

Ask The Application Engineer—35

Capacitance Sensors for Human Interfaces to Electronic Equipment

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Q: What is a capacitance sensor?

A: Capacitance sensors detect a change in capacitance when something or someone approaches or touches the sensor. The technique has been used in industrial applications for many years to measure liquid levels, humidity, and material composition. A newer application, coming into widespread use, is in human-to-machine interfaces. Mechanical buttons, switches, and jog wheels have long been used as the interface between the user and the machine. Because of their many drawbacks, however, interface designers have been increasingly looking for more reliable solutions. Capacitive sensors can be used in the same manner as buttons, but they also can function with greater versatility, for example, when implementing a 128-position scroll bar.

Integrated circuits specifically designed to implement capacitance sensing in human-machine interface applications are now available from Analog Devices. The AD7142¹ and the AD7143, for example, can stimulate and respond to up to 14 and eight capacitance sensors, respectively. They provide excitation to the capacitance sensor, sense the changes in capacitance caused by the user's proximity, and provide a digital output.

Q: How does capacitance sensing work?

A: A basic sensor includes a receiver and a transmitter, each of which consists of metal traces formed on layers of a printed-circuit board (PCB). As shown in Figure 1, the AD714x has an on-chip excitation source, which is connected to the transmitter trace of the sensor. Between the receiver and the transmitter trace, an electric field is formed. Most of the field is concentrated between the two layers of the sensor PCB. However, a fringe electric field extends from the transmitter, out of the PCB, and terminates back at the receiver. The field strength at the receiver is measured by the on-chip sigma-delta capacitance-to-digital converter. The electrical environment changes when a human hand invades the fringe field, with a portion of the electric field being shunted to ground instead of terminating at the receiver. The resultant decrease in capacitance—on the order of femtofarads as compared to picofarads for the bulk of the electric field—is detected by the converter.

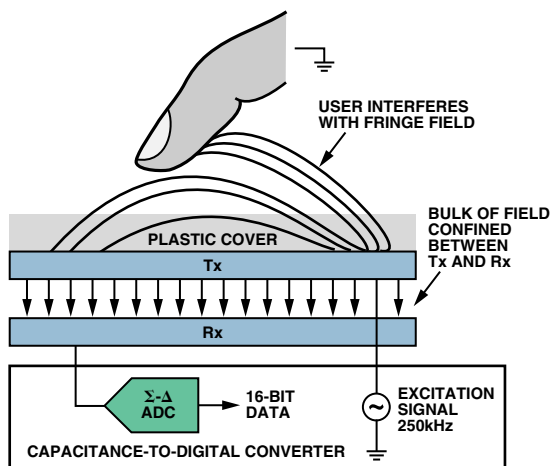


Figure 1. Sensing capacitance.

In general, there are three parts to the capacitance-sensing solution, all of which can be supplied by Analog Devices.

- The driver IC, which provides the excitation, the capacitance-to-digital converter, and compensation circuitry to ensure accurate results in all environments.
- The sensor—a PCB with a pattern of traces, such as buttons, scroll bars, scroll wheels, or some combination. The traces can be copper, carbon, or silver, while the PCB can be FR4, flex, PET, or ITO.
- Software on the host microcontroller to implement the serial interface and the device setup, as well as the interrupt service routine. For high-resolution sensors such as scroll bars and wheels, the host runs a software algorithm to achieve high resolution output. No software is required for buttons.

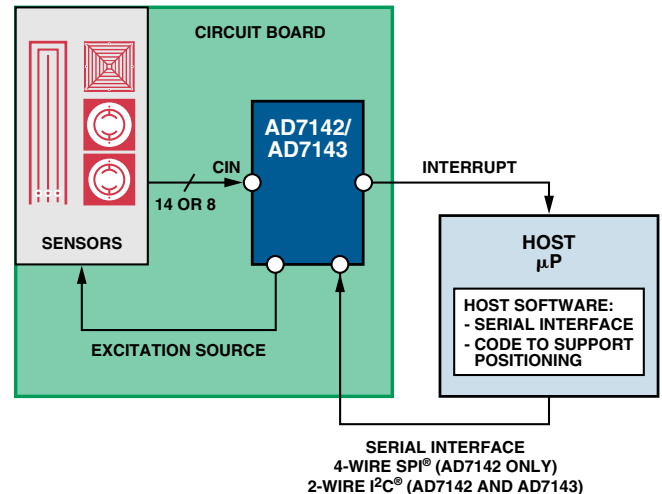


Figure 2. Three-part capacitance-sensing solution.

Q: What are the advantages of capacitive sensing?

A: Capacitance sensors are more reliable than mechanical sensors—for a number of reasons. There are no moving parts, so there is no wear and tear on the sensor, which is protected by covering material, for example, the plastic cover of an MP3 player. Humans are never in direct contact with the sensor, so it can be sealed away from dirt or spillages. This makes capacitance sensors especially suitable for devices that need to be cleaned regularly—as the sensor will not be damaged by harsh abrasive cleaning agents—and for hand-held devices, where the likelihood of accidental spillages (e.g., coffee) is not negligible.

Q: Tell me more about how the AD714x ICs work.

A: These capacitance-to-digital converters are designed specifically for capacitance sensing in human-interface applications. The core of the devices is a 16-bit sigma-delta capacitance-to-digital converter (CDC), which converts the capacitive input signals (routed by a switch matrix) into digital values. The result of the conversion is stored in on-chip registers. The on-chip excitation source is a 250-kHz square wave.

The host reads the results over the serial interface. The AD7142, available with either SPI[®]- or I²C[®]-compatible interfaces, has 14 capacitance-input pins. The AD7143, with its I²C interface, has eight capacitance-input pins. The serial interface, along with an interrupt output, allows the devices to connect easily to the host microcontroller in any system.

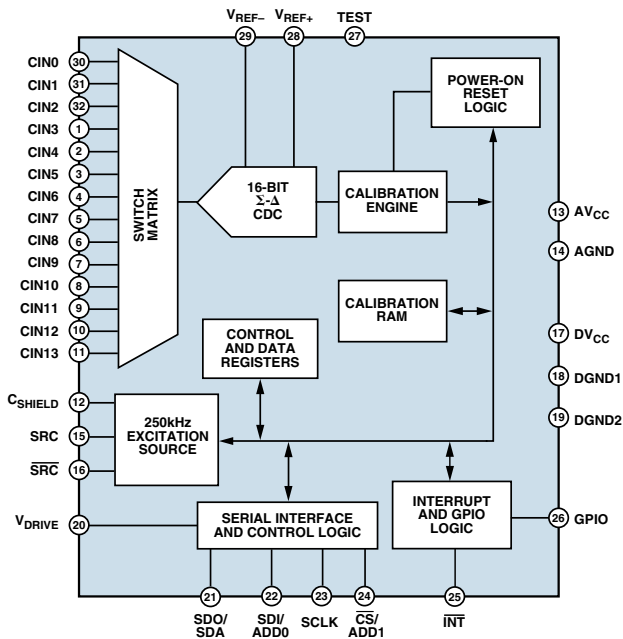


Figure 3. AD7142 block diagram.

These devices interface with up to 14 external capacitance sensors, arranged as buttons, bars, wheels, or a combination of sensor types. The external sensors consist of electrodes on a 2- or 4-layer PCB that interfaces directly with the IC.

The devices can be set up to interface with any set of input sensors by programming the on-chip registers. The registers can also be programmed to control features such as averaging and offset adjustment for each of the external sensors. An on-chip sequencer controls how each of the capacitance inputs is polled.

The AD714x also include on-chip digital logic and 528 words of RAM that are used for environmental compensation. Humidity, temperature, and other environmental factors can affect the operation of capacitance sensors; so, transparently to the user, the devices perform continuous calibration to compensate for these effects, giving error-free results at all times.

One of the key features of the AD714x is sensitivity control, which imparts a different sensitivity setting to each sensor, controlling how soft or hard the user's touch must be to activate the sensor. These independent settings for *activation thresholds*, which determine when a sensor is active, are vital when considering the operation of different-size sensors. Take, for example, an application that has a large, 10-mm-diameter button, and a small, 5-mm-diameter button. The user expects both to activate with same touch pressure, but capacitance is related to sensor area, so a smaller sensor needs a harder touch to activate it. The end user should not have to press one button harder than another for the same effect, so having independent sensitivity settings for each sensor solves this problem.

Q: How is the environment taken into account?

A: The AD714x measures the capacitance level from the sensor continuously. When the sensor is not active, the capacitance value measured is stored as the *ambient* value. When a user comes close to or touches the capacitance sensor, the measured capacitance decreases or increases. Threshold capacitance levels are stored in on-chip registers. When the measured capacitance value exceeds either upper or lower threshold limits, the sensor is considered to be active—as shown in Figure 4—and an interrupt output is asserted.

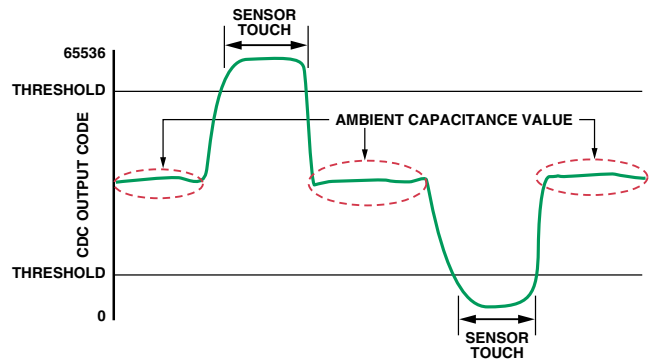


Figure 4. Sensor activation.

Figure 4 shows an ideal situation, where the ambient capacitance value does not change. In reality, the ambient capacitance changes constantly and unpredictably due to changes in temperature and humidity. If the ambient capacitance value changes sufficiently, it can affect the sensor activation. In Figure 5, the ambient capacitance value increases; Sensor 1 activates correctly, but when the user tries to activate Sensor 2, an error occurs. The ambient value has increased, so the change in capacitance measured from Sensor 2 is not large enough to bring the value below the lower threshold. Sensor 2 cannot now be activated, no matter what the user does, as its capacitance cannot decrease below the lower threshold in these circumstances. A worse possibility is that the ambient capacitance level continues to increase until it is above the upper threshold. In this case, Sensor 1 will become active, even though the user has not activated it, and it will remain active—the sensor will be “stuck” on—until the ambient capacitance falls.

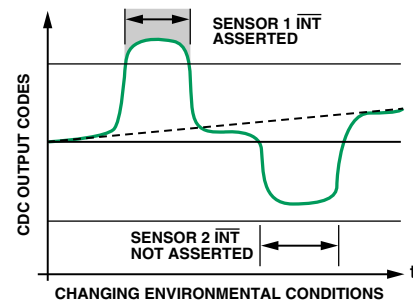


Figure 5. Sensor activation with changing ambient capacitance.

On-chip logic circuits deal with the effects of changing ambient capacitance levels. As Figure 6 shows, the threshold levels are not constant; they track any changes in the ambient capacitance level, maintaining a fixed distance away from the ambient level to ensure that the change in capacitance due to user activation is always sufficient to exceed the threshold levels. The threshold levels are adapted automatically by the on-chip logic and are stored in the on-chip RAM. No input from the user or host processor is required.

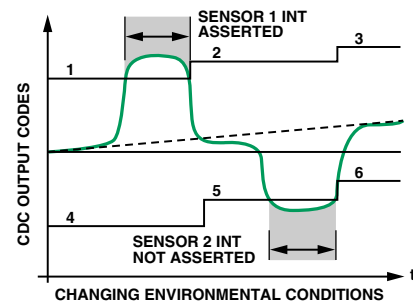


Figure 6. Sensor activation with auto-adapting thresholds.

Q: How is capacitance sensing applied?

A: As noted earlier, the sensor traces can be any number of different shapes and sizes. Buttons, wheels, scroll-bar, joystick, and touchpad shapes can be laid out as traces on the sensor PCB. Figure 7 shows a selection of capacitance sensor layouts.

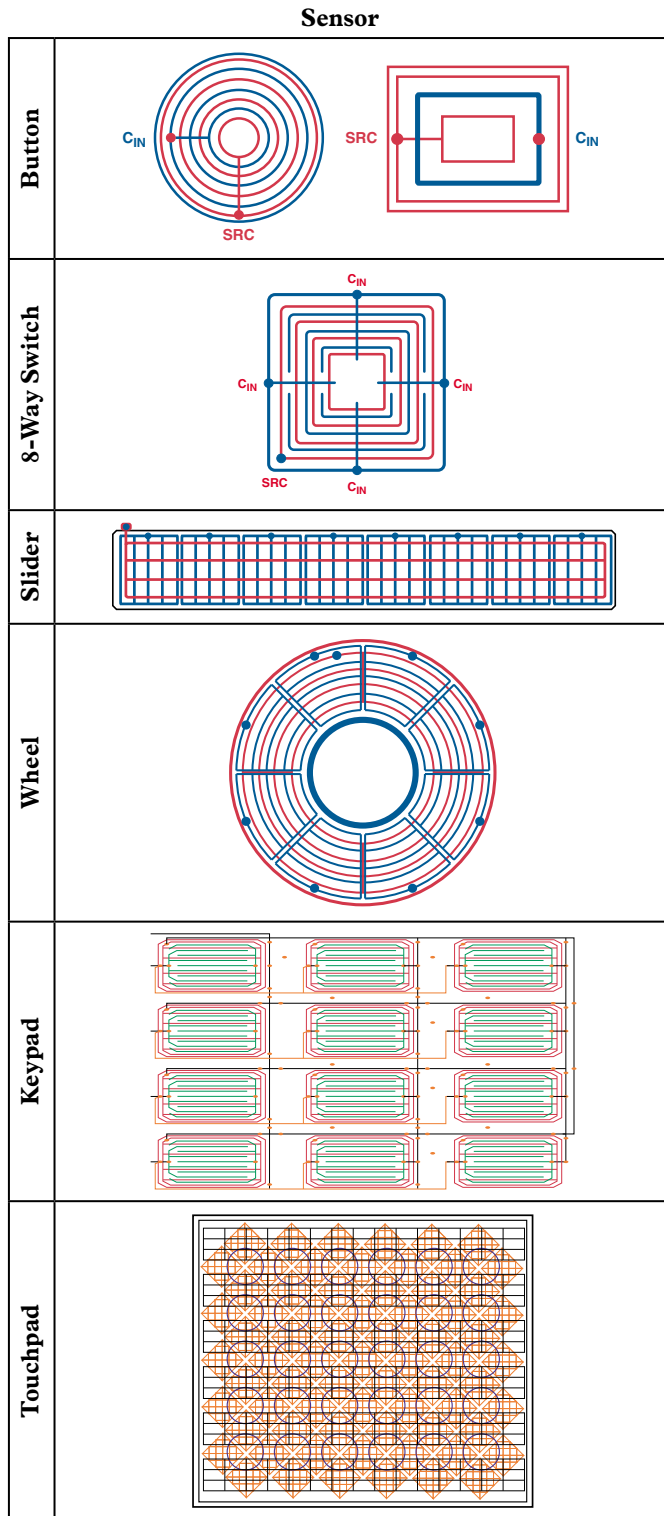


Figure 7. Selection of capacitance sensors.

Many options for implementing the user interface are available to the designer, ranging from simply replacing mechanical buttons with capacitive button sensors to eliminating buttons by using a joystick with eight output positions, or a scroll wheel that gives 128 output positions.

The number of sensors that can be implemented using a single device depends on the type of sensors required. The AD7142 has 14 capacitance input pins and 12 conversion channels. The AD7143 has eight capacitance inputs and eight conversion channels. The table below shows the number of input pins and conversion stages required for each sensor type. Any number of sensors can be combined, up to the limit established by the number of available inputs and channels.

| Sensor Type | Number of C_{IN} inputs required | Number of conversion channels required |
|-----------------|------------------------------------|--|
| Button | 1 | 1 (0.5 for differential operation) |
| 8-Way Switch | 4—top, bottom, left, and right | 3 |
| Slider | 8—1 per segment | 8—1 per segment |
| Wheel | 8—1 per segment | 8—1 per segment |
| Keypad Touchpad | 1 per row, 1 per column | 1 per row, 1 per column |

Measurements are taken on all connected sensors sequentially—in a “round-robin” fashion. All sensors can be measured within 36 ms, though, allowing essentially simultaneous detection of each sensor’s status—as it would take a very fast user to activate or deactivate a sensor within 40 ms.

Q: What design help can you offer first-time users?

A: Analog Devices has a number of resources available to designers of capacitance sensors. The first step in the design process is to decide what types of sensors are needed in the application. Will the user need to scan quickly through long lists, such as contacts on a handset or songs on an MP3 player? If so, then consider using a scroll bar or scroll wheel to allow the user to scan through those lists quickly and efficiently. Will the user need to control a cursor moving around a screen? An X-Y joystick would be a good fit for this application. Once the type, number, and dimensions of the required sensors have been fixed, the sensor PCB design can begin.

As part of the design resources available for capacitance sensing, a Mentor Graphics PADs layout library is available online. Many different types and sizes of sensors are available in this library as components, which can be dragged and dropped directly into a PCB layout. The library is available as an interactive part of the [Touch Controller System Block Diagram](#).² Also available is [AN-854](#),³ an application note that provides details, tips, and tricks on how to use the sensor library to lay out the desired sensors quickly.

When designing the PCB, place the AD7142 or AD7143 on the same board as the sensors to minimize the chances of system errors due to moving connectors and changing capacitance. Other components, LEDs, connectors, and other ICs, for example, can go on the same PCB as the capacitance sensors, but the sensor PCB must be glued or taped to the covering material to prevent air gaps above the sensors, so the placement of any other components on the PCB must take this into account.

For applications where RF noise is a concern, then an RC filter can be used to minimize any interference with the sensors. Using a ground plane around the sensors will also minimize any interference.

The PCB can have either two- or four layers. A 4-layer design must be used when there is no room, outside of the sensor active areas, to route between the IC and the sensors, but a 2-layer design can be used if there is enough routing room.

The maximum distance allowed between the sensor traces and capacitance input pin is 10 cm, but one sensor can be 10 cm from the pins in one direction, while another can be 10 cm from the pins in the opposite direction, allowing 20 cm between sensors.

Q: *My sensor PCB is ready, now what?*

A: Capacitance is notoriously difficult to simulate, so the sensor response in each application must be characterized to ensure that the AD7142/AD7143 is set up optimally for the application. This characterization process need only take place once per application, with the same setup values then being used for each individual product.

The sensors are characterized in the application. This means that any covering material must be in place on top of the sensor, and any other PCBs or components that may have an effect on the sensor's performance must be in place around the sensor.

For each conversion channel, we need to configure:

- Internal connection from the device's C_{IN} input pin to the converter. This ensures that each sensor is connected to the converter using one conversion channel.
- Sensor offset value, to offset for C_{BULK} . This is the capacitance associated with the electric field that is confined within the PCB, between the transmitter and receiver electrodes. This value does not change when the sensor is active, but instead provides a constant offset for the measurement fringe capacitance value.
- Initial values for upper and lower offset registers. These values are used by the on-chip logic to determine the activation threshold for each sensor.

The easiest way to perform the characterization is to connect the sensor PCB to the AD7142/AD7143 evaluation board—available from Analog Devices. The microcontroller and software that are included on the evaluation board can be used to characterize the sensor response and save the setup values.

Q: *What kind of response can I expect?*

A: The practical response from the sensor is defined by the converter's output change when the sensor goes from inactive to active. This change will depend on the area of the sensor—the larger the sensor area, the greater the change when the sensor is active. The sensor response will also depend on the thickness of the covering material—if it is very thick (4 mm or more), the sensor response will be minimal. The reason is that the electric field will not penetrate through very thick covering material, so the user will not be able to shunt enough of the field to ground to generate a large response. Figure 8 is a typical sensor response from a button sensor. It shows a change of about 250 LSBs between the sensor active and sensor inactive in this case.

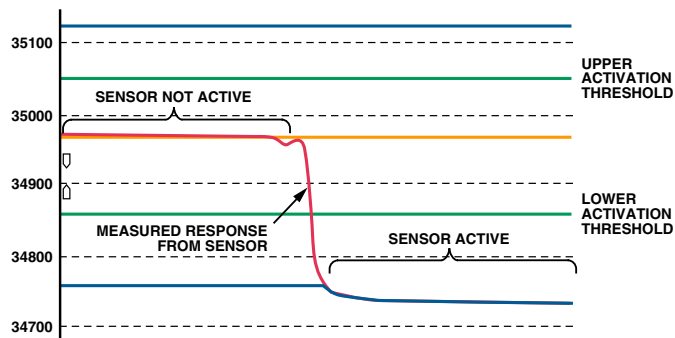


Figure 8. Typical response from a button sensor.

Q: *You mentioned software?*

A: The interaction between the host processor and the AD7142/AD7143 is interrupt-driven. The host implements the serial interface, either SPI or I²C. The AD7142/AD7143 will interrupt the host when a sensor is touched. The host can then read back data from the on-chip registers. If the sensors are buttons, or other simple on/off type sensors, the host simply reads back from the on-chip status registers; an active button causes a bit to be set in the status register. However, if the sensors have a high-resolution output, a software algorithm must run in the host interrupt routine to process the AD7142/AD7143 data.

The code is provided free of charge or royalties to customers who sign a license agreement with Analog Devices. For a scroll bar, the code typically occupies 500 bytes of data memory and 8k bytes of code memory. For a scroll wheel, the code typically occupies 600 bytes of data memory and 10k bytes of code memory.

Analog Devices provides [sample drivers](#),⁴ written in C-code, for basic configuration, button sensors, and 8-way switches using SPI- and I²C-compatible interfaces. Sample drivers for scroll wheels and scroll bars are available after signing a software license.

Q: *Ideas on assembling my finished product?*

A: No air gap is allowed between the sensor PCB and the covering material or product case because having one would cause less of the electric field to extend above plastic, decreasing the sensor response. Also, the plastic or other covering material might bend on contact, causing the user to interact with a variable electric field, and resulting in a nonlinear sensor response. Thus, the sensor PCB should be glued to the covering material to prevent any air gaps from forming.

Also, there can be no floating metal around the sensors. A “Keep Out” distance of 5 cm is required. Metal closer to the sensors than 5 cm should be grounded, but there can be no metal closer to the sensors than 0.2 mm.

Finally, the plastic covering the sensor's active areas should be about 2 mm thick. Larger sensor areas should be used with thicker plastic; and plastic thickness of up to 4 mm can be supported.

CONCLUSION

Capacitance sensors are an emerging technology for human-machine interfaces and are rapidly becoming the preferred technology over a range of different products and devices. Capacitance sensors enable innovative yet easy-to-use interfaces for a wide range of portable and consumer products. Easy to design, they use standard PCB manufacturing techniques and are more reliable than mechanical switches. They give the industrial designer freedom to focus on styling, knowing that capacitance sensors can be relied upon to give a high-performance interface that will fit the design. The designer can benefit from the Analog Devices portfolio of IC technology and products, plus the expertise and the hardware and software tools available to make it as easy and as quick as possible to design-in capacitance sensors. ▶

REFERENCES—VALID AS OF OCTOBER 2006

- ¹ ADI website: www.analog.com (Search) AD7142 (Go)
- ² ADI website: www.analog.com (Search) Touch Controller System Block Diagram (Go)
- ³ ADI website: www.analog.com (Search) AN-854 (Go)
- ⁴ http://www.analog.com/en/content/0,2886,760_1077_F107310,00.html#software