**TI Designs**

**Proximity Sensing of up to 30-cm Range With >15-dB SNR and Robust Capacitive Touch Reference Design**

**TI Designs**

Capacitive sensing-based touch button implementation is commonly used for the user interfaces in home appliances. Solutions based on low measurement resolution suffer from achieving reliable operation and faster user response. The TI Design TIDA-00474 hardware platform mitigates these challenges using EMI-resistant, high-resolution (up to 28 bits), high-speed capacitance-to-digital converters. The board is designed and tested in a cooker hood environment. Implementation details and test results are provided for capacitive button sensing and long range proximity sensing (up to 30 cm).

**Design Resources**

- **TIDA-00474** Design Folder
- **FDC2214** Product Folder
- **HDC1050** Product Folder
- **LMT01** Product Folder
- **TPS92513** Product Folder
- **MSP430G2553** Product Folder
- **TLV70433** Product Folder
- **TPD2E2U06** Product Folder
- **TPD6E001** Product Folder
- **TIDA-00472** Tools Folder
- **TIDA-00473** Tools Folder

**Design Features**

- Two Channels of High-Resolution (28 Bits) Proximity Sensing, Providing Tested Hardware Platform to Implement Gesture Recognition
- Six Capacitive Touch Button for Robust Touch Detection Against Moisture and Other Disturbances
- EMI-Resistant Architecture on Each Capacitive Sensing Channel to Protect the Detection Against Common Noise Sources
- Implements Proximity Sensing and Test Results With Copper on PCB and Indium Tin Oxide (ITO)-Based Implementations
- Low Power Consumption During Standby, Less Than 1-mA Current Consumption on DC Power Supply During Standby
- Highly Integrated LED Driver Circuit on Board With Digital Dimming, Overcurrent Protection, Over Temperature Protection and Adjustable Undervoltage Lockout Functions
- Provides Temperature Sensing and Humidity Sensing
- Fully Tested for Cooker Hood Equipment

**Featured Applications**

- Cooker Hoods
- Kitchen Appliances With Touch and Proximity Sensing Interfaces
1 Key System Specifications

Table 1. Key System Specifications

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SPECIFICATION</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitive sensor type</td>
<td>Copper on PCB, ITO sensor on glass</td>
<td></td>
</tr>
<tr>
<td>Input voltage</td>
<td>9-V nominal</td>
<td>Refer to TIDA-00473 for power supply design reference</td>
</tr>
<tr>
<td>Proximity sensing range</td>
<td>30 cm for static sensing</td>
<td></td>
</tr>
<tr>
<td>5 to 15 cm for gesture sensing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sample rate</td>
<td>&gt;30 SPS for proximity sensing</td>
<td></td>
</tr>
<tr>
<td>Calibration method</td>
<td>Dynamic baseline tracing</td>
<td></td>
</tr>
<tr>
<td>LED lamps voltage, current</td>
<td>350 mA</td>
<td></td>
</tr>
<tr>
<td>LED driver switching frequency</td>
<td>1 MHz</td>
<td></td>
</tr>
<tr>
<td>LED dimming PWM frequency</td>
<td>250 Hz</td>
<td></td>
</tr>
<tr>
<td>Operating temperature</td>
<td>–40°C to 85°C</td>
<td>Device specification</td>
</tr>
<tr>
<td>External sensors for cooker hood</td>
<td>Temperature and humidity</td>
<td></td>
</tr>
<tr>
<td>application</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standby current</td>
<td>0.89 mA on 3.3-V rail (with one-second wake-up period)</td>
<td></td>
</tr>
<tr>
<td>Tests</td>
<td>Proximity sensing performance tested with steam disturbances and inside an actual cooker hood</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Touch button performance tested with water on surface</td>
<td></td>
</tr>
<tr>
<td>Debugging communication port</td>
<td>UART or Spy-Bi-Wire™</td>
<td></td>
</tr>
</tbody>
</table>
2 System Description

This system is designed for the human machine interface application in cooker hood end equipment with proximity sensing, touch buttons, and dimmable LED lamp driving functions. Together with humidity and temperature sensors provided in this platform, one can implement the automatic speed control of the motor drive based on the temperature and the conditions of the air under the hood.

The proximity sensing feature of the design can be used for both wake-up from standby and gesture recognition functionalities to the end equipment. This feature is enabled by Texas Instruments' high-resolution capacitive-to-digital converter. The design is able to achieve a 30-cm distance of proximity sensing at static status. With multiple proximity sensors, the design also provides gesture recognition functions to the system, bringing a hand-free experience to the end users.

The design supports up to six touch buttons with EMI-robust capacitance sensing channels. The high resolution and EMI robust capacitance-to-digital converter enables the touch buttons to operate reliably in harsh environment conditions such as steam, water, and oily surfaces that are common in cooker hood applications.

A dimmable LED lighting function is also integrated into the design with two individual channels of highly integrated LED drivers, which can be controlled separately by digital PWM dimming.

This design guide covers component selection, quick starting with the firmware, and test results.

2.1 Capacitive Sensing

Capacitive sensing is becoming a popular technology to replace optical detection methods and mechanical designs for applications like proximity and gesture detection, material analysis, and liquid level sensing. The main advantages capacitive sensing has over other detection approaches are that it can sense different kinds of materials (skin, plastic, metal, liquid), it is contactless and wear-free, it has the ability to sense up to a large distance with small sensor sizes, the PCB sensor is low cost, and it is a low power solution.

Before discussing the equivalent circuit, some basic terms are introduced: electrode, traces, and capacitance.

An electrode is the physical conductive structure that a person interacts with. This structure is typically thought of as the copper on a printed circuit board (PCB), but can also be made of transparent materials such as indium tin oxide (ITO) or other conductive materials like silver. This design guide shows the performance of using an ITO electrode as a proximity sensor for cooker hood applications.

A trace is the conductive connection between the capacitance-to-digital convertor and the electrode. Similar to the electrode, the trace is typically a copper trace on a PCB or copper cable from the PCB to the sensor plate, but it could also be made of materials like ITO and silver.

Capacitance is the ability of a capacitor to store an electrical charge. A common form—a parallel plate capacitor—the capacitance is calculated by \( C = Q / V \), where \( C \) is the capacitance related by the stored charge \( Q \) at a given voltage \( V \). The capacitance (measured in Farads) of a parallel plate capacitor consists of two conductor plates and is calculated by:

\[
C = \frac{\varepsilon_r \times \varepsilon_0 \times A}{d}
\]

where

- \( A \) is the area of the two plates (in meters)
- \( \varepsilon_r \) is the dielectric constant of the material between the plates
- \( \varepsilon_0 \) is the permittivity of free space (8.85 \times 10 – 12 F/m)
- \( d \) is the separation between the plates (in meters)
Table 2 shows the dielectric constant of common materials:

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>DIELECTRIC CONSTANT ($\varepsilon_r$)</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Water steam</td>
<td>1</td>
<td>At 100°C, standard atmosphere</td>
</tr>
<tr>
<td>Water</td>
<td>78.46</td>
<td>25°C</td>
</tr>
<tr>
<td>Corn oil</td>
<td>2.6</td>
<td>37°C</td>
</tr>
<tr>
<td>FR-4</td>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td>Glass</td>
<td>7.6 to 8.0</td>
<td></td>
</tr>
<tr>
<td>Acrylic</td>
<td>2.8</td>
<td></td>
</tr>
</tbody>
</table>

The plates of a charged parallel plate capacitor carry equal but opposite charges spread evenly over the surfaces of the plates. The electric field lines start from the higher voltage potential charged plate and end at the lower voltage potential charged plate. The parallel plate equation ignores the fringing effect due to the complexity of modeling the behavior; however, the equation is a good approximation if the distance (d) between the plates is small compared to the other dimensions of the plates so the field in the capacitor over most of its area is uniform. The fringing effect occurs near the edges of the plates and, depending on the application, can affect the accuracy of measurements from the system. The density of the field lines in the fringe region is less than directly underneath the plates because the field strength is proportional to the density of the equipotential lines. This results in weaker field strength in the fringe region and a much smaller contribution to the total measured capacitance.

**Figure 1** displays the electric fields lines path of a parallel plate capacitor.
Figure 2 shows an equivalent circuit that provides a basis for understanding how the different aspects of the design contribute to the overall performance.

![Equivalent Circuit Diagram]

**Figure 2. Equivalent Circuit**

When describing the various capacitances found in a capacitive sensing solution, an equivalent circuit model can be helpful in visualizing the source of the different capacitances as well as the effect of each capacitance. Figure 2 is an example of an equivalent circuit to implement a single capacitive-sensing button.

Five different capacitances are shown in Figure 2. $C_{\text{ground}}$ is the capacitance between the local device under test (DUT) ground and earth ground. In some applications, local and earth ground are connected when the DUT uses mains power, but typically the local ground is capacitive coupled back to earth ground. In this design (the target system), the user interface board has local ground coupled with earth ground through a capacitive route.

$C_{\text{trace}}$ and $C_{\text{electrode}}$ are the capacitance between the trace and electrode structures back to the local ground. This capacitance is most directly affected by surrounding structures, typically ground pours, that are either on the same layer or on adjacent layers. Not shown is the capacitance between the trace and electrode structures and earth ground. Introducing these capacitances into the system brings higher bias capacitance to the measurement, which improves the static noise deviation level but also decreases the sensitivity of the system.

The capacitance $C_{\text{parasitics}}$ is a combination of the internal parasitic capacitance of the capacitance-to-digital convertor and any components within the circuit. This capacitance is also referenced to local ground. The touch capacitance, $C_{\text{sense}}$, is the parallel plate capacitance formed between the human body interaction and the electrode.

The goal of the design is to determine $C_{\text{sense}}$ with a maximum performance of sensitivity at a reasonable level of signal to noise ratio.
2.2 Capacitance-to-Digital Converter

The key specifications and care about of the capacitance-to-digital converter are low noise, EMI resistance, high resolution, and high-speed conversion. The device should be able to allow large input capacitance (nanofarads [nF]) to enable the use of remote sensors and tracking of environmental changes over temperature and humidity. The other desirable features are power saving modes and an interrupt feature on conversion completion. Features such as variable sensor excitation frequency make the system design very flexible.

For proximity detection, the detection range is limited by the minimum capacitance that can be measured. Therefore, a capacitance-to-digital converter with a deep sub-IF measurement capability can detect a wider range.

2.3 Humidity and Temperature Sensor

Measuring humidity and temperature for capacitive sensing applications helps to compensate the drift of passive component values. From a cooker hood system perspective, measuring the temperature and humidity levels under the hood would help to automatically adjust the suction motor speed and thereby achieve optimal efficiency and lower acoustic operation without much user intervention.

2.4 LED Lamp Controller

In cooker hoods, lighting is a common requirement, and the lighting can be based on incandescent lamps, Halogen lamps, or LED lamps. With the advent of high power, high luminous efficiency LEDs, using LED lamps has been increasing. LED lamps help achieve very high efficiency and easily controls PWM dimming. The common requirements of LED driver are integrating PWM control and MOSFETs, high frequency operation to help reduce the size of Inductor and capacitors, constant current control, and simple, efficient PWM dimming facility along with protections.
3 Block Diagram

Figure 3. System Block Diagram
4 Highlighted Products

The Robust, High-Resolution Capacitive Touch and Proximity Sensing User Interface With LED Lighting Design includes the following devices:

- **FDC2214**: EMI-Resistant 28-Bit Capacitance to Digital Converter
- **HDC1050**: Low Power, 3% Accuracy Digital Humidity Sensor with Integrated Temperature Sensor
- **LMT01**: 0.5°C Accurate 2-pin Temperature Sensor with a Pulse Train Interface
- **TPS92513**: 1.5-A Buck LED Driver with Integrated Analog Current Adjust
- **MSP430G2553**: MSP430G2x53 Mixed Signal Microcontroller
- **TLV70433**: 24-V Input Voltage, 150-mA, Ultralow Iq Low-Dropout Regulators
- **TPD2E2U06**: Dual-Channel High-Speed ESD Protection

For more information on each of these devices, see their respective product folders at [www.ti.com](http://www.ti.com).

4.1 FDC2214

This capacitance-to-digital converter belongs to the family of FDC2x1x devices from Texas Instruments.

In this device family of FDC2x1x, the FDC221x is optimized for high resolution, up to 28 bits, while the FDC211x offers fast sample rate, up to 13.3ksps, for easy implementation of applications that use fast moving targets. The very large maximum input capacitance of 250 nF allows for the use of remote sensors, as well as for tracking environmental changes over time, temperature and humidity.

The FDC2x1x family targets proximity sensing and liquid level sensing applications for any type of liquids. For non-conductive liquid level sensing applications in the presence of interferences such as human hands, the FDC1004 is recommended, which has integrated active shield drivers.

The FDC2x1x is a multi-channel family of noise- and EMI-resistant, high-resolution, high-speed capacitance-to-digital converters for implementing capacitive sensing solutions. The devices employ an innovative narrow-band based architecture to offer high rejection of noise and interferers while providing high resolution at high speed. The devices support a wide excitation frequency range, offering flexibility in system design. A wide frequency range is especially useful for reliable sensing of conductive liquids such as detergent, soap, and ink.

In contrast to traditional switched-capacitance architectures, the FDC2214 employ an LC resonator, also known as LC tank, as a sensor. The narrowband architecture allows unprecedented EMI immunity and greatly reduced noise floor when compared to other capacitive sensing solutions. Using this approach, a change in capacitance of the LC tank can be observed as a shift in the resonant frequency. Using this principle, the FDC is a capacitance-to-digital converter that measures the oscillation frequency of an LC resonator. The device outputs a digital value that is proportional to frequency. This frequency measurement can be converted to an equivalent capacitance.

**Figure 4. FDC2x1x Simplified Schematic**
4.2 **HDC1050**

The HDC1050 is a digital humidity sensor with an integrated temperature sensor that provides excellent measurement accuracy at very low power. The HDC1050 operates over a wide supply range and is a low-cost, low-power alternative to competitive solution in a wide range of common applications. The humidity and temperature sensors are factory calibrated.

Features of the device include:
- Relative humidity accuracy ±3% (typical)
- Temperature accuracy ±0.2°C (typical)
- 14-bit measurement resolution
- 100-nA sleep mode current
- Average supply current:
  - 710 nA at 1 SPS, 11-bit RH measurement
  - 1.3 μA at 1 SPS, 11-bit RH and temperature measurement
- Supply voltage: 2.7 to 5.5 V
- Small 3x3-mm device footprint
- I²C interface

**Figure 5. HDC1050 Simplified Schematic**
4.3 **LMT01**

The LMT01 is a high-accuracy, 2-pin temperature sensor with an easy-to-use pulse count interface, which makes it an ideal digital replacement for PTC or NTC thermistors both on and off board in automotive, industrial, and consumer markets. The LMT01 digital pulse count output and high accuracy over a wide temperature range allow pairing with any MCU without concern for integrated ADC quality or availability while minimizing software overhead. TI's LMT01 achieves flat ±0.5°C accuracy with very fine resolution (0.0625°C) over a wide temperature range of –20°C to 90°C without system calibration or hardware or software compensation.

Unlike other digital IC temperature sensors, the LMT01’s single wire interface is designed to directly interface with a GPIO or comparator input, thereby simplifying hardware implementation. Similarly, the LMT01’s integrated EMI suppression and simple 2-pin architecture makes it ideal for on-board and off-board temperature sensing. The LMT01 offers all the simplicity of analog NTC or PTC thermistors with the added benefits of a digital interface, wide specified performance, EMI immunity, and minimum processor resources.

![Figure 6. LMT01 Simplified Schematic](image-url)

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**Proximity Sensing of up to 30-cm Range With >15-dB SNR and Robust Capacitive Touch Reference Design**

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4.4 **TPS92513**

The TPS92513 and TPS92513HV are 1.5-A step-down (buck) current regulators with an integrated MOSFET to drive high current LEDs. Available with 42-V and 60-V input ranges respectively, these LED drivers operate at a user selected fixed-frequency with peak-current mode control and deliver excellent line and load regulation.

The TPS92513/TPS92513HV LED drivers feature separate inputs for analog and PWM dimming for no compromise brightness control achieving contrast ratios of greater than 10:1 and greater than 100:1, respectively. The PWM input is compatible with low-voltage logic standards for easy interface to a broad range of microcontrollers. The analog LED current set point is adjustable from 0 V to 300 mV using the IADJ input with an external 0 V to 1.8 V signal.

For multi-string applications using two or more TPS92513/TPS92513HV LED drivers, the internal oscillator can be overdriven by an external clock ensuring all of the converters operate at a common frequency, thereby reducing the potential for beat frequencies and simplifying the system EMI filtering. An adjustable input undervoltage lockout (UVLO) with hysteresis provides flexibility in setting start/stop voltages based upon supply voltage conditions.

The TPS92513 includes cycle-by-cycle overcurrent protection and thermal shutdown protection. It is available in a 10-pin HVSSOP PowerPAD™ package.

*Figure 7. TPS92513 Simplified Schematic*
4.5 MSP430G2553

The TI MSP430 family of ultra-low-power microcontrollers consists of several devices featuring different sets of peripherals targeted for various applications. The architecture, combined with five low-power modes, is optimized to achieve extended battery life in portable measurement applications. The device features a powerful 16-bit RISC CPU, 16-bit registers, and constant generators that contribute to maximum code efficiency.

The digitally controlled oscillator (DCO) allows wake-up from low-power modes to active mode in less than 1 μs. The MSP430G2553 is a ultra-low-power mixed signal microcontroller with built-in 16-bit timers, up to 24 I/O capacitive-touch enabled pins, a versatile analog comparator, and built-in communication capability using the universal serial communication interface. In addition, the MSP430G2553 has a 10-bit analog-to-digital (A/D) converter.

Typical applications include low-cost sensor systems that capture analog signals, convert them to digital values, and then process the data for display or for transmission to a host system.

![Figure 8. MSP430G2553 Functional Block Diagram](image-url)
4.6 TLV70433

The TLV704 series of low-dropout (LDO) regulators are ultralow quiescent current devices designed for extremely power-sensitive applications. Quiescent current is virtually constant over the complete load current and ambient temperature range. These devices are an ideal power-management attachment to low-power microcontrollers, such as the MSP430.

The TLV70433 operates over a wide operating input voltage of 2.5 to 24 V. Thus, the device is an excellent choice for both battery-powered systems as well as industrial applications that undergo large line transients.

The TLV70433 is available in a 3×3-mm SOT23-5 package, which is ideal for cost-effective board manufacturing.

![Figure 9. TLV704 Functional Block Diagram](image-url)
4.7 TPD2E2U06

The TPD2E2U06 is a dual-channel low capacitance TVS diode ESD protection device. The device offers ±25-kV contact and ±30-kV air-gap ESD protection in accordance with the IEC 61000-4-2 standard. The 1.5-pF line capacitance of the TPD2E2U06 makes the device suitable for a wide range of applications. Typical application interfaces are USB 2.0, LVDS, and I2C.

Figure 10. TPD2E2U06 Simplified Typical Application Schematic
5 System Design Theory

This system is designed targeting the human machine interface application for cooker hood applications.

5.1 Capacitive Sensing Circuit Design

In contrast to traditional switched-capacitance architectures, the FDC2214 employs an LC resonator, also known as an LC tank, as a sensor. The narrowband architecture allows unprecedented EMI immunity and greatly reduced noise floor when compared to other capacitive sensing solutions.

Using this approach, a change in capacitance of the LC tank can be observed as a shift in the resonant frequency. Using this principle, the FDC is a capacitance-to-digital converter that measures the oscillation frequency of an LC resonator. The device outputs a digital value that is proportional to frequency. This frequency measurement can be converted to an equivalent capacitance.

Figure 11 shows the schematic of the proximity sensor circuits that contains the LC tank mentioned. The combination of the L and C values determines the LC resonation frequency as shown in Equation 2:

\[ F = \frac{1}{2\pi\sqrt{LC}} \]  

(2)

This design uses 6.5 MHz as the resonance frequency of the LC tank because this frequency is away from common noise sources. To achieve the 6.5-MHz LC tank frequency, an inductor of 18 µH and capacitor of 33 pF are used in the circuit.

Increasing the capacitance value on the capacitive sensing circuit will cause the static baseline capacitance (see Section 5.5.1) to be higher. This improves the noise to baseline reference ratio, thus making the system more robust to disturbances, but this also reduces the sensitivity of the sensing circuit. Therefore, consider selecting the baseline capacitance during the design according to different application conditions.

Also consider additional pin, trace, and wire capacitance on the capacitive sensing circuit. The parasite capacitance can be determined by checking the FDC2214 conversion result. This is described in Section 7.1 of the test results. With this design, the parasite capacitance of the board, wire and proximity sensor is about 21.8 pF. Together with the capacitor in the LC tank, they create a static capacitance of 54.8 pF.

Typically, an interaction of human body to the proximity sensor brings a difference of 10s to 100s of femtofarads (fF; 1 fF = 0.001 pF) on the capacitance sensed. The sensed capacitance may vary depending on the sensor size, distance of the sensing target, overlay material, and so on.
Therefore, one of the design challenges for proximity sensing is the ratio between the capacitance sensed and the static capacitance of the system. Minimizing the static capacitance of the system is one of the most commonly considered solutions, but it is difficult to achieve due to the nature of the electronic components, the wire, and, sometimes, the frame of the end equipment.

The FDC2214 addresses this problem very nicely with 28 bits of high resolution conversion results, providing an accurate reading on small changes of the sensed capacitance.

The conversion value of the FDC2214 can be translated into capacitance by Equation 3:

\[
C_{\text{SENSOR}} = \frac{1}{L \times (2\pi \times f_{\text{SENSOR}})^2} - C
\]

Where:

- \( C \) is the parallel sensor capacitance (capacitance of the LC tank).
- \( f_{\text{SENSOR}} \) is calculated by Equation 4:

\[
f_{\text{SENSOR}} = \frac{\text{CH\_FIN\_SEL} \times f_{\text{REF}} \times \text{Count}}{2^{28}}
\]

Where:

- \( \text{CH\_FIN\_SEL} \) is the "sensor frequency select" bit value in FDC2214 register, which is 1 in this design
- \( f_{\text{REF}} \) is the reference frequency of the channel which is 40 MHz in this design

With the equations above, translate the conversion result into capacitance. For example, if the conversion result is 36716045 (0x2303E0D) counts, the sensed capacitance on the sensor is 14.013 pF.

Do not populate (DNP) components in the schematic shown in Figure 11 are the optional components to enhance noise filtering when the circuit is to be used under harsh environment conditions (see SNOU138 for more information).
5.2 Sensor Design

5.2.1 Proximity Sensor Design

As shown in Equation 1, the sensor capacitance is related with the area of the plates of the capacitor. In this design, the proximity sensing circuit is used in a single-ended sensor configuration. The proximity sensor itself is one of the plates of the capacitor while the target object acts as the other plate of the capacitor. This means the larger the area of the sensor, the more sensitivity there will be.

Figure 12 shows a detailed graph of capacitance versus distance for the various sensor area sizes.

The target of this TI Design is to achieve proximity detection at a 30-cm distance; therefore, a sensor with area size of 47.6 cm² is designed to meet the specification. Figure 13 shows the dimension of the proximity sensor.

With a 5-cm height, this sensor can be implemented to most user interfaces of the island-type cooker hoods.
To expand the design to different types of cooker hoods, larger size of sensor is designed and tested. These sensors are with area size of 117.6 cm\(^2\), 10 cm high. They can be implemented in the wall-mounted cooker hoods with larger user interfaces.

Cooker hood types:

- **Island Type**
  
  An island hood is an obvious choice for a cooking island in a kitchen. Most island hoods are available for ducting out and recycling. Island cooker hoods usually have a slim user interface of 6 to 8 cm high.

![Figure 14. Island Type Cooker Hood](image)

- **Chimney Hoods, Wall-Mounted, and Vertical Type**
  
  These are installed against a wall and are not suitable for kitchen islands. The most well-known chimney hood has a pyramid shape, but there are more different styles in the market today. A “vertical hood” is a new kind of chimney hood that sits horizontally against the wall and angles outwards from the base to the top of the hood. This is ideal if the cook is tall and does not want head height restrictions.

  Chimney, wall-mounted, and vertical hoods usually have larger panel to interact with the user, in which larger size of sensors can be implemented.

![Figure 15. Wall-Mounted Type Cooker Hood With Inclined User Interface](image)
Many of the latest models of the cooker hoods are equipped with display units, and some even have LCD screens behind the front panel. This brings challenge to proximity sensor design since less space is left for conventional copper sensors.

This TI Design has test results with copper on PCB used as sensor and with ITO material, which provides good transparency as well as good sensitivity.

**Figure 16** shows a comparison of the data obtained using different sensors.

![Figure 16. Proximity Sensitivity of Different Sensors](image-url)
5.2.2 Touch Button Sensor Implementation

To implement the touch buttons, three variants of PCBs are developed with the copper areas of small, medium, and higher diameter, and the performance is validated.

Larger electrode sizes provide more sensitivity to a touch event and a larger touch effective area on the panel. However, with the same center distances between the buttons, large electrodes also bring more chances of false detection and interferences with the adjacent buttons when the user touches on the space between the buttons.

![Variant KEY-A](image1)

![Variant KEY-B](image2)

![Variant KEY-C](image3)

**Figure 17. Touch Button Variants**

All three variants have six touch button implementations on the board with the same center distance of 26.8 mm. They have different electrode area sizes: KEY-A with a 6-mm diameter, KEY-B with a 10-mm diameter, and KEY-C with a 15-mm diameter.

Providing a ground pour to the bottom layer can help reduce the noise floor on the sensing channel but also can decrease the sensitivity of the sensor. A hatched ground pour with less capacitance coupled to the electrodes is recommended.

Planes and pours near the electrode and trace must be connected to a potential and cannot be left floating or in a high impedance state. Such structures serve as a mechanism for noise coupling and are strongly discouraged.
With the high-resolution conversion result provided by the FDC2214, buttons with small sizes as in KEY-A variant (6-mm diameter) are already providing sufficient sensitivity to reliably detect a touch event. In the end application, the designer of the system can apply a larger decal over the electrodes of the buttons to guide user operation on the keypad as shown in Figure 19.

Gray area is the touch-effective area. Yellow is the electrode with LED through hole in the center. Blue is the finger touch on the buttons.

With same center distance, smaller buttons have better performance avoiding false touch on multiple buttons at the same time.

Figure 19. User Interaction With Buttons
5.3 **LED Driver Circuit Design**

For cooker hood applications, there are usually LED lamps installed under the hood on both sides. In most cases, the requirement for lighting capacity for a cooker hood is 200 lm. To meet this requirement, this design uses the MX3AWT-A1-0000-000e51 from CREE, which can provide a minimum of 100 lm at a 300-mA forward current. Two pieces of the MX3AWT-A1-0000-000e51 are implemented in the design with separate control circuit so the application can control each LED separately by digital dimming.

The LED driver implemented in the design is the TPS92513. Figure 20 shows the schematic of the LED driving circuit based on this device.

![Figure 20. Schematic of LED Driving Circuit](image)

The design requirements for each LED driving circuit as follows:

- **V\textsubscript{IN}** range of 8.1 to 12 V
- UVLO set to 8 V with 1-V hysteresis
- One LED output, **V\textsubscript{OUT}** = 3.7 V
- 0.365-A LED current (at **V\textsubscript{ISENSE}** = 300 mV for best accuracy)
- Switching frequency of 1 MHz
- LED current ripple of 5 mA or less

Following the design procedure guideline from *Section 9.4 Detailed Design Procedure* of *SLVSCX6*, the design uses a 0.1-μF ceramic capacitor with a 10-V or greater rating for **C\textsubscript{COMP}** (C1) and **C\textsubscript{BOOT}** (C3). Connect IADJ to VIN through a 10-MΩ resistor (R12) to clamp it at 1.8 V and provide an ISENSE voltage regulation point of 300 mV. Connect a 10-nF capacitor (C2) from IADJ to ground. Connect ISENSE to \(R_{\text{ISENSE}}\) through a 1-kΩ resistor (R2).
Calculate UVLO resistor value

Use the following equations to determine the values of R1 and R15.

\[
R1 = \frac{V_{HYS} \times \left[ V_{EN} - \left( 1 \times R_{ESD} \right) \right] - I_{HYS} \times R_{ESD} \times V_{START}}{I_{HYS} \times V_{EN}}
\]

(5)

\[
R2 = \frac{R1 \times \left[ V_{EN} - \left( R_{ESD} \times \left( 1 + I_{HYS} \right) \right) \right]}{\left( V_{STOP} - V_{EN} \right) + \left( 1 + I_{HYS} \right) \times \left( R1 + R_{ESD} \right)}
\]

(6)

Where:
- \( V_{HYS} = V_{START} - V_{STOP} = 1 \) V
- \( R_{ESD} = 10 \) K\( \Omega \)
- \( V_{EN} = 1.22 \) V
- \( I_{HYS} = 2.9 \) µA

This results in \( R1 = 268.23 \) K\( \Omega \), \( R15 = 45.77 \) K\( \Omega \), and in the hardware implementation, the design uses \( R1 = 267 \) K\( \Omega \) and \( R15 = 45.9 \) K\( \Omega \).

Calculate RT resistor (R3) value

\[
R_{RT} (\text{K}\Omega) = \frac{20633}{1000^{1.092}} = 109.13 (\text{K}\Omega)
\]

(7)

The design uses a 100-K\( \Omega \) resistor, which results in a 1.083-MHz switching frequency in theory.

Calculate ISENSE resistor (R4)

\[
R_{ISENSE} = \frac{300 \text{ mV}}{0.365 \text{ A}} = 0.822 \Omega
\]

(8)

The design uses a 0.82-Ω resistor with a 0.5-W power level.

Calculate inductor value (L1)

According to Equation 9, the inductor value can be determined:

\[
L = \frac{V_{OUT} \times \left( V_{IN} - V_{OUT} \right)}{I_R \times V_{IN} \times f_{SW}}
\]

(9)

Where:
- \( V_{OUT} = 4.07 \) V (3.7 V with a 10% margin)
- \( V_{IN} = 8.1 \) V (9 V with a -10% margin)
- \( I_R = 75 \) mA (as recommended by datasheet)
- \( f_{SW} = 1.083 \) MHz

The inductance results in 24.9 µH, with \( I_{RMS} = 0.366 \) A and \( I_{PEAK} = 0.403 \) A, LPS5015-333MR is selected with 33 µH and ISAT with 30% drop at 0.6 A, \( I_{RMS} \) of 0.7 A with 40°C rise.

Following the design procedure, select a 10-µF/50-V input capacitor as \( C_{IN} \) (C4) and 4.7-µF/16-V output capacitor as \( C_{OUT} \) (C3).

Calculate the diode power dissipation (D)

According to the calculation above, the average current on the output diode is:

\[
I_{D_{AVE}} = I_{LED} \times (1 - \text{Duty}) = 365.85 \text{ mA} \times (1 - 33.6\%) = 242.79 \text{ mA}
\]

(10)

\[
P_{DIODE} = I_{D_{AVE}} \times V_F = 242.79 \text{ mA} \times 0.7 \text{ V} = 170 \text{ mW}
\]

(11)

MBR0520LT1G with average forward current of 0.5 A is a good fit for the hardware implementation.
5.4 Control of Key Components

The key components in this design are the sensor devices of the FDC2214, HDC1050, and LMT01. This section covers how to control these devices from the MCU and user application.

5.4.1 Controlling FDC2214

The FDC2214 can be accessed via I2C interface with defined command sequence. (see Section 9.5 Programming of SNOSCZ5). The device works as slave on the I2C bus with configurable address by setting the ADDR pin low or high. (ADDR → Low: Address = 0x2A; ADDR → High: Address = 0x2B). The user may fix the ADDR pin level as shown in Figure 21:

![Figure 21. Schematic of FDC2214](image)

I2C bus signal lines (SDA and SCL) are open drain signals, pull-up resistors are required on these signal lines. Typically, 4.75-KΩ pullup resistors can be used. To avoid unexpected interference on the I2C bus signals, 33-pF capacitors to ground are recommended.

The device also provides a Shutdown (SD) control pin; when the SD signal is high, the device enters Shutdown Mode. The main purpose for the shutdown mode is to save the system power consumption; however, in the meantime, it disables the I2C logic of the device. With this, multiple FDC2x1x devices can be connected to the same I2C bus, even with same slave address.

Another merit brought by the Shutdown pin is that the internal logic of the device will get reset by entering the Shut Down mode. This provides users with error handling option when operation enters unexpected status.

When the Shutdown pin transits from high to low, the device will take a 2-ms (max) wakeup time, during which the I2C command will not be recognized. Also, entering Shutdown Mode will return all registers to their default state.

Initialize the device during Sleep Mode (Sleep Mode is also the default mode after powered or exited from Shutdown). Find an initialization sequence recommendation in Section 10.2.3.2 Recommended Initial Register Configuration Values of SNOSCZ5.

During normal operation, the application or MCU can check the status of registers of the FDC2214 to get the conversion results as well as error status of the device and each channel. The device provides an interrupt signal output pin (INTB) to send notifications to the application or MCU. The user can configure the triggering events of the INTB signal. It is also possible to check the register status and values periodically through the I2C bus without checking the status of INTB signal.

This design uses a periodic checking method to check the conversion results. With this method, the user may save one input interrupt pin on the MCU and keep the timing sequence of the application software not interrupted.
Figure 22 shows an operation flowchart that is implemented in this design from power up to normal operation of the FDC2214.

- Set FDC software driver to "initializing" mode
- Set SD low to enable FDC operation
- Initialize FDC control variables
- FDC initializing
- Re-initialize
- Setting applied
- Any error or power save
- FDC working
- FDC stops

Figure 22. FDC2214 Control Flowchart

With multiple FDC2214 devices in the system, the user can provide clock source from a single external crystal. In this design, 625L3C040M00000 from CTS electronic components is used as the clock source of the two FDC2214 devices in the system with a 40-MHz oscillation frequency. The clock signals are routed out from the crystal to the CLKIN pin of each FDC2214 device through a 33-Ω resistor.

Using this crystal, the MCU may also disable the oscillation by controlling the enable pin of the crystal to further save the power consumption of the system.

Figure 23 shows the schematic of the clock source of the FDC2214 devices in the design.

Figure 23. Clock Source of FDC2214 Devices
5.4.2 Controlling HDC1050

Like the FDC2214 devices, the HDC1050 can be accessed also through the I2C interface. In this design, the HDC1050 works as an off board humidity sensor, which is connected to the control board through a 4-pin connector.

Figure 24 shows the schematic of the HDC1050 sensor board.

After powering up, the HDC1050 is in sleep mode. In this mode, the HDC1050 waits for the I2C input, including commands to configure the conversion times, read the status of the battery, trigger a measurement, and read measurements. Once it receives a command to trigger a measurement, the HDC1050 changes the state from sleep mode to measurement mode. After completing the measurement, the HDC1050 returns to sleep mode.

The device is also internally equipped with a heater element. The heater is an integrated resistive element that can test the sensor or to drive condensation off the sensor. The heater can be activated using HEAT, bit 13 in the configuration register. The heater helps to reduce the accumulated offset after long exposure at high humidity conditions.

The following flowchart shows the control flow of the device:

---

**Figure 24. HDC1050 Sensor Board Schematic**

**Figure 25. Flowchart of HDC1050 Control**
5.4.3 Interfacing LMT01

The LMT01 temperature sensor used in this design is a high accuracy sensor based on pulse counting output method. This design connects the output of the LMT01 to a comparator input pin of the MSP430 MCU. Because the LMT01 output is a constant current output at high level of 112.5 to 143 µA and low level of 28 to 39 µA, to use the internal voltage reference of the comparator at 0.25 VCC (typ. 0.825 V), a 10-KΩ resistor to ground is used on the output pin of the LMT01 as shown in Figure 26. This generates the pulse sequence on the input pin of the MSP430 comparator with a high level of 1.125 to 1.43 V and low level 0.28 to 0.39 V, which is well fitting the detection range of the comparator.

![Figure 26. LMT01 Schematic](image)

To save system power consumption, the LMT01 is not constantly powered. The VP signal is connected to a GPIO of the MSP430, and in the software, the LMT01 is powered every one second for a single conversion.

The LMT01 takes up to 54 ms to convert the temperature and after that starting to send out pulses. The higher the temperature the more pulses is to be generated on the VN pin.

\[
\text{Temp} = \left(\frac{\text{PC}}{4096} \times 256^\circ\text{C}\right) - 50^\circ\text{C}
\]  

(12)

Where:
- PC is the pulse count
- Temp is the temperature reading

A conversion plus pulse train period of 104 ms maximum is guaranteed in the user software. This design keeps an interval of 110 ms for the total conversion.

The LMT01 can be powered down at any time to conserve system power. Use a power down wait time of 50 ms (minimum) before the device is turned on again.

5.5 Software Design

5.5.1 Proximity and Touch Detection

As explained in the previous sections, the proximity detection based on capacitance sensing mainly detects the difference between the reference capacitance and the capacitance measured currently. In the application, it is very difficult and impractical to have a fixed value as the reference capacitance due to the fluctuating environment factors, such as humidity, temperature, or even the possible potential changes on the metal case of the end equipment.

Therefore, monitoring and tracing the fluctuation on the environment factors is very important to minimize the possibility of false triggering or missed triggering on the proximity sensing detection.

**Baseline**— The reference capacitance baseline capacitance.

**Drift**— The fluctuation on the baseline capacitance caused by environmental factor changes but not by human interactions.

**NOTE:** In this document, capacitance sensed is described in the unit of counts, which is generated by the FDC2214 after each conversion. The relationship between capacitance and counts is described in Section 5.1.
This design introduces a dynamic reference capacitance (baseline capacitance) monitoring method by filtering the reading of the conversion results on the proximity sensing channels.

Figure 27 shows a simplified flow chart of the baseline detector in the software. The baseline detector uses a first-order filter with a configurable cutoff frequency to generate a stable baseline reference value. It also keeps monitoring the proximity sensing result to switch off recording once a valid event is detected. This forms a cross reference between the proximity detection result and the baseline detection value. Therefore, a delay unit is implemented to provide a hysteretic response to the baseline detector to prevent the actual proximity event from driving the baseline low before the switch for recording is triggered.

Because the drift caused by environmental factor changes happens rather slowly over time, typically over several seconds (which is shown in Section 7), the delay unit in the flowchart can be set to a delay of seconds. Set this value to 2 seconds.

![Figure 27. Baseline Detector Flowchart](image)

The proximity event detector of this design works in the way shown in Figure 28. The accumulation of the difference between the conversion result and the baseline value over a given number \( n \) of continuous samples is used to be compared with a pre-defined threshold to determine whether a proximity event is valid or not. And this value can be later on used to quantify the proximity level of the event.

Compared to the baseline drift, the proximity event is much faster. The detection is usually expected within 1 second. With the setting of the FDC2214, a sample rate of 30 SPS is expected. Therefore, according to difference use cases, the number of samples \( n \) can be selected up to 30.

![Figure 28. Proximity Event Detector Flowchart](image)

Depending on different use cases, the application is expected to have proximity event timeout requirement. To prevent the baseline detector and proximity event detector from being stuck in an active status, a timeout exit can be applied to the proximity detector module (as in this design).
Touch event detection on the buttons follow the same idea but with a faster response and higher threshold values to provide a timely response as well as to avoid false triggers. Also, as the regular button detection, filtering is applied to avoid multiple false triggers in one touch event. Figure 29 shows the flowchart of the touch button event recognition.

\[ C_{\text{SENSE}} - C_{\text{BASE}} > \text{Key}_\text{TH} \? \]

No press

Yes

Filter samples to avoid glitch

No glitch

No

Yes

Press detected

Figure 29. Touch Button Event Recognition

\( C_{\text{SENSE}} \) is the capacitance sensed on the button electrodes. \( C_{\text{BASE}} \) is the static baseline capacitance calculated on the same button over time. \( \text{Key}_\text{TH} \) is the pre-defined threshold for a valid touch event. A touch on the space between two buttons with ground pour on the bottom layer, or when water presents on the surface of the overlay, may result in both buttons having a valid reading as touched. This case has to be considered to avoid false operation.

This can be done by comparing the amplitude of both buttons and the one with higher reading is the button pressed by the user.
5.5.2 Gesture Recognition

This design implements two channels of proximity sensing circuits to achieve the gesture recognition function. The purpose of adding the feature to cooker hood applications is to provide end user experience of hand-free operations.

The proximity sensors are designed to be placed horizontally next to each other with a 20-mm distance. It is expected that the user triggers the gesture command at a distance within 15 cm to the sensors to avoid miss detection and false triggering. When the user waves a hand in front of the sensors in the detection range, a data pattern of reading is expected to be as shown in Figure 30:

![Figure 30. Gesture Command Pattern](image-url)
With properly tuned proximity level and timing thresholds, the application can detect the gesture command by the user. An example of the detection flow for the application is shown in Figure 31. In this flowchart, Pa and Pb are proximity levels detected on each of the two proximity sensors. D_TH is the proximity level threshold that can be set according to the application requirement, while t_TH, tout and t_OVER are the timing thresholds to determine the movement speed of the user gesture command.

Figure 31. Gesture Command Detection
6 Getting Started: Firmware

This section describes how the firmware work and how to adjust the parameter settings to perform customized tests.

6.1 Task Handler

A simple task handler is implemented in the firmware. When the program enters main routine, it performs an initialization of all the peripherals, driver modules, and tasks.

The task handler uses the internal watchdog timer of the MSP430 to generate a 0.5-ms interval and keeps ticking in the ISR of the watchdog interval interrupt. A 32-bit counter Global_Timing_Counter holds the counting of ticks in units of 1 ms.

In the main loop, taskHandler() is called to execute the active tasks at their pre-defined intervals. This firmware has defined three tasks: taskA runs with period of 2 ms; taskB runs with period of 10 ms; taskC runs every 1 second. To change the task period, the user can use the configTask().

Starting and stopping the execution of one task can be done by calling startTask() and stopTask() routines. When calling startTask(), the user is able to assign a start offset time to the task to avoid multiple tasks from being executed in the same time slot.

6.2 Configuring FDC2214 Registers

Source files drv_fdc2x14.c and drv_fdc2x14.h are provided for controlling the FDC2214 devices in this design and can be re-used to customized applications based on MSP430 MCUs. In drv_fdc2x14.c, the following function calls are implemented:

- **void fdc2x14Init(fdc2x14Control_t*)**
  This function initializes the set values of the FDC2214 registers into pre-defined global variables. Later on, the set values are to be written into the FDC2214 registers. The parameter of the function is a pointer to the data structure that holds the set values of the corresponding FDC2214 device.

- **uint16_t fdc2x14GetRegister(fdc2x14Control_t*, enum_fdcRegAddr_t)**
  This function returns the register value of the target register in the target FDC2214 device given by the parameters. The internal registers of the FDC2214 device are all with a 16-bit data length. Therefore, this function returns a 16-bit unsigned integer value, which can be later on cast into register bit map types.

- **void fdc2x14SetRegister(fdc2x14Control_t*, enum_fdcRegAddr_t, uint16_t)**
  This function sets the 16-bit unsigned integer value specified in the parameter into the target register of the target FDC2214 device.

- **void fdc2x14Handler(fdc2x14Control_t*)**
  The handler is to be executed in a task periodically. In the handler, the program determines the working mode of the target FDC2214 device and performs initialization, checking and reading the conversion results, and shutting down the device. In this design, this handler is called in the task with a 10-ms period.
In drv_fdc2x14.h, the register bit map as well as the register address enumerates to make coding with FDC2214 registers easier. An example of the register bit map is given in Figure 32:

```c
typedef union regSTATUS{
    struct
    {
        unit16_t CH3_UNREADCONV :  1; //0
        unit16_t CH2_UNREADCONV :  1; //1
        unit16_t CH1_UNREADCONV :  1; //2
        unit16_t CH0_UNREADCONV :  1; //3
        unit16_t RESERVED0 :  2; //4-5
        unit16_t DRDY :  1; //6
        unit16_t RESERVED1 :  2; //7-8
        unit16_t ERR_ALW :  1; //9
        unit16_t ERR_AHW :  1; //10
        unit16_t ERR_WD :  1; //11
        unit16_t RESERVED2 :  2; //12-13
        unit16_t ERR_CHAN :  2; //14-15
    }bit;
    uint16_t byte;
}regSTATUS_t;
```

**Figure 32. STATUS FDC2214 Register Bit Map**
6.3 Configuring HDC1050 Registers

Source files drv_hdc1050.c and drv_hdc1050.h control the HDC1050 device in this design and can be reused to customized applications based on MSP430 MCUs. In drv_hdc1050.c, the following function calls are implemented:

- `void hdc1050Init(void):` This function initializes the set values of the HDC1050 registers into pre-defined global variables. Later on, the set values are to be written into the HDC1050 registers.

- `void hdc1050SetConfiguration(regCONFIGURATION_t)` and `void hdc1050GetConfiguration(regCONFIGURATION_t*):` These two software driver level function calls set and get the configuration register of the HDC1050.

- `void hdc1050TriggerConversion(enum_hdcRegAddr_t):` Because the HDC1050 is, at default, working in sleep mode, the application needs to trigger the conversion of the HDC1050 with an I2C command. In this design, this function is defined as static.

- `void hdc1050ReadConversionResults(void):` This function reads out the conversion result on both humidity and temperature from the HDC1050 and converts the results into units of %RH and °C. In this design, this function is defined as static.

In drv_hdc1050.h, the register bit map as well as the register address enumerates to make coding with the HDC1050 registers easier. An example of the register bit map is given in Figure 33:

```c
//HDC1050 Register bit definitions
typedef union regCONFIGURATION{
    struct
    {
        uint16_t RESERVED0 : 8;  //0-7
        uint16_t HRES : 2;      //8-9
        uint16_t TRES : 1;      //10
        uint16_t BTST : 1;      //11
        uint16_t MODE : 1;      //12
        uint16_t HEAT : 1;      //13
        uint16_t RESERVED1 : 1; //14
        uint16_t RST : 1;       //15
    }bit;
    uint16_t byte;
}regCONFIGURATION_t;
```

Figure 33. CONFIGURATION HDC1050 Register Bit Map
7 Test Results

The tests of the design are performed both with the test bench shown in Figure 34 and on the cooker hood equipment.

Figure 34. Test Bench Setup

The control board is connected to the 5-cm ITO proximity sensor through a 40-cm wire. The sensor is attached to a 4-mm thick acrylic panel. Conversion results are read from the FDC2214 on the control board and sent to PC for data logging through an isolated USB-UART convertor.

The touch button interface is connected to the control board with a 4-mm thick acrylic panel as an overlay. Both the proximity sensor and touch button electrodes are attached to their overlay with 467MP tape from 3M.
The test on cooker hood equipment is performed with an existing cooker hood model from the market. Figure 35 shows the setup of the test taken.

Figure 35. Test Setup on Cooker Hood Equipment
7.1 Proximity

The hardware characteristic on proximity sensing circuit is tested both by reading the conversion results and by observation from the oscilloscope.

The test results are listed in Table 3:

Table 3. Static Parasitic Capacitance Built Up

<table>
<thead>
<tr>
<th>TEST CONDITION</th>
<th>AVERAGE COUNTS</th>
<th>EQUIVALENT CAPACITANCE (pF)</th>
<th>RESONANT FREQUENCY (OSCILLOSCOPE) (MHz)</th>
<th>EQUIVALENT CAPACITANCE (pF)</th>
<th>REMARK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor, wire, and probe are not present</td>
<td>36716045</td>
<td>14.01275973</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensor and wire are not present, probe on</td>
<td>35383424</td>
<td>17.62066189</td>
<td>5.278</td>
<td>17.51600370</td>
<td>3.6 pF</td>
</tr>
<tr>
<td>Sensor is not present, 40-cm wire is connected, probe on</td>
<td>34616252</td>
<td>19.88925446</td>
<td>5.157</td>
<td>19.91435362</td>
<td>2.3 pF</td>
</tr>
<tr>
<td>5-cm ITO sensor and 40-cm wire on, probe on</td>
<td>33997918</td>
<td>21.83058614</td>
<td>5.066</td>
<td>21.83241667</td>
<td>1.9 pF</td>
</tr>
<tr>
<td>5-cm ITO sensor and 40-cm wire on, probe on with palm of hand in front at 10-cm distance</td>
<td>33925504</td>
<td>22.06490777</td>
<td>5.058</td>
<td>22.00600553</td>
<td>0.2 pF</td>
</tr>
</tbody>
</table>

The test results listed here show the static parasite capacitance on the proximity sensing circuit of the board of this design is roughly 14 pF. However, with a 40-cm long wire (not shielded), an additional 2.3 pF is added to the channel. The equivalent capacitance formed by the sensor electrode and the static lab environment is roughly 1.9 pF.

The input capacitor of the passive probe of the oscilloscope is adding about 3.6 pF to the measurement and this has to be taken into consideration when probing the sensing circuit.

Figure 36 gives an example on the observation of the resonance frequency on the sensing circuit by the oscilloscope.

Figure 36. Resonance Frequency on Proximity Sensing Channel
The waveform is captured on CH1 of sensor 1 (U7) (TP21) against GND, with a 5-cm ITO sensor and 40-cm wire on, probe on with palm of hand in front at 10-cm distance.

Proximity sensing test is performed by data logging from the FDC2214 conversion results. The settings on the proximity sensing channels of FDC2214 device are:

- Continuous sampling (AUTOSCAN = false)
- Sensor full current activation (SENSOR_ACTIVATE_SEL = 0)
- External 40-MHz crystal (REF_CLK_SRC = 1)
- Deglitch at 10 MHz (DEGLITCH = 0x05)
- \( f_{\text{REFx}} = f_{\text{CLK}} = 40 \text{ MHz} \) (CHx_FIN_SEL = 1, CHx_FREF_DIVIDER = 1)
- \( I_{\text{DRIVE}} = 0.146 \text{ mA} \); \( V_{\text{pk}} = 1.76 \text{ V} \) (CHx_IDRIVE = 0x0F)

Figure 37 is an example on how the logged data presents the proximity events.

The data shows 3 times of a palm of the hand getting close to the sensor plate at an approximately 30-cm distance followed by 3 times of 25 cm and 3 times of 20 cm.

The performance is later measured by averaging the data logged and translate into \( \text{SNR}_{\text{POWER}} \) (signal to noise ratio) by the following equations:

\[
\text{Power of signal} = \frac{\sum_{i=0}^{n} (\text{Signal}_i - \text{Baseline})^2}{n}
\]

(13)

Where:
- \( n \) is the number of samples
- \( \text{Signal} \) (or \( \text{Noise} \)) is the conversion result logged in unit of counts
- \( \text{Baseline} \) is the static capacitance sensed in unit of counts

\[
\text{SNR}_{\text{POWER}} \text{ (dB)} = 10 \times \log_{10} \left( \frac{\text{Power of signal}}{\text{Power of noise}} \right)
\]

(14)

Typically in an application, it is preferred that the \( \text{SNR}_{\text{POWER}} \) to be at least 3 dB or above for the application to be able to recognize and capture the signal.
Figure 38 shows the SNR\textsubscript{POWER} performance of each sensor:

![Figure 38. SNR\textsubscript{POWER} of Sensors](image)

The horizontal axis of the chart is the proximity event distance in unit of CM while the vertical axis of the chart is the SNR\textsubscript{POWER} in unit of dB.

This result shows when the sensor is attached to the cooker hood, the SNR\textsubscript{POWER} dropped by approximately 10 dB. This is caused by the large metal case of the cooker hood behind the sensor electrode. It acts as the other plate of the parallel plate capacitor with large surface area collecting environmental disturbances.

As seen in this chart, with the high-resolution FDC2214 and the dynamic baseline detection algorithm running in the application, on a 5-cm ITO sensor installed on the cooker hood, still the design can achieve a good SNR\textsubscript{POWER} of around 15 dB for a 30-cm proximity event.

Data collected for the chart above are listed in Table 4:

<table>
<thead>
<tr>
<th>Sensor Configuration</th>
<th>30 cm</th>
<th>25 cm</th>
<th>20 cm</th>
<th>15 cm</th>
<th>10 cm</th>
<th>5 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-cm ITO on bench</td>
<td>20.85859</td>
<td>25.66200</td>
<td>33.63446</td>
<td>42.54063</td>
<td>48.88956</td>
<td>55.73754</td>
</tr>
<tr>
<td>5-cm ITO on hood</td>
<td>14.62094</td>
<td>20.77838</td>
<td>23.48066</td>
<td>27.39045</td>
<td>34.15781</td>
<td>45.78367</td>
</tr>
<tr>
<td>10-cm ITO on bench</td>
<td>18.21617</td>
<td>25.55279</td>
<td>37.91180</td>
<td>44.17950</td>
<td>51.53531</td>
<td>56.91011</td>
</tr>
<tr>
<td>10-cm copper on bench</td>
<td>21.99690</td>
<td>27.59546</td>
<td>35.57290</td>
<td>43.49316</td>
<td>50.77182</td>
<td>58.94755</td>
</tr>
</tbody>
</table>
With the high resolution signal readings, a hand waving from left to right gesture command in front of the user interface followed by right-to-left and repeated is detected by the capacitance-to-digital converter as shown in Figure 39. (CH0 is the reading from the sensor on the left and CH1 is from sensor on the right.)

The settings on the proximity sensing channels of the FDC2214 for gesture command are listed below:

- AUTOSCANN on CH0 and CH1 (AUTOSCANN = true, RR_SEQUENCE = 0)
- RCOUNT on both channels are set to 0xFFFF
- SETTLECOUNT on both channels are set to 0x400
- Sensor full current activation (SENSOR_ACTIVATE_SEL = 0)
- External 40-MHz crystal (REF_CLK_SRC = 1)
- Deglitch at 10 MHz (DEGLITCH = 0x05)
- \( f_{REFx} = f_{CLK} = 40 \text{ MHz} \) (CHx_FIN_SEL = 1, CHx_FREF_DIVIDER = 1)
- \( I_{DRIVE} = 0.146 \text{ mA}; V_{pk} = 1.76 \text{ V} \) (CHx_IDRIVE = 0x0F)

![Figure 39. Gesture Commands Seen From the Data Log](image-url)
7.2 **Touch Buttons**

The touch button test is performed on Key3 and Key4 of the 6-button touch circuit board. The settings on the touch button channels of FDC2214 device are listed as follows:

- Scan sampling on CH0, CH1, CH2, CH3 (AUTOSCAN = true)
- Scan sequence: CH0, CH1, CH2, CH3 (RR_SEQUENCE = 0x02)
- Sensor full current activation (SENSOR_ACTIVATE_SEL = 0)
- External 40-MHz crystal (REF_CLK_SRC = 1)
- Deglitch at 10 MHz (DEGLITCH = 0x05)
- Same settings on all channels
- Reference count = 0xffff
- Settle count = 0x400
- \( f_{REF} = f_{CLK} = 40 \text{ MHz} \) (CHx_FIN_SEL = 1, CHx_FREF_DIVIDER = 1)
- \( I_{DRIVE} = 1.006 \text{ mA}; V_{pk} = 1.70 \text{ V} \) (CHx_IDRIVE = 0x1C)

The board under test is structured with an overlay stack as described in Section 5.2.2. Figure 40 shows the conversion result data logging over a 150-second time period on one button with a 15-mm diameter electrode.

![Figure 40. Touch Button Press Data Log](image)

In Figure 40, the static status baseline conversion result is at an average level of 12287500 counts, which can be calculated back into capacitance of 386.76 pF using Equation 3 and Equation 4.

During the test, there are three button-press events happen to the button, and each press with duration of approximately 3.5 seconds. Touch press adds additional capacitance to the sensing circuit from 1.5 to 1.8 pF. The signal-to-noise ratio from the test data is 59.04 dB.

One of the common disturbances on the touch pads is the moisture on the surface, especially water, because it has a high relative permittivity of approximately 80 at 25°C standard atmosphere. Water on the surface adds an additional capacitance sensed to the sensing channel as well as introduces cross disturbances to the adjacent buttons.
The data log chart in Figure 41 shows the test result for two adjacent buttons with water on the surface (15-mm diameter electrodes).

![Data Log Chart](image)

**Figure 41. Touch Button Press Data Log With Water on Surface**

In this test, three presses on Key3 are followed by three presses on Key4, and three presses in the space between Key3 and Key4. The static status baseline conversion result is at an average level of 12271380 counts on Key3 (387.86 pF). When presses are performed on one button, the other button has a conducted disturbance with low amplitude (3000 counts or 0.2 pF). This disturbance can be easily filtered out by application software. When presses are performed in the space between the buttons, on both buttons, there is a larger false signal detected with relatively high amplitude (12500 counts or 0.85 pF). This false signal can also be determined by the application software by checking the signal on adjacent button at the same time.

**Figure 42** shows the test condition for the aforementioned test.
7.3 **LED**

The following waveforms show the LED current and dimming control signal from the MSP430 at 250 Hz. Channel 4 of the oscilloscope waveforms is the LED current and Channel 1 is the dimming control PWM from MSP430.

![LED Current and Dimming Signal at 50% Duty Cycle](image)

**Figure 43. LED Current and Dimming Signal at 50% Duty Cycle**

![LED Current and Dimming Signal at 10% Duty Cycle](image)

**Figure 44. LED Current and Dimming Signal at 10% Duty Cycle**
Figure 45. LED Current and Dimming Signal at 99% Duty Cycle
7.4 **Standby Current Consumption**

With a wakeup period of 1 second, the design is capable to handle the proximity sensing event detection for waking up the application. Therefore, standby current consumption test is done with a one-second wakeup period.

During the sleep mode of the system, the FDC2214 devices on board are in shutdown mode by setting the SD signals high, and at the same time the external oscillator (Y2) is disabled. All backlight LEDs and LED lights are turned off. The LMT01 temperature sensor is not powered and the HDC1050 is in sleep mode. The MSP430 is set in LPM0 mode during standby and is woken up by the internal watchdog timer at 0.5-ms interval. Power consumption is measured on R14 with J8 open.

In the following waveform, channel 2 is the voltage measured over R14.

![Waveform of Voltage Across R14](image)

**Figure 46. Voltage Across R14**

The average voltage over R14 when the system is in standby is 12 mV as shown in the waveform, since R14 is 20.06 Ω. This means the standby current on 3.3 V is 0.598 mA.

While the peak current consumption happens when the FDC2214 is turned on and started converting. The voltage measured is 183 mV, indicating a peak current consumption of 9.123 mA, but only over a period less than 10 ms.

The overall average current consumption on 3.3 V during standby mode of the system is only about 0.78 mA.
8 Design Files

8.1 Schematics

To download the schematics, see the design files at TIDA-00474.

Figure 47. Schematics Page 1
Figure 48. Schematics Page 2
8.2 **Bill of Materials**

To download the bill of materials (BOM), see the design files at TIDA-00474.

8.3 **PCB Layout**

To download the PCB layout, see the design files at TIDA-00474.

8.4 **Altium Project**

To download the Altium project files, see the design files at TIDA-00474.

8.5 **Gerber Files**

To download the Gerber files, see the design files at TIDA-00474.

9 **References**


10 **About the Author**

LEBO "RENTON" MA joined TI as a system engineer in Shanghai and supported Hercules and the C2000™ family since 2012. Renton came to TI from Renesas Electronics where he was a field application engineer and later a technical marketing for body applications in automotive market for MCUs for seven years. After joining TI, Renton designed firmware and core logic on modeling tools for automotive applications and residential air conditioning systems. Renton has bachelor degrees in electronic engineering and English from Dalian University of Technology.
Revision B History

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