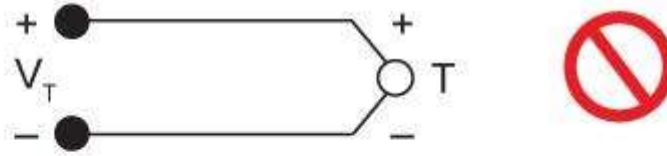
By all means add your two cents in the comments area below and we can update the list as needed. It's a list in 'flux'.
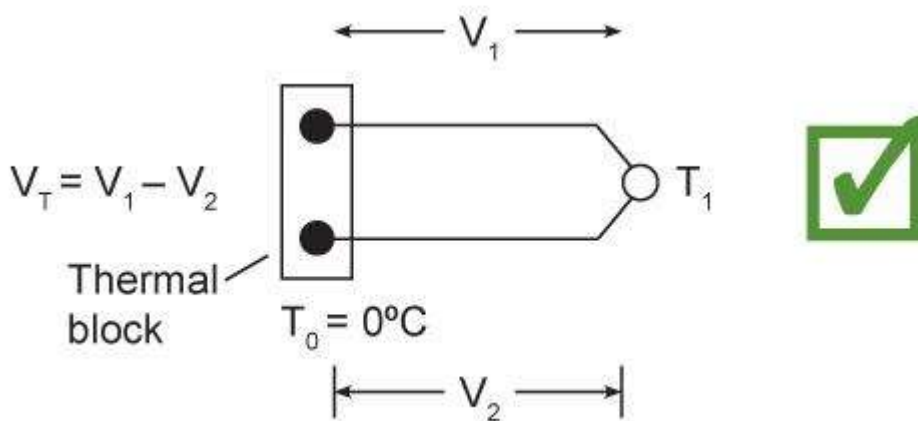
Temperature sensors
Temperature is the most common of all physical measurements. We have temperature measurement-and-control units, called thermostats, in our home heating systems, refrigerators, air conditioners, and ovens. Temperature sensors are used on circuit boards, as part of thermal tests, in industrial controls, and in room controls such as in calibration labs and data centers. Though there are many types of temperature sensors, most are passive devices: Thermocouples, RTDs (resistance temperature detectors), and thermistors.

Thermocouples (T/Cs) are the most common type of sensor because they don't require an excitation signal. They consist of two wires made of dissimilar metals joined at the point of measurement. Based on the Seebeck effect, T/Cs operate on the premise that each metal develops a voltage differential across its length based on the type of metal and the difference in temperature between the ends of the wire. By using two metals, you get two different voltages V_1 and V_2. The difference (V_T) represents temperature. Note that there is no voltage across the thermocouple junction, shown as T in Figure 1a, below. That's a common mistake. You will often hear that a thermocouple develops a voltage across the junction, which is incorrect. The voltage is developed over the length of each wire.

(a)

$+$

V_T

$-$

$+$

T

$-$

🚫

(b)

$\leftarrow V_1 \rightarrow$

$V_T = V_1 - V_2$

Thermal block

$T_0 = 0°C$

T_1

$\leftarrow V_2 \rightarrow$

✅

Thermocouples are designated using letters. For example, a Type-J T/C has iron and constantan (a copper-nickel alloy) wires. Most thermocouple wire is color coded.

Thermocouples require that the far ends of the wire be at the same temperature and that temperature must be known (Figure 1b). Thus, instruments that use thermocouples will have an isothermal block with an embedded sensor to measure the temperature at that point. This is called cold-junction compensation. With one end of the wires at an equal and known temperature, a circuit can measure V_T and calculate the unknown temperature.

Thermocouple curves are nonlinear and thus require linearization. That can be done in hardware of software, tho mostly in software with today's digital instruments through an equation or reference table.

Thermocouples are common because of their wide temperature range (type J can run up to 760°C), low cost, robustness, and simple signal-conditioning circuit. Wires can be run over long distances with proper shielding because the voltages are in microvolts/°C. They're often used in industrial applications such as ovens and furnaces.

Resistance-temperature detectors (RTDs) have a smaller range, typically a few hundred degrees Centigrade, but they have better accuracy and resolution than thermocouples. RTDs use precision wire, usually made of platinum, as the sense element. The element needs a known excitation current, typically 1mA. RTDs come in two-, three-, and four-wire configurations. Four-wire configurations, usually used as reference probes in calibration labs, have the best accuracy because two wires carry current and two are used for measuring the resistance across the element.

RTDs are specified with a base resistance, typically 100.0Ω at 0°C for platinum wire, and a resistance slope. For example a so-called 385 Pt100 RTD has a slope of 0.00385Ω/Ω/°C from 0°C to 100°C. At 100°C, the resistance is 138.5Ω. For applications between 0°C and 100°C, RTDs may be considered linear. RTDs are often used in regulated industries such as food processing where the temperature ranges aren't as wide as for thermocouples, but a higher accuracy is needed.

Because RTDs produce resistance as a function of temperature, the instrumentation often uses them in bridge circuits to maximize resolution. From there, the bridge output is digitized and linearized in software.

Thermistors are also resistance-based temperature sensors, but their resistance/temperature curve has a negative slop and is highly nonlinear. But, they produce a higher change in resistance for a given change in temperature than RTDs. They're often used where the highest resolution is needed, though over a relatively narrow temperature range. As a result, thermistors are often used in medical devices, home thermostats, and machines. Engineers often use thermistors to measure temperature in circuit such as [power supplies](#).

Thermistors produce a significantly higher resistance than RTDs, typically [2000Ω to 10,000Ω](#). Thus, they can operate at a significantly smaller excitation current, which reduces loss in wires. As a result, thermistors are often used in two-wire circuits.

Some temperature applications:

[Soldering iron driver bridge controls temperature](#)
[Simple diode serves as a sensor for a thermal probe](#)
[Platinum-RTD-based circuit provides high performance with few components](#)

Some videos on Temperature Sensing:

How to Select the Right Temperature Sensor For Your Application

Temperature Sensor using Thermistor

Arduino Tutorial (LM35 Temp Sensor)

For more on temperature sensing:

- [Temperature sensors are improving, but select carefully](#)
- [Designing with temperature sensors, part five: IC temperature sensors](#)
- [Fooled by a thermocouple: Temperature sensing gone awry](#)
- [Use a transistor as a heater](#)
- [Accurate temperature sensing with an external P-N junction](#)
- [Bob Pease on the LM57 temperature comparator as a temp sensor](#)
- [Wringing out thermistor nonlinearities](#)

Current sensors

Current sensors
Temperature may be the most popular physical measurement among electrical engineers, but

electrical measurements such as current just may top the list. Current sensors cover the range from the simple to the complex. In its most basic form, a current sensor is simple a resistor.

Often current sense resistors have low values - typically 1Ω or less depending on the application. They're placed in circuit and you measure the voltage across the resistor to calculate the current. Ohm's Law, nothing else.
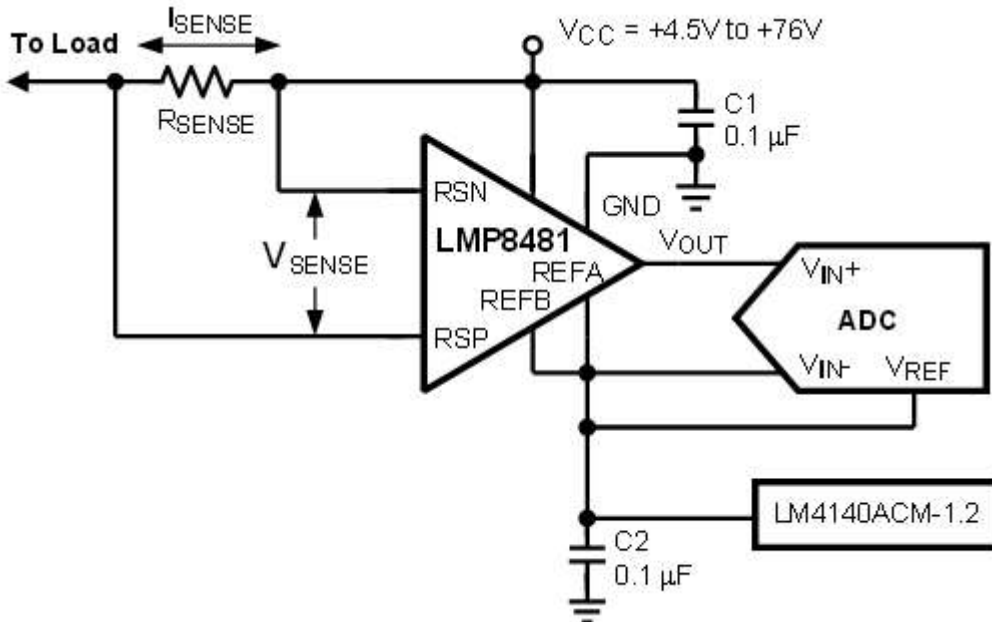
A simple low value resistor can be used as a current sense element across a current sense amplifier (Image courtesy of Texas Instruments)

Series shunt resistors are fine if you can tolerate the inevitable voltage loss, but that's not often the case. Furthermore, the frequency of the current is often an issue. When nonintrusive measurements are needed, you have to resort to some kind of magnetic current probe. You can find many practical applications for current probes from Doug Smith on his High-Frequency Measurements page.

Current measurements take place not just in the lab, but in just about everything these days. Any decent battery charger has some kind of current sense resistor to monitor charge current and shut down in an overcurrent condition occurs. Sense resistors can placed on either the high side or low side of the charge circuit.

Current-sense ICs provide a high-impedance input and convert the unknown current into a voltage or current for use with an ADC or microcontroller with a built-in ADC. Current sensing is also popular in motor-drive circuits and just about any electrical energy application.

Where AC measurements are concerned, you may need some kind of magnetic sensor that converts the magnetic field around a wire into a voltage. A typical magnetic current sensor is a ferrite ring that has a wire passing through it carrying the unknown current.

In some cases, you can connect the sensor directly to instrumentation but in others, you need some signal conditioning. For example, the DRV401 provides sensor excitation, filtering, fault protection, and degaussing for use in motor-drives.

Some current-sense applications call for isolation between the sense resistor and the measurement circuits. When that occurs, you can use an isolation amplifier and modulator in shunt-based motor-

control applications.

Some Design Ideas current sense applications:

[Sense automobile high-side current with discrete components](#)
[Improved Kelvin contacts boost current-sensing accuracy by an order of magnitude](#)

Some videos on Current sensing:

SparkFun According to Pete #32 - Current Sensing

Current Sensing: Low Side, High Side, and Zero Drift

Hall-Effect Based Current Sensors

For more on current sensing:
[Sensors and ICs simplify current measurements](#)
[How to select precision resistors for 4–20 mA current loop](#)
[Low-cost current monitor tracks high dc currents](#)
[High-side current-sense circuit problem](#)

Pressure and strain sensors

Pressure and strain sensors
Industrial and manufacturing systems rely heavily on pressure sensors and strain gages for the measurement and control of gases and weights. When I worked as an applications engineer, I helped customers with applications such as weighing systems and natural gas storage.

A company that produced gypsum wallboard (sheet rock) used strain gages in hoppers that would hold the gypsum powder. The hopper would vibrate to release the powder as needed for production. At an oil refinery, four tall storage tanks had a strain-gage sensor at the top and bottom of each tank. Each of the eight sensors connected to a data-acquisition system that calculated differential pressure between the sensors, converting each calculation into a 4-20mA signal for driving analog dials in a control room.

In each case, the sensors connected to Wheatstone Bridge circuits in the instrumentation, which also provided excitation power for the sensors. When I was called to the refinery to fix a problem, we found that the power source chosen by the customer was insufficient to drive all of the sensors.

A strain gage is typically made of a material that changes resistance when deformed, or put under strain. Because the change in resistance is small, these sensors are often connected in one segment of [Wheatstone Bridge](#) circuit where the other three resistances are known.

[Data-acquisition systems](#), such as the one described in the refinery application, often provide

excitation voltage to the bridge circuit and the external sensor. Bridge circuits may be quarter-bridge, half-bridge, or full-bridge configurations. A full-bridge application can use four or six wires. The figure below shows a six-wire configuration. The sense wires are used to measure the voltage at the bridge circuit, eliminating losses in power wiring that delivers V_{EXC}.

Pressure sensors, typically used to measure air, gas, or fluid pressure, are often designed using piezoelectric sensors or quartz sensors. Their [analog outputs](#) can be either voltage, such as 1-5V, or current, such as 4-20mA. The outputs can represent pressure in units of bars, kg/cm^2, or PSI. [Sensors are designed](#) to measure either absolute pressure, relative to a vacuum, differential pressure--the pressure between two points, or gauge pressure, which is pressure relative to atmospheric conditions.

While you may think of pressure sensors mainly for industrial use, other pressure measurements can take place in automotive, ergonomic, and other applications. For example, [flexible pressure sensors](#), which are really more like strain gages, are used in designing products such as mattresses and automotive seats.

Some videos on Pressure sensing:

How to Select the Right Pressure Sensor For Your Application

MEMS Pressure Sensor Operation

For more on pressure sensing:
[Choosing the right pressure sensors for engine test](#)

Position sensors

Position sensors

There was once a time when position sensors were used for detecting motion in industrial systems, aircraft, ships, and other large systems. Accelerometers, which measure motion in as many as three axes, were used to measure vibration in machines for predictive maintenance or in aircraft wings for test.

Then something happened. Sensors became small and inexpensive enough to be used in consumer products. I recall visiting a company in the 1990s that was developing MEMS (micro-electromechanical) accelerometers. In the lab, an engineer demonstrated how the device could be used in a game controller. That seemed incredible at the time but today, that's commonplace. Next, a company named after a fruit embedded accelerometers in phones and tablet computers, opening up a huge market for these sensors.

Accelerometers typically have internal [piezoelectric devices](#) that produce a voltage in response to motion. MEMS devices also respond to motion. You typically need an op-amp for signal conditioning before digitizing the sensor's output although many have signal-conditioning circuits built into the package and produce signals large enough for direct interfacing to digitizers. Actually, an accelerometer responds to a force applied to the sensor in the opposite direction.

Accelerometers detect linear motion. Gyroscope sensors let you measure rotational motion while inertial-measurement units (IMUs) combine accelerometers and gyroscopes.
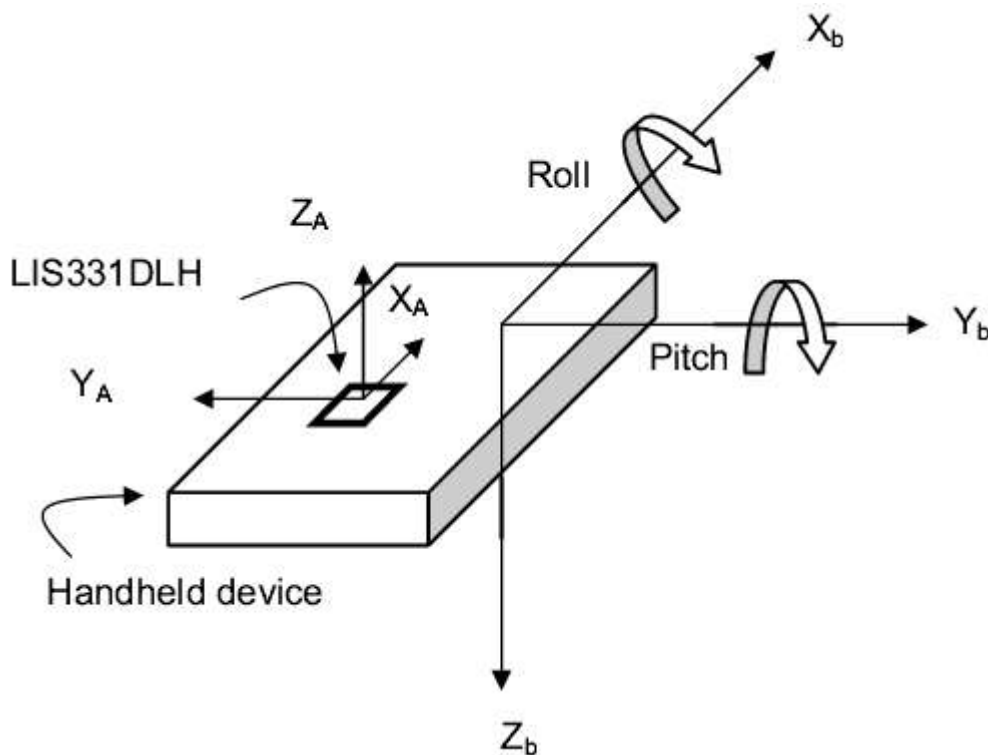
Accelerometers are used in handheld devices and other applications that need to sense movement (Image courtesy of ST Microelectronics)

[Motion-sensor applications](#) include acceleration, vibration and shock detection and measurement. All of these sensors are heavily used in robotics.

Traditional accelerometers and gyroscope sensors used in test, measurement, and control applications produce analog outputs. Thus, they need power supplies and signal-conditioning, which may involve filters. Other sensors, particularly those that are MAMS based, produce digital outputs for direct interfacing to microcontrollers. Much of the literature and user forums you'll find online revolve around the interfacing and [programming](#) required to develop a sensor-based system with a microcontroller.

Many robotics applications use accelerometers, gyroscopes, and IMUs that are already assembled on circuit boards designed to work with microcontrollers, including the open-source [Arduino](#) and [BeagleBone](#). I saw numerous applications in robotics this year while visiting the [WPI robotics department](#) to see demonstrations of senior projects.

Some position sensor applications:

[Convert your smartphone into a pedometer and tracking device](#)

Some videos on Position/acceleration sensing:

How to Select the Right Angular Position Sensor For Your Application

How to Select the Right Gyroscope For Your Application

For more on position sensing:
[Motion sensors de-mystified](#)
[Seven tips for making better accelerometer measurements](#)
[Modeling the MEMS gyroscope](#)
[That fictitious force](#)
[Comparing the effectiveness of sensors in mobile operating systems](#)
[Shock and vibration tests demand proper sensors](#)
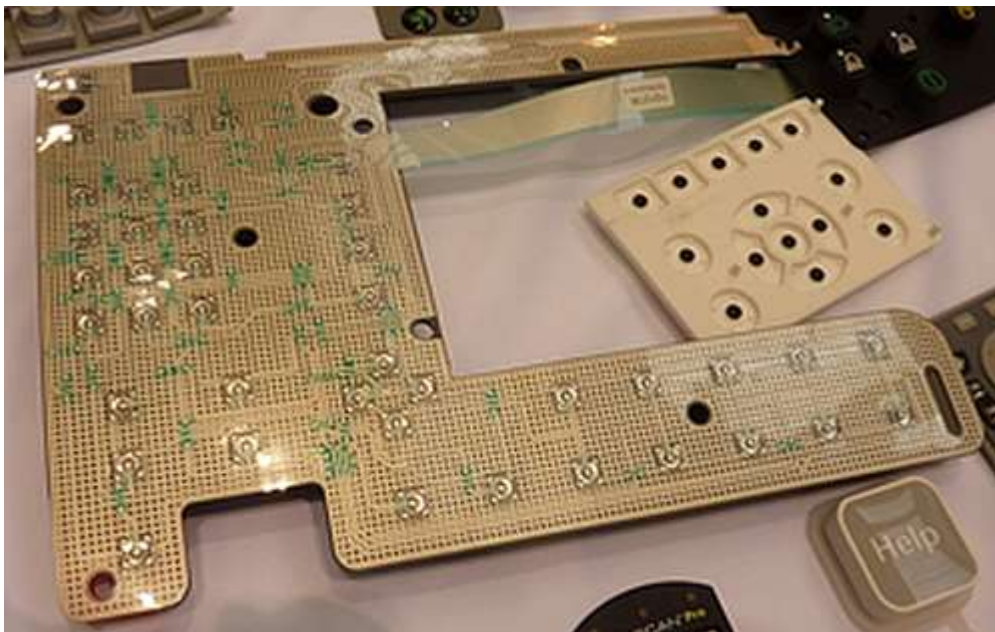
Capacitive sensing

Capacitive sensing
Sensing capacitance took on a whole new meaning with touch screens, particularly with the iPhone and iPad became popular. Capacitive sensing began its life long before the iPhone, having been used to detect fluid levels, humidity, and material properties.

Capacitive sensors are typically made of [several layers of materials](#), often on a circuit board. In touch-screen or button applications, a sensor IC detects not absolute capacitance, but a change in capacitance, indicating the location of your finger. Because these screens rely on the change in capacitance based on your skin, they don't work with your fingernails. The figure below (courtesy of Texas Instruments) shows an equivalent circuit for a touch screen.
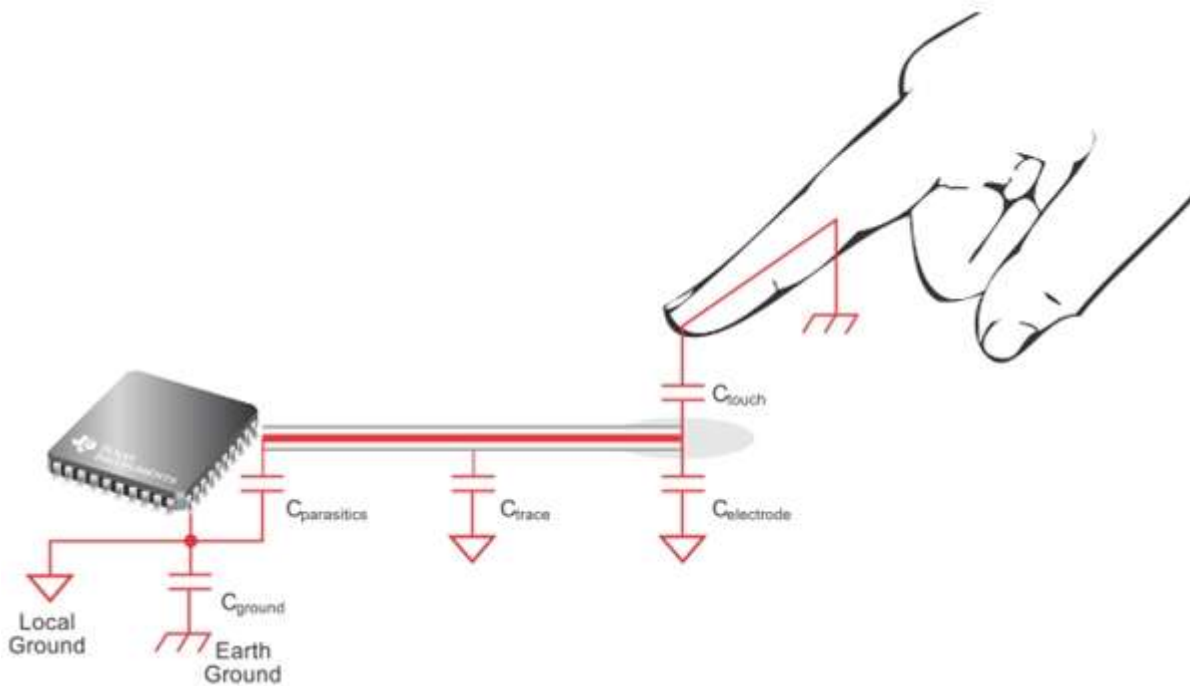
Capacitive sensing is also used for human interfaces to replace mechanical buttons. These sensors are fabricated into circuit boards, such as the one shown below.

With capacitive sensing, your finger is never in contact with the sensing device. Thus, there's no mechanical wear (unless you break the screen on your phone). Your finger interferes with a local electric field, which changes capacitance and is sensed by an IC, digitized, and sent to a microcontroller. The capacitive-sensing IC produces an excitation signal that creates the local electric field in the sensing surface.

There are three major considerations in an effective capacitive touch-sensor array: SNR, scan time, and finger threshold. Noise comes from three sources: radiated noise, conducted noise, and environmental changes. Radiated and conductive noise are, of course, EMI issues. Environmental issues arise from changes in temperature and humidity. If the noise exceeds a threshold, the sense

circuit may detect that as a touch when no touch occurred.

A capacitive sensing IC scans the buttons or screen locations. Thus, there can be timing issues between when a change in capacitance occurs and when the IC scans that location. Because a scan occurs for a fixed amount of time at each location, the sensing IC applies a counter to the charge time of a known capacitor. Changes in the total capacitance (accounting for the touch or lack of touch) cause a counter to create a number proportional to current. It's essentially an integration process. If the count exceeds a specific value, the circuit interprets that as a touch and the system acts upon that event.

Some capacitive sensing applications:

Solve low-frequency-cutoff problems in capacitive sensors
Finger-heating effect in mutual capacitive touch sensor design
Electrode design in capacitive touch sensor applications
Capacitive sensing—Integrating multiple interfaces

Some videos on Capacitive sensing:

Capacitive sensor, theory and design

Projected capacitive touch sensors, theory and design guides

How the Capacitance touch sensor (button-switch) works

SparkFun Engineering Roundtable 9-24-12: Capacitive Sensing with Chris Taylor

For more on capacitive sensing:
An introduction to capacitive sensing, part 1
Electrode design in capacitive touch sensor applications
Mechanical Buttons to capacitive sensing—A step-by-step guide—Part IV
Designing reliable capacitive touch interfaces
Determining the right switch technology for consumer, industrial interfaces
Understanding touch control technologies

Humidity sensors

Humidity sensors

Many environmental tests performed as part of product characterizations rely on testing over a range of humidity. After all, many products must work in the deserts of Arizona to forests of New England.

Humidity measurements are also use in applications such as aviation, weather, and scientific applications. Our home appliances have become smarter; humidity sensors have found their way into white goods such as refrigerators. During the heating season, I keep a wireless humidity transmitter in my guitar case so I know when to humidify it without having to open the case.

In 2009, EDN's then analog editor Paul Rako wrote "I am always interested when I see a humidity sensor." In this case, he was referring to a sensor from Honeywell. This sensor uses a capacitive technology where the capacitive value changes with humidity. It's another application of sensing capacitance, which we discussed regarding touch-screen technology.

A humidity tutorial from Vaisala shows that humidity instruments started as mechanical devices that used horse hair. As technology improved, the wet/dry bulb became popular. Next came the chilled mirror, which used light that reflected in a wider pattern in the presence of dew. When electrical humidity sensors entered the scene, they started as resistive devices but have now become capacitive. Early capacitive sensors used aluminum oxide (AL_2O_3) but have since moved to polymer-based technologies.

Honeywell's data sheet says "The RH sensor uses a laser trimmed, thermoset polymer capacitive sensing element with on-chip integrated signal conditioning." It doesn't get into the details about how the sensor actually works. In general, a capacitive humidity sensor can collect moisture from the environment, which changes the value of the capacitance.

Humidity-sensor ICs such as that from Honeywell provide you with a digital output, making it a complete sensing system for embedded applications. As a result, you can find humidity-measurement modules for platforms such as Arduino and BeagleBone.
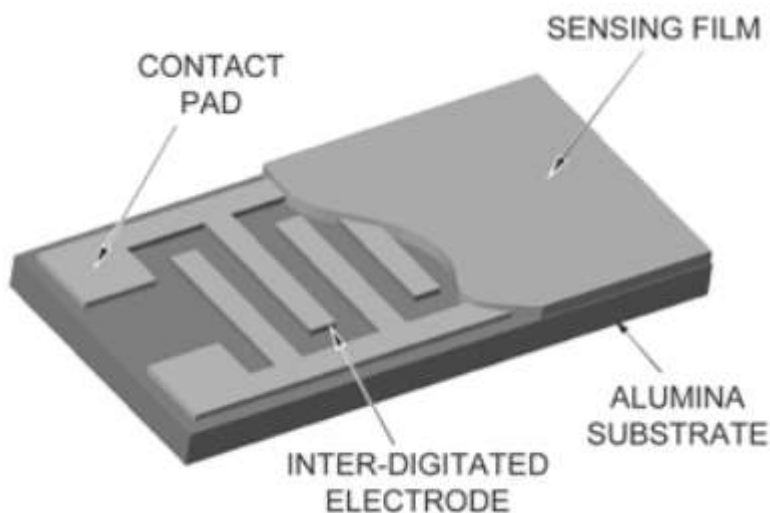
An interdigitated electrode design is one technique used in capacitive relative humidity (RH) sensors (Image courtesy of Hygrometrix app note 2004-2)

Temperature/humidity probes connect to digital instruments or transmitters, providing you with measurement results. Probes such as the HUMICAP line from Vaisala provide both analog (voltage

for humidity, resistive for temperature) and digital (RS-485) outputs for connecting to instruments and other systems. Humidity instruments range from handheld and consumer-grade devices to industrial and scientific models.

Some humidity sensor applications:

[Measure humidity and temperature on one TTL line](#)
[Transmitter senses triple relative-humidity figures](#)
[Low-cost relative-humidity transmitter uses single logic IC](#)
[Remote humidity sensor needs no battery](#)

Some videos on Humidity sensing:

Humidity sensors

How to Select the Right Humidity Sensor For You Application

A Humidity Sensor Circuit For Arduino

**For more on humidity sensing:**
[How do You Measure Humidity?](#)
[Relative humidity integrated on chip](#)

Inductive sensors

Inductive sensors
Inductors and inductance can strike fear into the hearts of normally sane engineers, but inductance is the basis for many sensing applications. Inductive sensors are used heavily in machine applications to sense the proximity of a metal object.

The concept of an inductive sensor is easy: Excite the inductor with an AC signal, which creates a magnetic field. When a metal object approaches the proximity sensor, [eddy currents](#) from the inductor's magnetic field flow in the target. That produces a load on the sensor's inductive circuit. Circuits in the sensor detect the reduced amplitude, which produces a lower output voltage in a linear proximity sensor. In a proximity switch, the crossing of a threshold trips the switch.
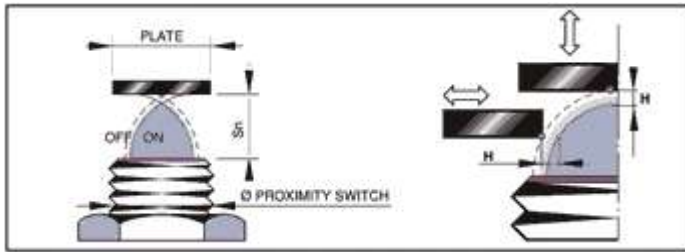
Inductive proximity detectors are used for non-contact detection of metallic objects (Image courtesy of Fargo Controls)

When the switch changes state, it can cause many things to occur. For example, the switch could be used as an interlock to remove power, preventing a dangerous condition for occurring. Switches may connect to counters that track how many times a metal object passes a given location. A microcontroller could, for example, use the pulses to count rotations in a machine where the pulses are created by gear teeth passing near the sensor.

Switches come with two-three, or four-wire outputs. A two wire provides a NO or NC output. Three wires provide a means for you to connect a source, load, and return line. Four wires provide two switches, NO and NC, plus source and return lines.

Many inductive proximity sensors have a tubular shape, such as the type shown below from [Allen-Bradley/Rockwell Automation](). The shape lets you mount the sensor on a plate or bracket. Other packages include flat packs for mounting on a flat surface.

Analog proximity sensors let you detect the distance that a metal object is from the sensor. The output, linear over a given range, can be a current or voltage, depending on the model. Analog outputs are available in three-wire configurations for source, load, and return lines.

Some videos on Proximity sensing:

The Working Principle of Inductive Sensor

How to Select the Right Proximity Sensor For Your Application

Proximity Sensor Basics (capacitive)

For more on proximity sensing:

[Applications and considerations of capacitive proximity sensing](#)

[Detect charged bodies with electronic electroscope](#)

Light sensors

Light sensing

There are many ways to detect light using electronic components. Every cell phone and digital camera has a light-sensing array for taking photos. Engineers use other light-sensitive components such as photoresistors, photodiodes, and photodetector ICs in all kinds of applications. Photodiodes are particularly useful as detectors of light in fiber-optic networks.

Over the years, engineers have contributed many circuits to EDN [Design Ideas](#) that use photosensitive devices. Photoresistors are used when you need a resistive analog response to a light level. Photodiodes are both digital devices and analog devices. As digital devices, they turn on and off when they sense a given level of light. Analog photodiodes produce an analog quantity based on received light. You can use these sensors in applications such as circuit to control relays and timers.

The Design Idea "[Photoresistor provides negative feedback to an op amp, producing a linear response](#)" describes a circuit that combines a photoresistor with a high-brightness LED. The LED is driven so that its light shines on the photodiode, which is part of a feedback loop that adjusts an op amp's gain. "[Smart photoresistor timer needs few components](#)" shows you how to connect a photoresistor to a microcontroller, using the resistor sensor that turns on a timer at dusk.

A recent Design Idea by Glen Chenier shows a circuit for [detecting light in a fiber-optic communication network](#). The circuit uses chopper-stabilized transimpedance amplifiers to convert the photodiode current into a voltage. Using two photodiodes and transimpedance amplifiers, the circuit can detect leakage current even when there is light flowing on two directions in the two fibers.

There are also IC light sensors that you can apply. The [MLX75305](#), a light-to-voltage converter, integrates a photodiode, transimpedance amplifier, and output transistor into one device. The result: a linear voltage output with respect to light intensity. Such a device might have reduced component count in Chenier's application described above.

Light-sensitive ICs can also double as proximity sensors. The [ISL 29044](#) contains a photodiode for sensing ambient light, but it also has an infrared LED that, when used in conjunction with the photodiode, functions as a proximity sensor. It produces an I^2C digital output for communicating with a microcontroller.

Some videos on Light sensing:

Optical sensors

SparkFun Infrared Sensor Overview

How to use an Optical Sensor with a Microcontroller

For more on light sensing:
[Photo-sensing circuits: The eyes of the electronic world are watching](#)
[How optical sensing solves the toughest sensing challenges](#)
[Collecting light power: voltaic or conductive?](#)
[Image sensors evolve to meet emerging embedded vision needs - Part 2: HDR processing](#)

Sound and vibration sensing

Sound and vibration sensing
Sound and vibration sensing is a subset of the accelerometers previously covered. Many machines vibrate during use and may make noise, both of which need to be measured and analyzed. A typical example is a washing machine. When not evenly balanced, it can vibrate excessively. As part of the test and qualification process, engineers will monitor the vibrations and noise of such products.

Sensors such as accelerometers, combined with data-acquisition equipment and specialized software, let you analyze the vibrations. MEMS-based microphones are often used in sound capture and analysis. [Analog and digital MEMS microphone design considerations](#) from EE Times explains how MEMS microphones work and what kind of signal-conditioning circuits they need. For example, you need a high-impedance input stage following the MEMS microphone because of its typical 200Ω output impedance.

Most data-acquisition systems used for acoustic analysis will sample the sensor's output at around 50ksamples/s and provide a high-resolution ADC. For example, the [DT3837](#) USB module from Data Translation samples at 52.7 ksamples/s on each of four channels. Each channel has a dedicated 24-bit delta-sigma ADC. The [NI 9234](#) CompactRIO four-channel digitizer from National Instruments also has a 24-bit ADC, which samples at 51.2 ksamples/s.

MEMS digital microphones integrate an ADC into the sensor, providing direct digital output in [I^2S](#) (inter-IC sound) and PDM (pulse-density modulation) formats. You can connect them directly to microcontrollers. Digital microphones are often used in [smart phones](#), tablet computers, laptops computers, headphones (for noise cancellation) and [hearing aids](#). Going a step further, researchers at the University of Utah developed a MEMS microphone that can be [implanted in the middle ear](#).

Some sound/vibration sensing applications:

[Bender senses shocks](#)

Some videos on sound and vibration sensing:

How to Select the Right Silicon Microphone Sensor For Your Application

Module 14 - Lecture 1 - Vibration Measurement

Vibration Energy Harvesting for Wireless Sensor Networks

For more on sound sensing:
Tools to tame noise and vibration
Audio synthesis and noise reduction in modern vehicles
DIY laser mic, visualize sound waves, iPhone 5 DAC