Application Report

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Capacitive Proximity Sensing Using the FDC1004

David Wang

ABSTRACT

Capacitive proximity sensing can be implemented in a wide variety of applications with the use of TI's FDC1004 and with the flexibility of the sensor design in many system environments. Not only are there advantages of using capacitive proximity sensing compared to alternative detection methods, there are also guidelines to follow to ensure maximum performance and stability with the sensing system. This application note describes in detail the basics of proximity sensing and sensor topology considerations that affect various system parameters.

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1 Basics of Proximity Sensing

Unlike a parallel plate topology that works on the principles of the parallel plate capacitor, the topologies for proximity sensing use the fringing electric fields to measure the capacitance, as shown in Figure 1. The majority of proximity sensing applications uses either the parallel fingers or the isolated sensor topology. A shield on the bottom sides of the electrodes is common in most applications to reduce the noise and stray parasitic capacitances in the surrounding environment from affecting the measurements. For more information on shielding in capacitive sensing, refer to the *Capacitive Sensing: Ins and Outs of Active Shielding* application note (SNOA926).

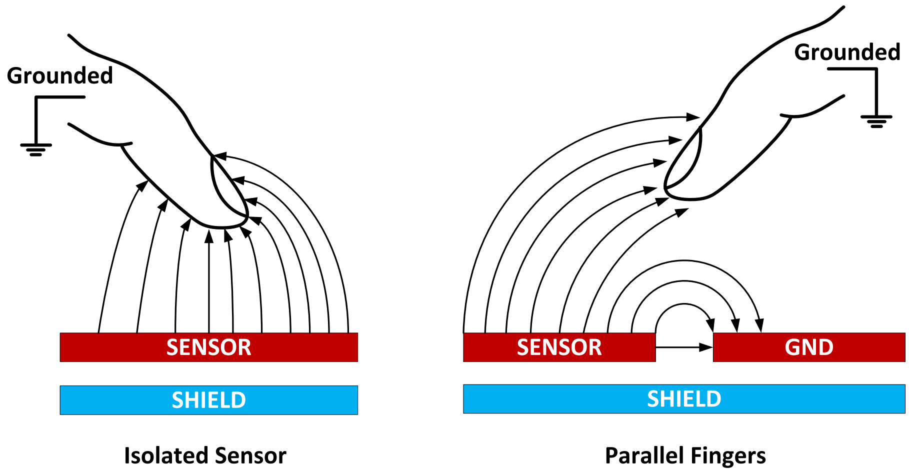

Figure 1. Fringing Electric Fields of the Isolated Sensor and Parallel Fingers Topology

Modeling the fringing effect and working through the calculations requires the use of a simulations tool. Figure 2 shows a Finite Element Methods Magnetics (FEMM) simulation of the electric flux density of the parallel fingers topology with a shield underneath. The purple regions in Figure 2 represent the highest density of the electric flux/fields. The density and intensity of the electric fields are highest in the region closest to the inner edges of the sensor and ground electrodes, and will exhibit the highest sensitivity. For example, a human finger (grounded target) in between the electrodes would contribute more towards the measured capacitance compared to the finger near the outer edges of either of the electrodes.

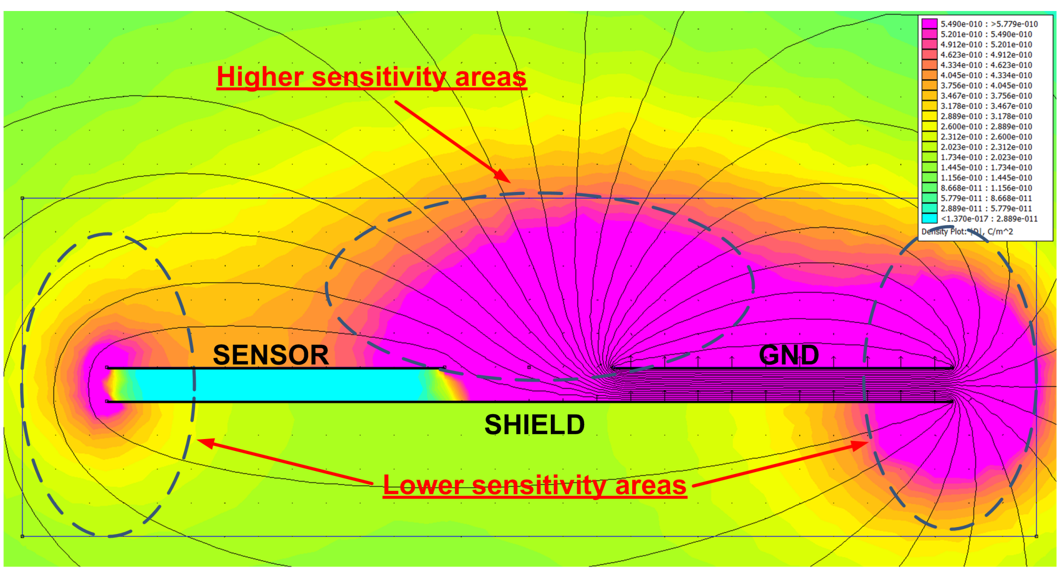

Figure 2. FEMM Simulation of the Electric Flux Density for the Parallel Fingers Topology

2 Sensor Topology Considerations

Two of the most common topologies for proximity sensing are the parallel fingers and the isolated sensor topology. Each has their own advantages and disadvantages based on the type of target that is being sensed.

2.1 Topology Comparison

Table 1 shows a summary of the best sensor topology for different system objectives and performance measurements.

Table 1. Comparison of Sensor Topologies

System Objective	Topology Selection	Why
Sensing grounded objects such as the human body	Isolated sensor	Isolated sensor allows the majority of field lines to terminate to the human body without GND electrode
Sensing ungrounded objects	Either	Dielectric and capacitance change is small compared to threshold detection
Higher proximity distance sensitivity	Isolated sensor	No dedicated GND electrode nearby to terminate field lines
Higher sensitivity and dynamic range	Isolated sensor	No dedicated GND electrode nearby to terminate field lines
Less risk for saturated measurements	Parallel fingers	Isolated ground plane

The isolated sensor is the best topology for various materials, sensing range detection, and sensitivity but the parallel fingers topology is capable of performing better in several conditions. One primary consideration in selecting the sensor topology is how the electrodes are coupled to a ground plane/electrode. The FDC1004 Capacitive-to-Digital Converter can accommodate a capacitive offset of up 100 pF. If the ground plane/electrode is coupled tightly so that the capacitance measured between the sensor electrode and ground is larger than the 100-pF maximum offset capabilities of the FDC1004, the capacitance measurements will always be saturated. Care must be taken in the size of electrodes and PCB stackup of the sensor design to avoid saturation due to a large capacitance value. The parallel fingers design can be less susceptible to saturation if an isolated ground plane is present in the system because the GND electrode and ground plane will not be common.

2.2 Grounded Versus Ungrounded Targets

There are countless target materials that can be sensed using the capacitive approach, but it is possible to group these targets into two categories: grounded targets and ungrounded targets. Within the ungrounded targets categories, low and high dielectric constant materials can be distinguished in separate categories. Table 2 shows the dielectric constants of common materials. Proximity sensing range for materials that have low dielectric constants (close to the dielectric constant of air) are limited to very small sensing ranges since the change in capacitance, dictated by the parallel plate capacitor equation, is small.

- Grounded target examples – human body, metal plates/cases
- Ungrounded target examples
  - Low dielectric constant – air, plastic, plexiglass, wood
  - High dielectric constant – various types of alcohol, water

Table 2. Dielectric Constants of Common Materials

Material	Dielectric Constant
Air	1
Alcohol	16–31
Drywall	1.4–2.9
Paper	2.3
PVC	3
Plexiglass	3.2
Silicon	11–12

Table 2. Dielectric Constants of Common Materials (continued)

Material	Dielectric Constant
Wood	2–6
Water at 20°C	80.4
Water at 50°C	78.5

2.2.1 Target and Topology Analysis

Both topologies have the capability to detect grounded objects. The main difference between the topologies with detecting grounded objects is the sensitivity of the system. Depending on the location of the nearest common ground potential source, the isolated sensor topology is typically more sensitive than the parallel fingers topology especially at longer distances away from the electrodes. For ungrounded targets, the two topologies have similar performance, but measurements can saturate for the isolated sensor if the coupling to a ground plane or ground source is larger than the 100-pF offset range of the FDC1004.

Figure 3 shows plots of capacitance versus range for grounded and ungrounded targets. For grounded targets, both topologies show good sensitivity, with the isolated sensor showing slightly better performance versus the parallel finger topology. For ungrounded targets, both topologies suffer a decrease in sensitivity, showing lower dynamic range and interception of the noise floor at much closer range. The FEMM simulation data shown in Figure 3 does not factor in other ground sources in the system. The simulation data only takes into consideration the target object and the electrodes: sensor, ground, and shield.

The FEMM simulations used a sensor size of 4 cm × 1 cm for the isolated sensor with a shield layer of the same size 1 mm directly below. The parallel fingers topology was paired with a GND electrode the same size with a 5-mm gap spacing between the sensor and GND electrode. The shield layer spanned from the outer edges of the two electrodes 1 mm below.

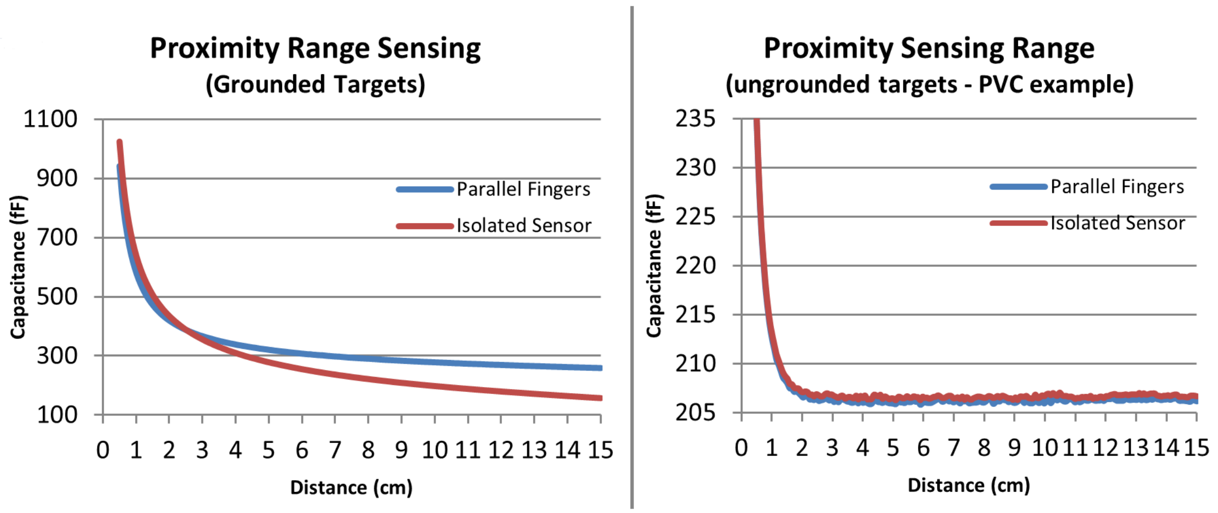

Figure 3. Capacitance vs Distance Comparison for Grounded and Ungrounded Targets

One advantage that the parallel fingers topology has over the isolated sensor with ungrounded targets is sensitivity based on location of the nearest ground potential source. If the ground source is much smaller than the electrodes and at a distance much greater than the electrodes, the isolated sensor will be less sensitive at shorter sensing ranges than the parallel fingers since the parallel fingers topology has a reference ground electrode paired with the sensor electrode.

2.3 Proximity Sensing Range and Sensitivity

Proximity sensing range and sensitivity is affected by a variety of factors: Sensor stackup, surface area of the electrodes, the nearest common ground potential source and external interference/noise, most of which are dependent on the system environment. Figure 4 and Figure 5 display the capacitance measurements over time with a human hand target 18 cm away from the parallel and isolated sensor topology. No filtering is performed on the data. Measurements were also taken from 19 cm away with the human hand target to compare against measurements with the hand 18 cm away. The data was collected using a sensor size of 2 cm x 1 cm on a standard two-sided copper PCB with the sensor electrode on top and shield electrode directly below. For the parallel fingers topology, a ground electrode with the same material type and dimension was placed 0.5 cm away from the sensor/shield electrode.

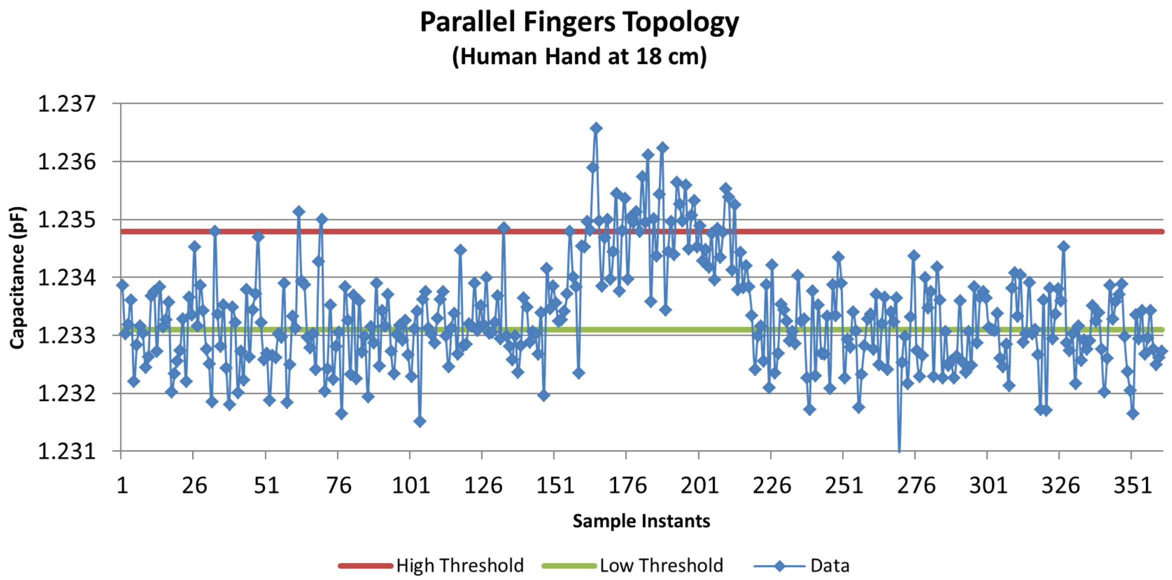

Figure 4. Parallel Fingers Topology Sensing Data

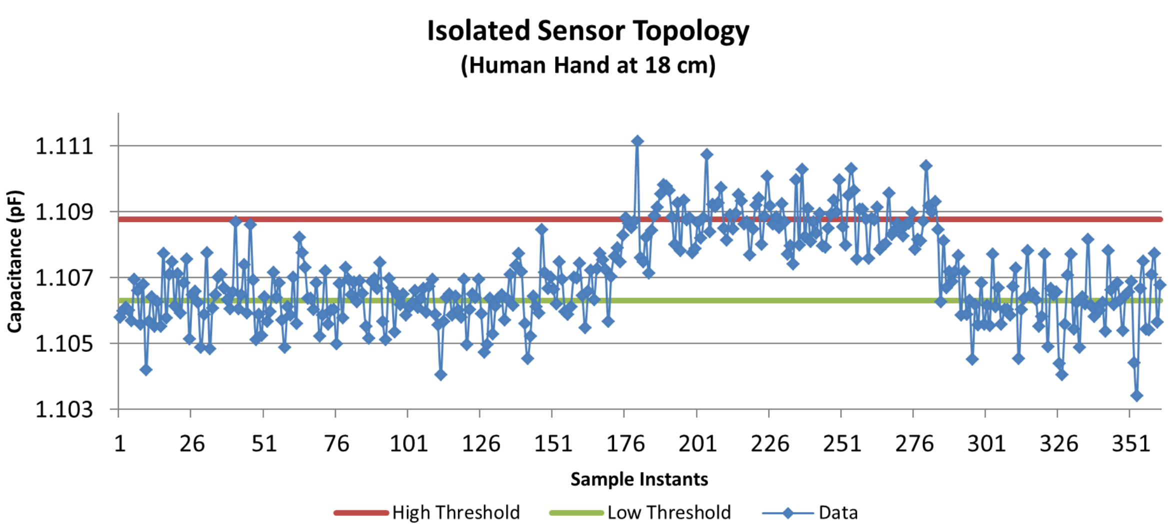

Figure 5. Isolated Sensor Topology Sensing Data

Table 3. Sensing Range Performance Comparison, Human Hand (Grounded Target)

	Parallel Fingers		Isolated Sensor	
	18 cm	19 cm	18 cm	19 cm
Average at 18/19 cm (pF)	1.2348	1.2344	1.1088	1.1084
Baseline Average (pF)	1.2331	1.2332	1.1063	1.1060
Change in Cap (fF)	1.7	1.2	2.5	2.4

Table 3 compares the sensing range performance between the parallel fingers and isolated sensor. The isolated sensor detects a human hand sooner with slightly more noise margin than the parallel fingers. For the parallel fingers case, the change in capacitance between the baseline average and the averaged measurements with the hand at 19 cm is too small to distinguish the difference between the noise and the target. A small moving average can be applied to the data in real time to help filter out the peak-to-peak noise along the signal and increase the confidence/reliability in detecting the target.

3 Proximity Sensing Range Performance Data

Proximity sensing range was measured for various sensor area sizes using a human hand (grounded) as the target. The sensing range is based on a detection threshold shift of 3 fF from the baseline measurement (no target present). A square two-layer, double-sided copper PCB with standard thickness (62 mils, 1-oz copper) was used for the sensor and shield electrodes. The shield electrode was the same size as the sensor electrode and directly underneath the sensor. Figure 6 shows the sensor stackup used to measure the sensing range.

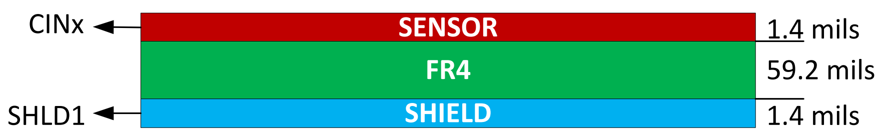

Figure 6. Sensor Stackup for Sensing Range

Table 4 shows sensing range versus target size measurements. A detailed graph of capacitance versus distance for the various sensor area sizes is shown in Appendix A.

Table 4. Proximity Sensing Range Based on Sensor Area Size

Sensor Area Size (cm^2)	Proximity Sensing Range (cm)
0.25	15
1	17
4	19
9	22
16	25
25	28
36	31
49	33
64	37
81	39
169	50

The size of the shield and distance to the sensor electrode significantly affects the sensing range. A shield that is larger than and closer to the sensor electrode reduces the sensitivity and maximum range, but it limits the amount of interference seen by the sensor electrode. A smaller shield further away from the sensor electrode has an opposite effect on sensitivity and detection range. For more information on shielding effects, refer to the *Capacitive Sensing: Ins and Outs of Active Shielding* application note (SNOA926).

Another consideration in determining the sensing range is the noise associated within system. The peak-to-peak and RMS noise seen on the sensor will increase as the sensor area size increases since it acts as a wideband antenna, picking up any interference present in the surrounding environment. Assuming Gaussian noise (normal distribution with mean value 0), the threshold level should be $> 3\ \sigma$ to achieve < 0.3% false detection rate, where σ is the standard deviation/RMS noise value. The standard deviation of the noise for the data above is 0.6 fF (at 100 SPS), so a detection threshold of > 1.8 fF is required. A 3- to 4-fF threshold is a valid condition with plenty of margin. As mentioned previously, a moving average on the real-time data can be used to help filter out the noise for a higher SNR and cleaner detection transition of the target for smaller threshold levels.

4 Typical Applications

Capacitive proximity sensing applications can be categorized based on use cases and target end equipment in short range (< 15 cm) and long range (up to 50 cm) detection. The features of the FDC1004 allow minimum sensor size for a given sensing distance and maximum sensing distance for a given sensor size.

	Short Range (< 15 cm)	**Long Range (up to 50 cm)**	**Collision Avoidance**	**Gesture Sensing**
Uses	display wakeup door activation presence detection	display wakeup door activation on/off activation	collision warning emergency brake/stop foreign object detection	User controls
Target End Equipment	**Automotive** car door sensor **Industrial** thermostat proximity sensors displays HMI **White Goods** refrigerator coffee machine soap dispenser	**Automotive** door kick sensor **Consumer** laptops computer screens **Industrial** HMI plumbing fixtures	**Automotive** Automatic doors and gates **Industrial** elevators garage doors automatic doors robots	**Automotive** doors Infotainment display **Consumer** Audio equipment MP3 players **Industrial** thermostat **White goods** dishwasher stove fan

Sensor Area Size Data

Figure 7 shows a detailed graph of capacitance versus distance for the various sensor area sizes.

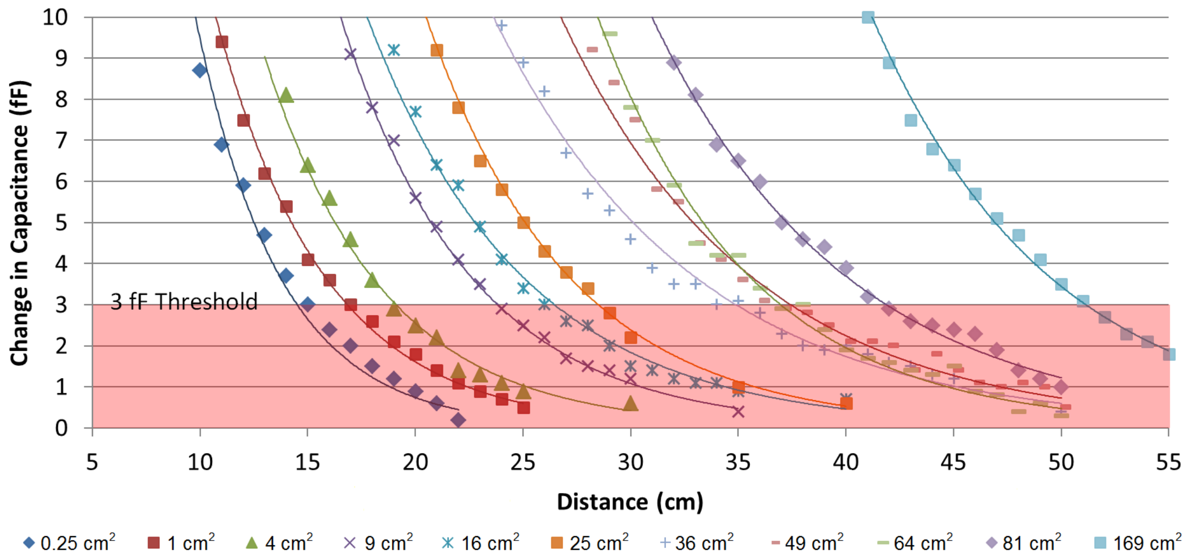

Figure 7. Capacitance vs Distance for Various Sensor Area Sizes

Revision History

Changes from Original (March 2015) to A Revision **Page**

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.