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 AD7142[1] 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.

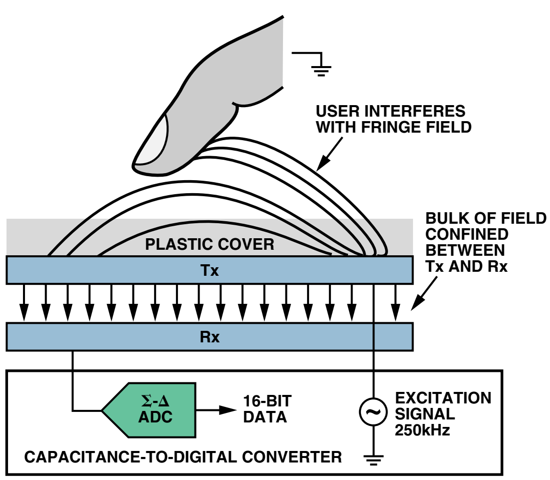

Figure 1. Sensing capacitance.

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.

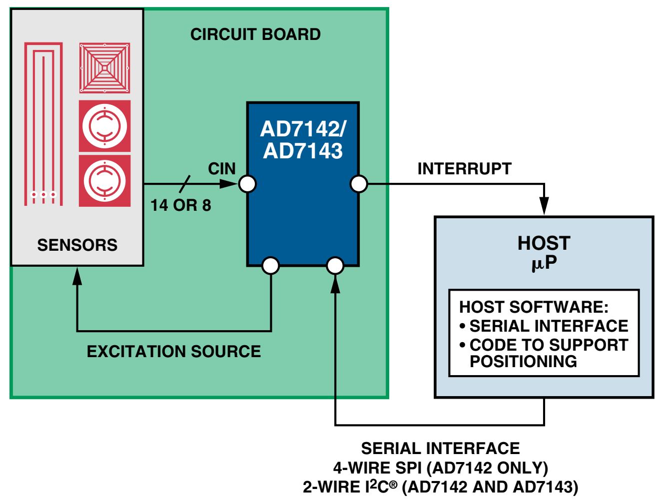

Figure 2. Three-part capacitance-sensing solution.

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 I^2C-compatible interfaces, has 14 capacitance-input pins. The AD7143, with its I^2C 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.

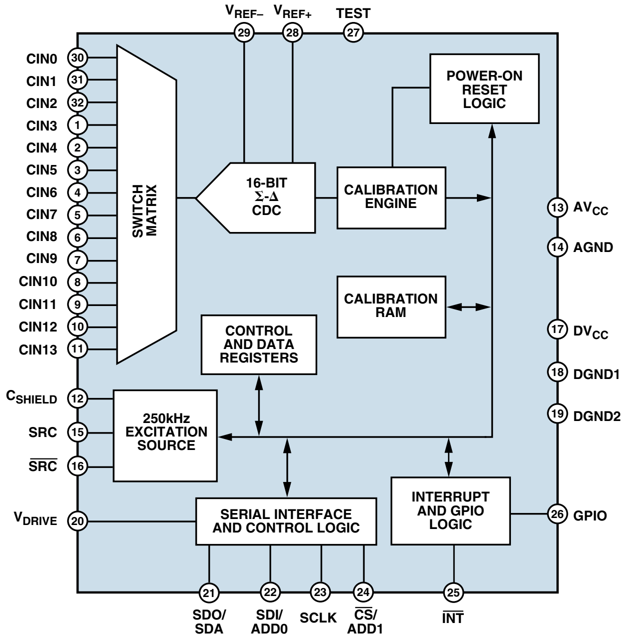

Figure 3. AD7142 block diagram.

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.

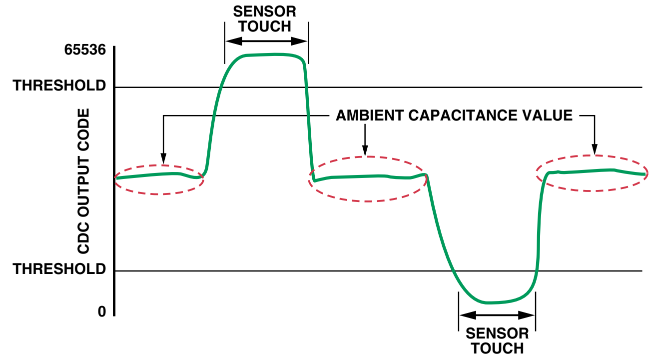

Figure 4. Sensor activation.

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.

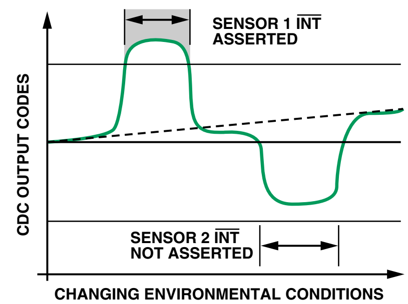

Figure 5. Sensor activation with changing ambient capacitance.

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.

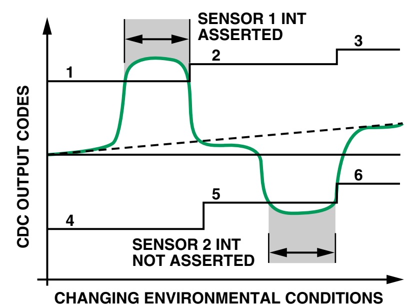

Figure 6. Sensor activation with auto-adapting thresholds.

***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-bars, joypads, and touchpad shapes can be laid out as traces on the sensor PCB. Figure 7 shows a selection of capacitance sensor layouts.

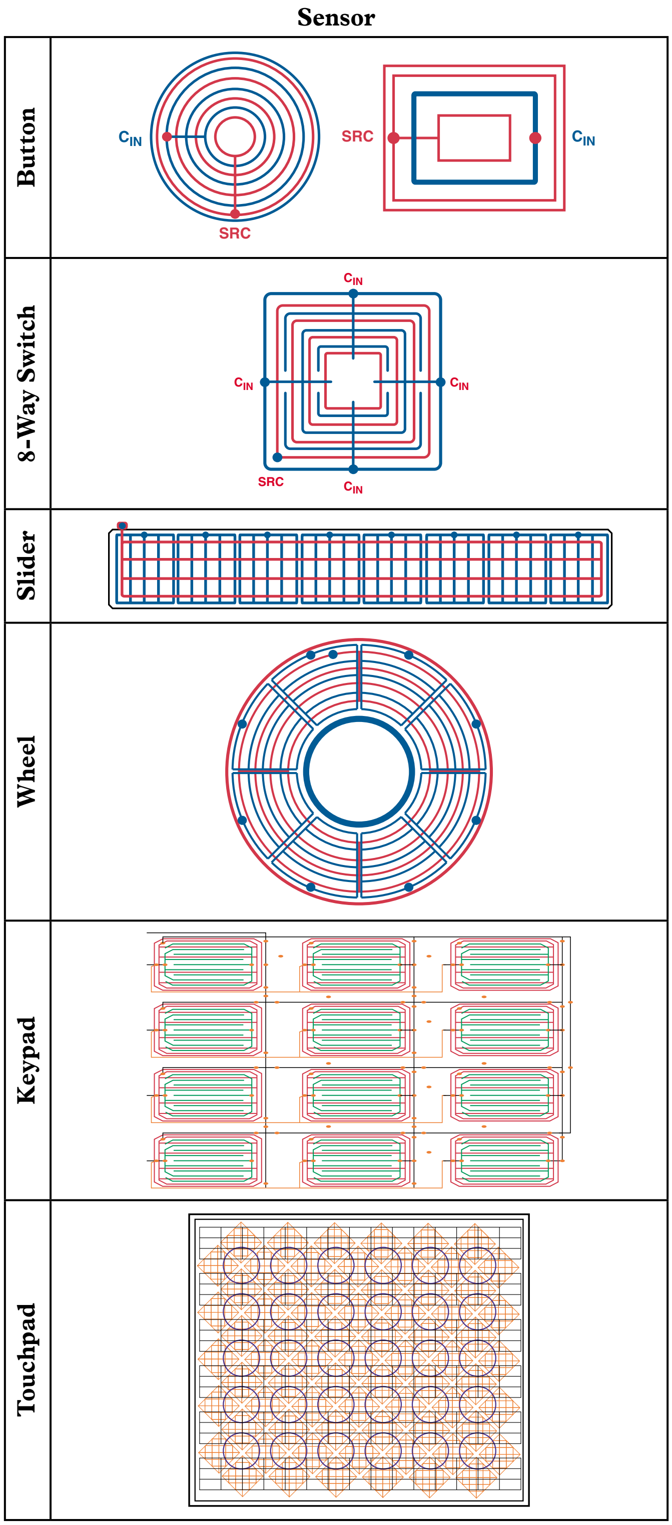

Figure 7. Selection of capacitance sensors.

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 joypad 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 joypad 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, 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.