TI Designs
Backlight and Smart Lighting Control by Ambient Light and Proximity Sensor

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TI Designs provide the foundation that you need including methodology, testing and design files to quickly evaluate and customize the system. TI Designs help *you* accelerate your time to market.

Design Resources

|	
TIDA-00373	Tool Folder Containing Design Files
OPT3001	Product Folder
FDC1004	Product Folder
HDC1000	Product Folder
MSP430FR5969	Product Folder
TLV713P	Product Folder
LM3630A	Product Folder
TPD2E2U06	Product Folder

TI E2E™ Community

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Design Features

- Detects Human Proximity Using Copper PCB Material or Other Conductive Materials
- Good Human Eye Spectral Matching
- <1% IR Response
- Optical Power Sensitivity (0.01 to 83,886 Lux)
- HDC1000 Humidity and Temperature Sensor
- Dynamically Adjusts Backlight Brightness
- UV Filter for Outdoor Use
- EM Connector for Wireless Solutions

Featured Applications

- Building Automation
- Proximity Detection
- Smart Thermostat
- Smart Lighting
- Control Panels
- Connector for Wireless Solutions
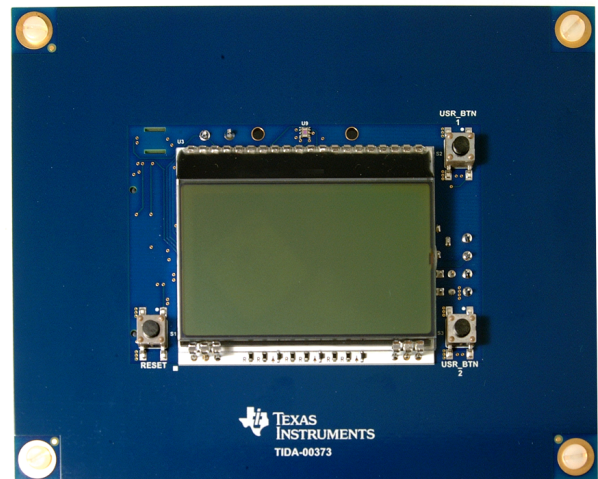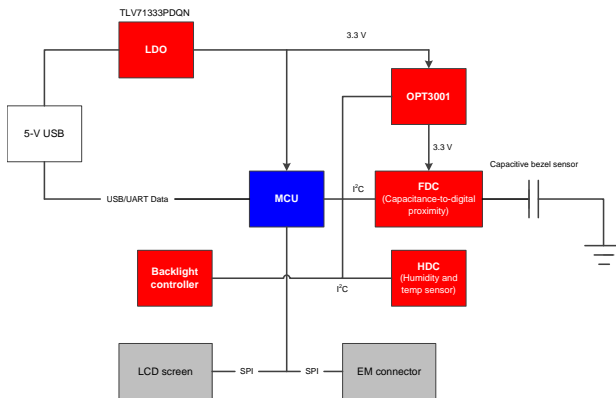
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1   Key System Specifications

Table 1. Key System Specifications

PARAMETER	SPECIFICATION	DETAILS
Sensor type	Copper PCB sensor	See Section 3.1.2
Input voltage	5 V nominal (VBUS from USB)	See Section 6.1
Lux sensing range	0.01 lux to 83 klux	
Capacitive sensing distance threshold	20 cm	See Section 4.4
Sample rate	10 Hz for proximity detection	See Section 5
Calibration method	User button for offset calibration	
Operating temperature	−20°C to 70°C (limited by LCD screen)	
Working environment	Indoor and outdoor	
Environmental compensation	Temperature and Humidity	
IEC ESD testing	Contact discharge: ±4 kV; Air discharge: ±8 kV	
IEC EFT testing	EFT: ±2 kV	
Radiated immunity testing	Tested from 25 to 300 kHz to determine motor/ and SMPS noise effects	
Debugging communication port	UART / EM Connector	

2 System Description

This system conserves power and extends the life of the backlight elements by dynamically adjusting a backlight's brightness in reference to the ambient light in the surrounding environment. Backlight brightness adjustments also allow a more comfortable viewing experience for the user. More power savings and backlight life can be achieved through a sleep or standby mode. The proximity wake up feature can sense a human is close and wakes up the system.

The optical light sensor made by Texas Instruments has good human eye spectral matching, which allows the system to adjust the backlight brightness to be most comfortable when viewed by the human eye. A simple algorithm determines the ideal backlight brightness when the backlight is activated.

Proximity wake up is enabled by Texas Instruments' capacitive-to-digital converter. A capacitive sensor located around the edge of the board provides a 360-degree sensing field around the board. Proximity detection works best when approaching the front of the device.

This design guide covers component selection, measurement theory, system calibration, and environmental compensation.

2.1 Ambient Light Sensor

An ambient light sensor allows the system to measure and react to changes in the lighting environment. The reference design can dynamically adjust the backlight brightness to best suit the viewing situation. An optimal viewing experience for the user can be easily implemented by adjusting the backlight brightness. A simple relationship between backlight brightness and ambient light can be programmed in software. In other systems, the collected ambient light data can be used in other ways as well.

2.2 Capacitance-to-Digital Converter

Using a capacitance-based proximity detection, a subsystem requires high resolution and low noise capacitance measurements to detect proximity using capacitance-to-digital technology. To determine if a person is close to the sensor, the proximity detection subsystem must be able to detect any capacitive changes above the baseline measurements. As the resolution for the capacitance measurement increases and the noise decreases, the proximity detection range and repeatability increases.

Another consideration for the selection of the capacitance-to-digital converter is the ability to handle measurement changes due to varying environmental conditions. This TI Design uses two methods to mitigate environmental variations: a separate environmental sensor (Section 2.3) and software filtering (Section 5.1).

The four-channel FDC1004 capacitance-to-digital converter combines unique features and functions with low power and 16-bit noise performance over a ±15-pF range to make it easy for designers to use capacitive sensing to increase the intelligence and awareness of their systems. The device can support an offset capacitance up to 100 pF, allowing for remote sensing in harsh environments or where electronics cannot be located. The device also includes a strong shield driver to help minimize interferers, to help focus the sensing direction, and to reduce the system performance impact of temperature variations. Finally, the FDC1004 allows an external offset capacitance to track environmental changes or to automatically correct for drift in the system over time.

2.3 Proximity and Environmental Sensor Design

The capacitance-to-digital converter technology from TI can operate with a wide variety of sensor geometries and conductive materials. This TI Design uses two rectangular bezel sensors: one is perfectly rectangular, and the other has a few more corners on the back side but is still basically rectangular. Because the FDC1004 device is simply measuring capacitance to ground of a sensor plate, and as long as the sensor material is conductive, there is no specific requirement for geometry or material. The overall sensor area does impact the effective sensing range. Therefore, this TI Design is an example for incorporating capacitance-to-digital technology for proximity detection into industrial end equipment with a high degree of design flexibility.

The actual sensor geometry (rectangular bezel) selected emulates a small industrial control panel, which typically contains a display or control in the middle of the device housing. The range of proximity detection is correlated to the size of the capacitive sensor. As the sensor size increases, the distance at which proximity can reliably be detected also increases. The total area of the copper PCB proximity sensor is 86 cm^2. The proximity sensor has a "shield" of an identical geometry. The purpose of these shields is to reduce effects of electromagnetic interference (EMI) and to direct the sensors to look in only one direction. The shield is also used to help minimize temperature and humidity effects on the measured capacitance due to PCB expansion or contraction.

To reduce the effects from environmental variations on the proximity measurements, this TI Design has an environmental sensor located on the design's backside. This environmental sensor also has a shield, which prevents it from seeing any capacitive changes due to human presence. Therefore, because the environmental sensor on the backside of the board and the proximity sensor on the topside of the board "see" the same environmental conditions, the FDC1004 measures the difference between the two, effectively eliminating the effects due to environmental variations. In this TI Design, the environmental sensor does not have an identical geometry to the proximity sensor, as shown in Figure 1. This sensor requires characterization over environmental changes as well as firmware correction because the different geometries do not respond in an identical manner. This characterization and correction is described in more detail in Section 4.4.
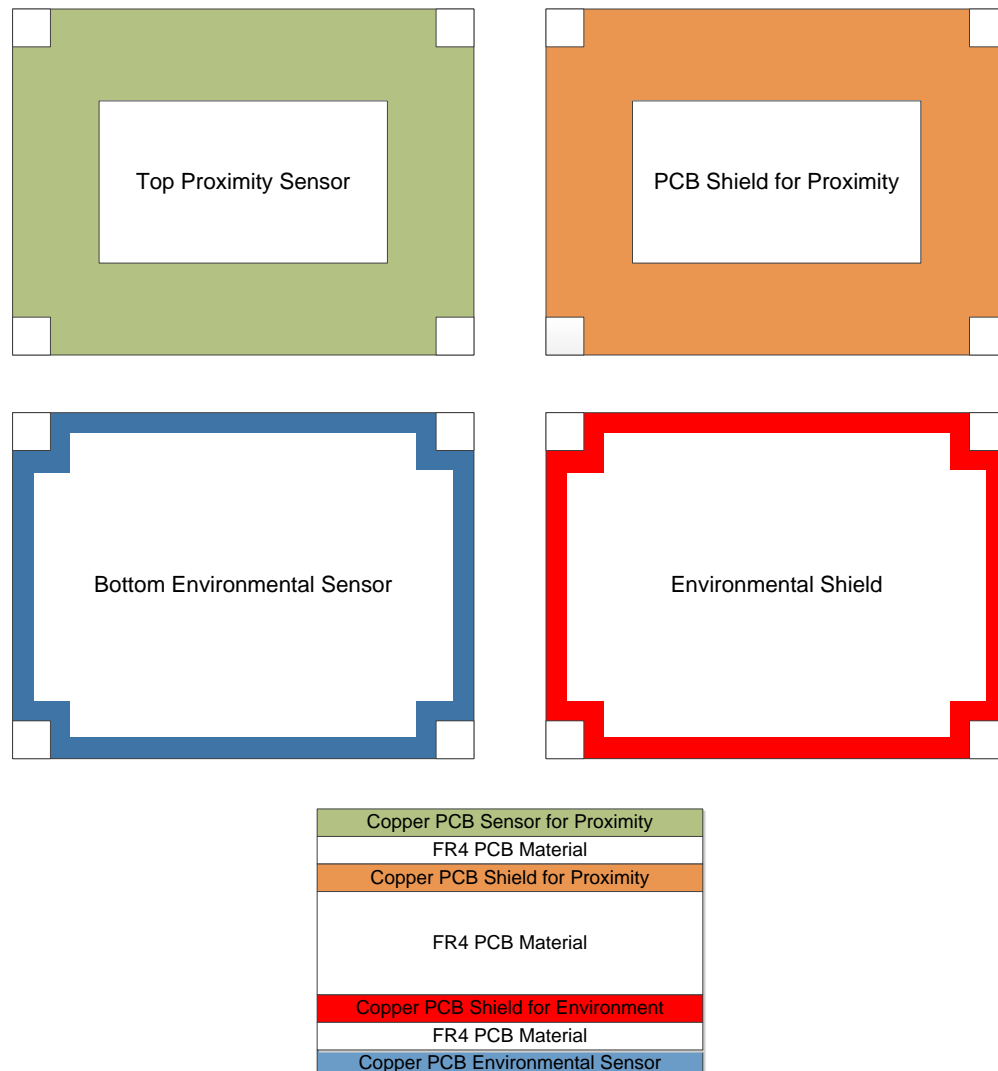

Figure 1. Sensor Geometries

2.4 Humidity and Temperature Sensor

An integrated humidity and temperature sensor decreases complexity of system design and overall foot print of finished product. With one read command, the temperature and humidity can be collected. The use of a single device saves power and decreases communication time and cycles needed to collect necessary information.

Humidity and temperature data is important for two reasons. With the data collection and connected nature of this design, the device can act as a sensor node and transmit the environment data to a gateway or to another device that can communicate this information over the web. Second, the environment data allows for temperature or humidity compensation if the need arises.

2.5 Microcontroller

The Precise Backlight and Smart Lighting Control reference design has a few microcontroller requirements because the rest of the parts are low power and easy to control. Only one I^2C bus is necessary to communicate with the various sensors and the backlight controller because each has a unique address. One SPI bus is used to control the LCD screen. A UART is used purely during debug and testing, but is a nice option to have. To demonstrate the technology of Texas Instruments, this design uses a MSP430™ microcontroller. The MSP430FR5969 meets all listed design requirements and is low power.

The MSP430FR5969 microcontroller uses FRAM memory instead of flash (SLAT151), which consumes less power for the entire system. In addition, the MSP430FR5969 device has eUSCI modules for I^2C, SPI, and UART, all used in this TI Design. Finally, the MSP430FR5969 device incorporates EnergyTrace++™ technology, which is helpful during system debugging.

EnergyTrace technology for MSP430 microcontrollers is an energy-based code analysis tool that measures and displays the application's energy profile and helps to optimize it for ultra-low-power (ULP) consumption. This technology implements a new method for measuring MCU current consumption. Power is traditionally measured by amplifying the signal of interest and measuring the current consumption and voltage drop over a shunt resistor at discrete times.

In debuggers that support EnergyTrace technology, a software-controlled DC-DC converter generates the target power supply. The time density of the DC-DC converter charge pulses equals the energy consumption of the target microcontroller. A built-in calibration circuit in the debug tool defines the energy equivalent for a single charge pulse. The width of each charge pulse remains constant. The debug tool counts every charge pulse and the sum of the charge pulses are used in combination with the time elapsed to calculate an average current. Using this approach, even the shortest device activity that consumes energy contributes to the overall recorded energy.

2.6 Backlight Controller

A simple low-power backlight controller is necessary to save power and enable the dimming features of the LCD backlight on the reference design. The backlight controller chosen has 255 different brightness levels; this decreases the overhead operating operations needed compared to other controllers that use pulse width modulation (PWM) signals to control LED brightness levels. This backlight controller can also use a PWM signal to control the brightness if more customization is needed. It is easy to send commands over I^2C to control the brightness level.
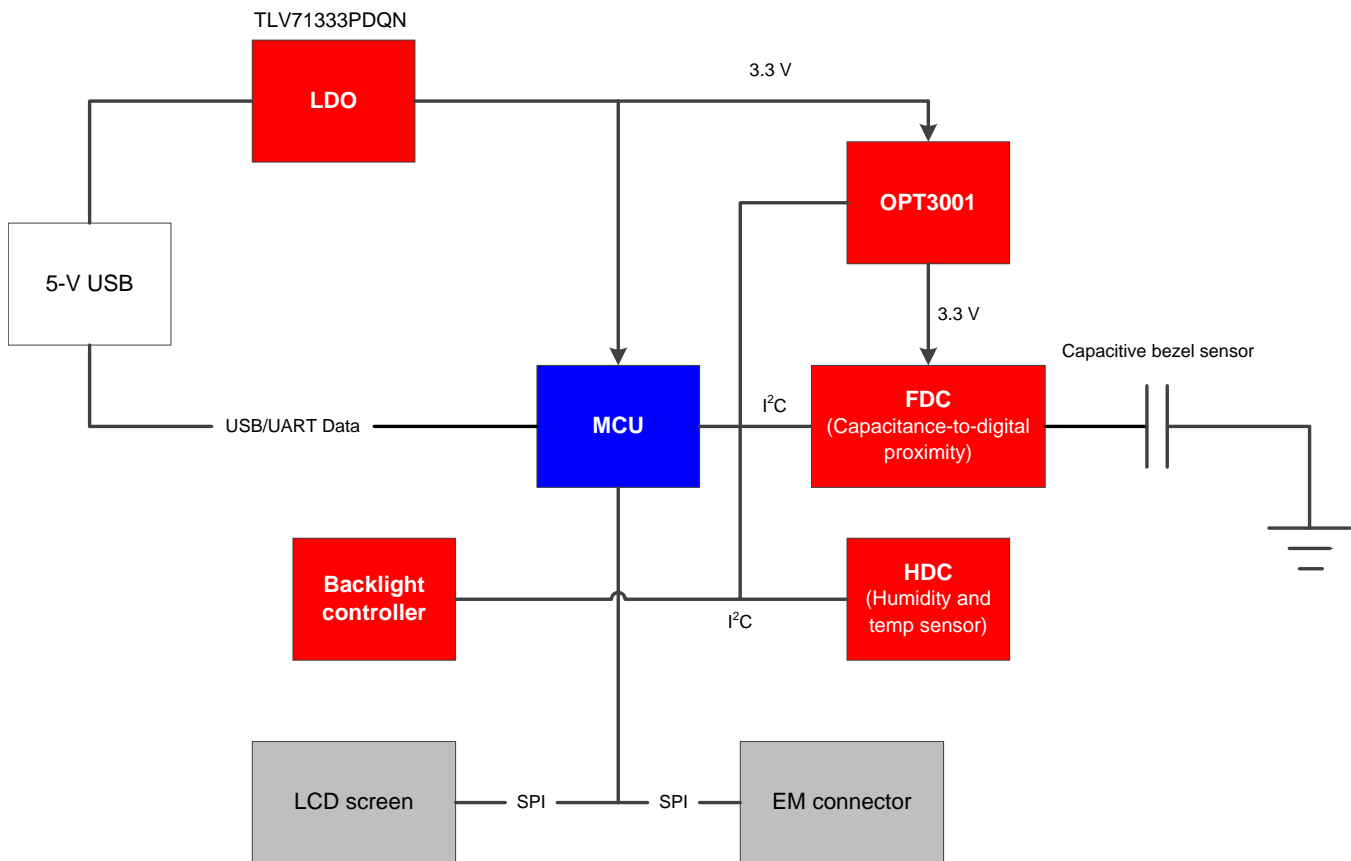
3 Block Diagram

TLV71333PDQN

Figure 2. TIDA-00373 Block Diagram

3.1 *Highlighted Products*

The Backlight and Smart Lighting Control reference design features the following devices:

- OPT3001: Single-chip lux meter, measuring light intensity as visible by the human eye with IR rejection
- FDC1004: Four-channel capacitance-to-digital converter for capacitive sensing solutions
- HDC1000: Digital humidity sensor with integrated temperature sensor
- MSP430FR5969: 16-MHz ULP microcontroller featuring 64-KB FRAM, 2-KB SRAM, 40 I/O
- TLV71333P: Low quiescent current LDO with excellent line and load transient performance
- LM3630A: High-efficiency, dual-string white LED driver
- TPD2E2U06: Dual-channel, ultra-low capacitance ESD-protection device

3.1.1   OPT3001

The OPT3001 device is a sensor that measures the intensity of light. The spectral response of the sensor is tightly matched to the photopic response of the human eye and includes significant infrared rejection. The OPT3001 is a single-chip lux meter, measuring the intensity of light as seen by the human eye. The precision spectral response and strong IR rejection of the device enables the OPT3001 to accurately measure the intensity of light regardless of its source. The strong IR rejection also aids in maintaining high accuracy when industrial design calls for mounting the sensor under dark glass for aesthetics. The OPT3001 is designed for systems that create light-based experiences for humans, and an ideal preferred replacement for photodiodes, photoresistors, or other ambient light sensors with less human eye matching and IR rejection. The small form factor (2.0 × 2.0 × 0.65 mm) allows the device to fit almost anywhere.
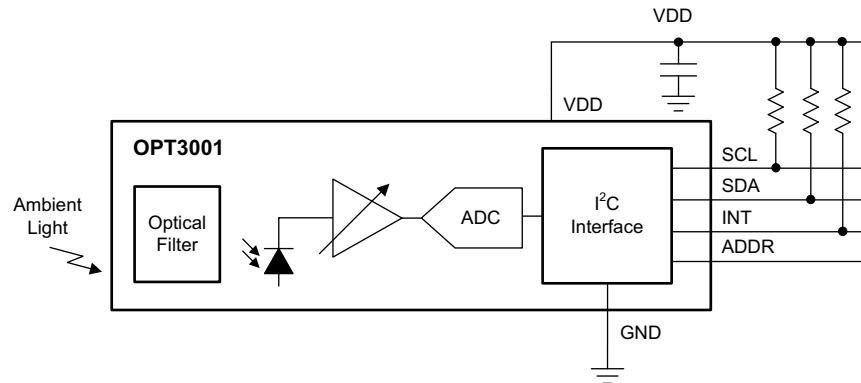
Figure 3. OPT3001 Functional Block Diagram

Features:

- Precision optical filtering to match human eye
    - Rejects >99% (typ) of IR
- Automatic full-scale setting feature simplifies software and ensures proper configuration
- Measurements: 0.01 lux to 83 klux
- 23-bit effective dynamic range with automatic gain ranging
- 12 binary-weighted full-scale range settings: <0.2% (typ) matching between ranges
- Low operating current: 1.8 µA (typ)
- Operating temperature range: –40°C to 85°C
- Wide power-supply range: 1.6 to 3.6 V
- 5.5-V tolerant I/O
- Flexible interrupt system
- Small-form factor: 2.0 × 2.0 × 0.65 mm

3.1.2   FDC1004

Capacitive sensing with grounded capacitor sensors is a very low-power, low-cost, high-resolution contactless sensing technique that can be applied to a variety of applications ranging from detecting proximity and sensing gestures to analyzing materials and sensing remote liquid levels. The sensor in a capacitive-sensing system is any metal or conductor, allowing for a low-cost and highly flexible system.

The FDC1004 is a high-resolution, four-channel capacitance-to-digital converter to implement capacitive sensing solutions. Each channel has a full-scale range of ±15 pF and can handle a sensor offset capacitance of up to 100 pF, which can be either programmed internally or can be an external capacitor for tracking environmental changes over time and temperature. The large offset capacitance capability allows for the use of remote sensors.

The FDC1004 also includes shield drivers for sensor shields, which can reduce EMI and help focus the sensing direction of a capacitive sensor. The small footprint of the FDC1004 allows use in space-constrained applications. The FDC1004 is available in a 10-pin WSON package and features an I²C interface for an MCU.
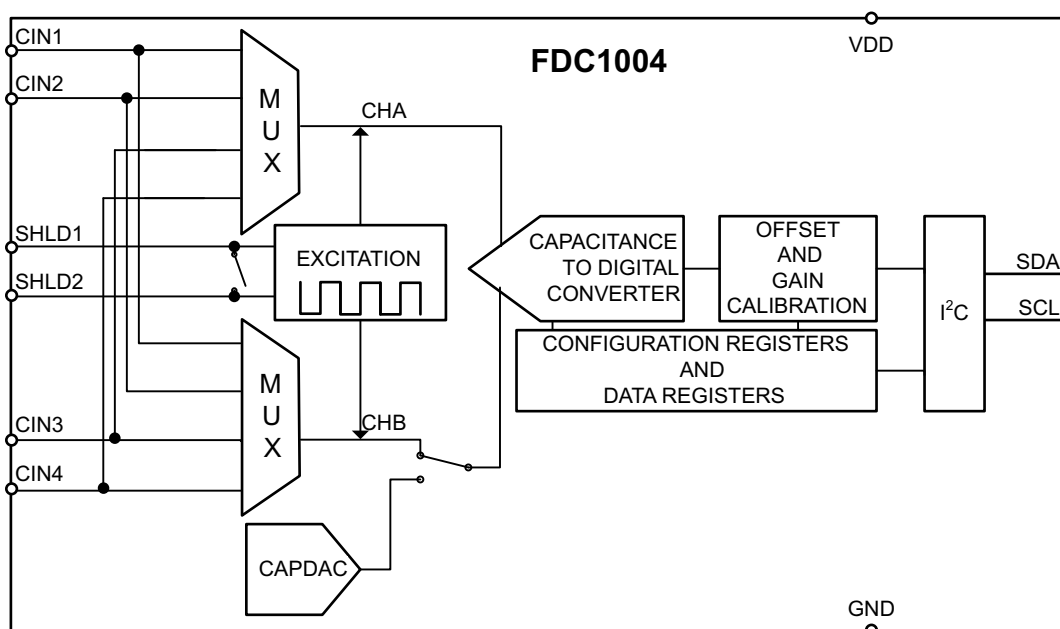
Figure 4. FDC1004 Functional Block Diagram

- Input range: ±15 pF
- Measurement resolution: 0.5 fF
- Maximum offset capacitance: 100 pF
- Programmable output rates: 100/200/400 S/s
- Maximum shield load: 400 pF
- Supply voltage: 3.3 V
- Temp range: –40°C to 85°C
- Current consumption:
  – Active: 750 µA
  – Standby: 29 µA
- Interface: I²C
- Number of channels: 4

3.1.3   HDC1000

The HDC1000 is a digital humidity sensor with an integrated temperature sensor that provides excellent measurement accuracy at very low power. The device measures humidity based on a novel capacitive sensor. The humidity and temperature sensors are factory calibrated. The innovative Wafer Level Chip Scale Package (WLCSP) simplifies board design with the use of an ultra-compact package. The sensor element of the HDC1000 is placed on the bottom part of the device, which makes the HDC1000 more robust against dirt, dust, and other environmental contaminants. The HDC1000 is functional within the full –40°C to 125°C temperature range.
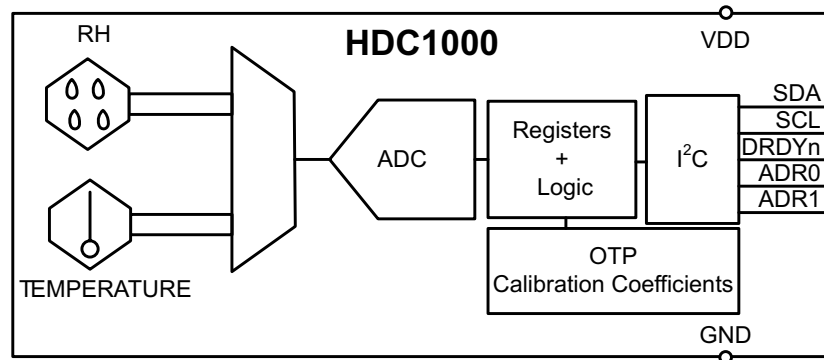
Figure 5. HDC1000 Functional Block Diagram

- Relative humidity (RH) operating range: 0% to 100%
- 14-bit measurement resolution
- Relative humidity accuracy ±3%
- Temperature range
  - Operating –20°C to 85°C
  - Functional –40°C to 125°C
- Temperature accuracy ±0.2°C
- 200-nA sleep mode current
- Average supply current:
  - 820 nA @ 1 sps, 11-bit RH measurement
  - 1.2 µA @ 1 sps, 11-bit RH and temperature measurement
- Supply voltage: 3 to 5 V
- Tiny 2×1.6-mm device footprint
- I²C interface

3.1.4 MSP430FR5969

The MSP430 ULP FRAM platform combines uniquely embedded FRAM and a holistic ULP system architecture, allowing innovators to increase performance at lowered energy budgets. FRAM technology combines the speed, flexibility, and endurance of SRAM with the stability and reliability of flash with much lower power.

The MSP430 ULP FRAM portfolio consists of a diverse set of devices featuring FRAM, the ULP 16-bit MSP430 CPU, and intelligent peripherals targeted for various applications. The ULP architecture showcases seven low-power modes, optimized to achieve extended battery life in energy-challenged applications.
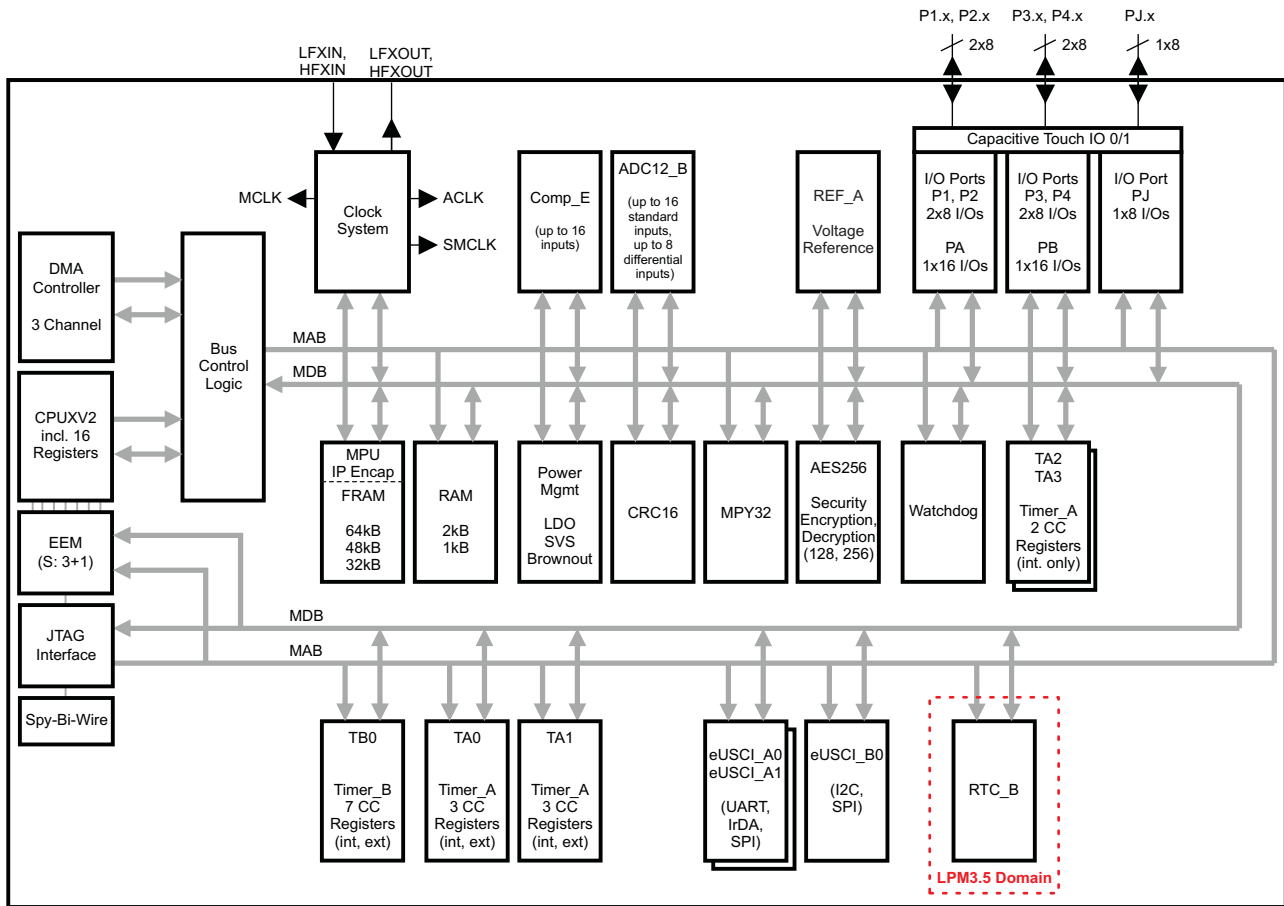
Figure 6. MSP430FR5969 Functional Block Diagram

- Embedded microcontroller
  - 16-bit RISC architecture up to 16-MHz clock
  - Wide supply voltage range
    (1.8 [(1)] to 3.6 V)
- Optimized ULP modes

[(1)] Minimum supply voltage is restricted by SVS levels.

MODE	CONSUMPTION (TYPICAL)
Active mode	103 µA/MHz
Standby (LPM3 with VLO)	0.4 µA
Real-time clock (LPM3.5 with crystal)	0.5 µA
Shutdown (LPM4.5)	0.02 µA

- ULP FRAM
  - Up to 64KB nonvolatile memory
  - ULP writes
  - Fast write at 125 ns per word (64KB in 4 ms)
  - Unified Memory = Program + Data + Storage in one single space
  - 10^{15} write cycle endurance
  - Radiation resistant and nonmagnetic
- Intelligent digital peripherals
  - 32-bit hardware multiplier (MPY)
  - Three-channel internal DMA
  - Real-time clock with calendar and alarm functions
  - Five 16-bit timers with up to seven capture/compare registers each
  - 16-bit cyclic redundancy checker (CRC)
- High-performance analog
  - 16-channel analog comparator
  - 14-channel 12-bit analog-to-digital converter (ADC) with internal reference and sample-and-hold
    - 200 ksps at 75-µA consumption
- Multi-function I/O ports
  - All pins support capacitive touch capability with no need for external components
  - Accessible bit-, byte- and word-wise (in pairs)
  - Edge-selectable wake from LPM on all ports
  - Programmable pullup and pulldown on all ports
- Code security and encryption
  - 128-bit or 256-bit AES security encryption and decryption coprocessor
  - Random number seed for random number generation algorithms
- Enhanced serial communication
  - eUSCI_A0 and eUSCI_A1 support
    - UART with automatic baud-rate detection
    - IrDA encode and decode
    - SPI at rates up to 10 Mbps
  - eUSCI_B0 supports
    - I^2C with multi-slave addressing
    - SPI at rates up to 8 Mbps
  - Hardware UART and I^2C bootstrap loader
- Flexible clock system
  - Fixed-frequency DCO with ten selectable factory-trimmed frequencies
  - Low-power low-frequency internal clock source (VLO)
  - 32-kHz crystals (LFXT)
  - High-frequency crystals (HFXT)
- Development tools and software
  - Professional development environments
  - Development kit (MSP-TS430RGZ48C)
- For complete module descriptions, see the *MSP430FR59xx and MSP430FR58xx Family User's Guide* (SLAU367)

3.1.5 TLV71333P

The TLV713 series of low-dropout (LDO) linear regulators are low-quiescent current LDOs with excellent line and load transient performance and are designed for power-sensitive applications. These devices provide a typical accuracy of 1%.

The TLV713 series is designed to be stable without an output capacitor. The removal of the output capacitor allows for a very small solution size. However, the TLV713 series is also stable with any output capacitor if an output capacitor is used. A 1-µF capacitor is placed at the input and output of this design for more stability.

The TLV713 also provides inrush current control during device power-up and enabling. The TLV713 limits the input current to the defined current limit to avoid large currents from flowing from the input power source. This functionality is especially important in battery-operated devices.

The TLV713 series is available in standard DQN and DBV packages. The TLV71333P provides an active pull-down circuit to quickly discharge output loads.
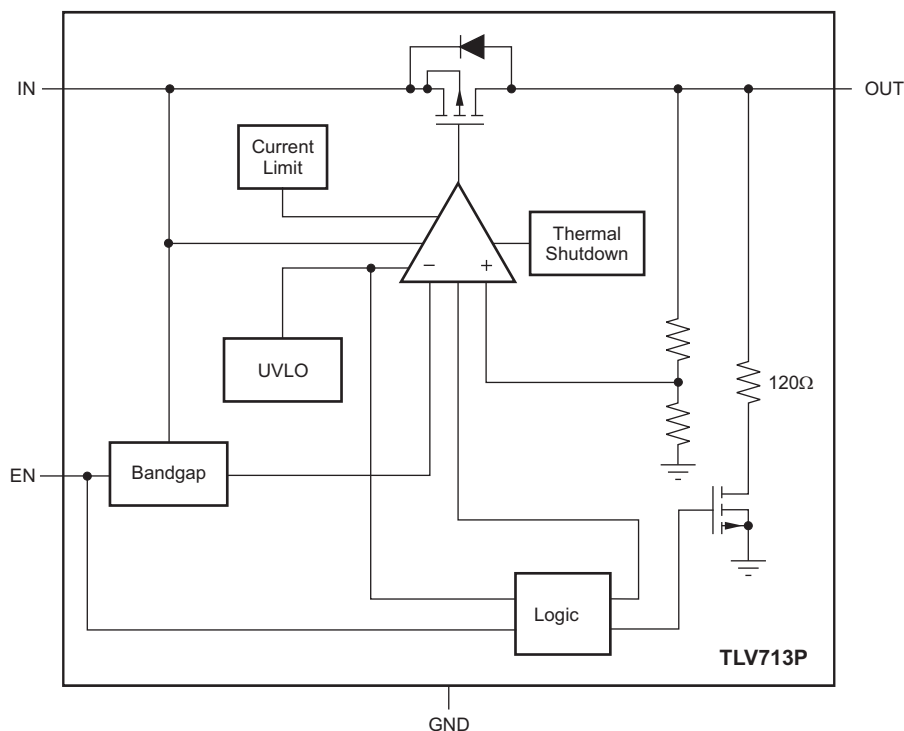
Figure 7. TLV71333P Functional Block Diagram

- Stable operation with or without capacitors
- Foldback overcurrent protection
- Package: SOT23-5 and X2SON
- Very low dropout: 230 mV at 150 mA
- Accuracy: 1%
- Low I_Q: 50 µA
- Input voltage range: 1.4 to 5.5 V
- Available in fixed-output voltages: 1.0 to 3.3 V
- High PSRR: 65 dB at 1 kHz

3.1.6 LM3630A

The LM3630A is a current mode boost converter, which supplies the power and controls the current in up to two strings of 10 LEDs per string. Programming is done over an I²C-compatible interface. The maximum LED current is adjustable from 5 to 28.5 mA. At any given time, maximum LED current and LED brightness is further adjusted with 256 exponential or linear dimming steps. Additionally, PWM brightness control can be enabled, allowing for LED current adjustment by a logic-level PWM signal.

The boost switching frequency is programmable at 500 kHz for low-switching loss performance or 1 MHz to allow the use of tiny low profile inductors. A setting for a 10% offset of these frequencies is available. Overvoltage protection is programmable at 16 V, 24 V, 32 V, or 40 V to accommodate a wide variety of LED configurations and Schottky diode or output capacitor combinations.

The device operates over the 2.3- to 5.5-V operating voltage range and –40°C to 85°C ambient temperature range. The LM3630A is available in an ultra-small 12-bump DSBGA package.
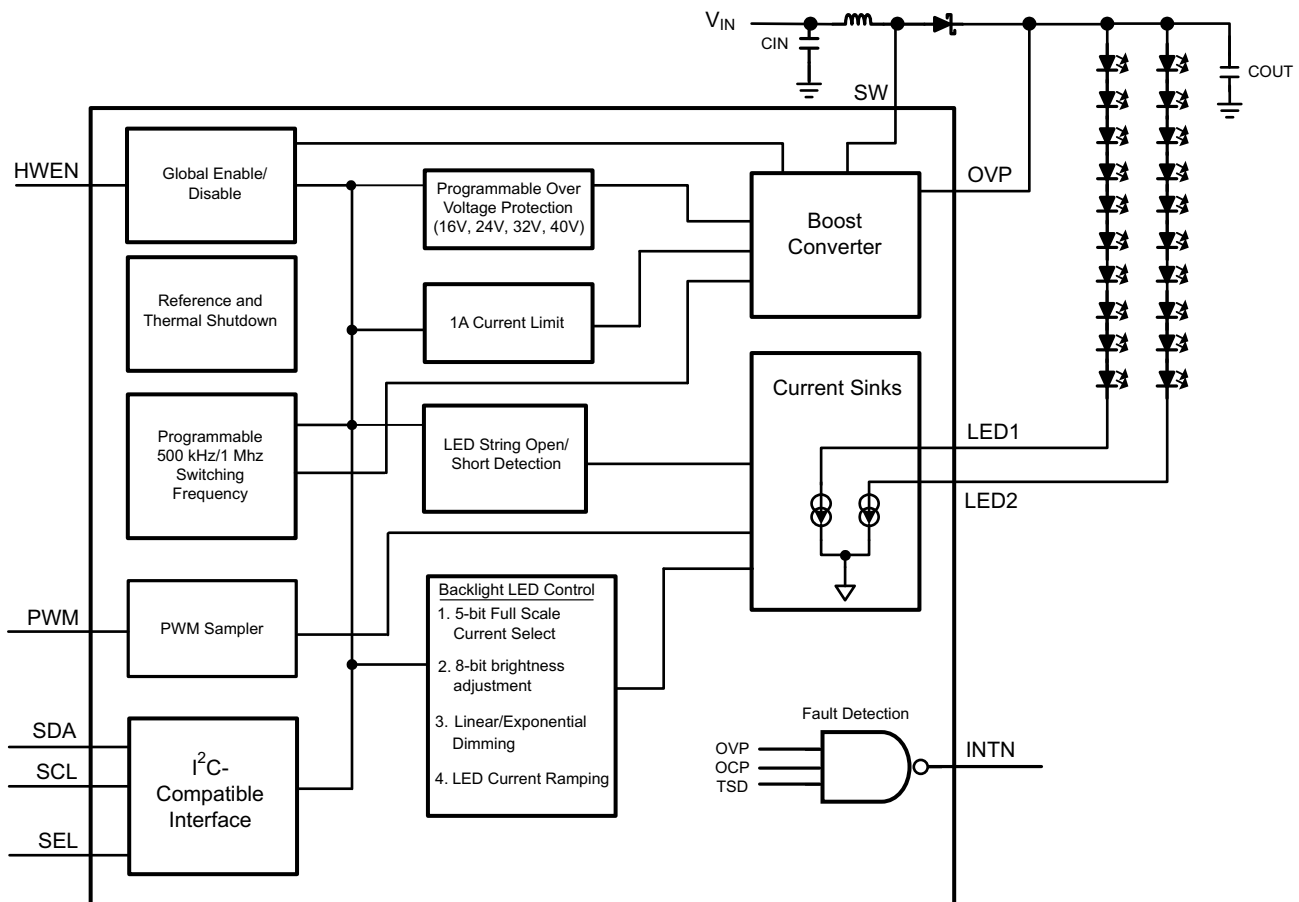
Figure 8. LM3630A Functional Block Diagram

3.1.7 TPD2E2U06

The TPD2E2U06-Q1 is a transient voltage suppressor (TVS) ESD protection diode array with low capacitance. It is rated to dissipate ESD strikes above the maximum level specified in the IEC 61000-4-2 international standard. The 1.5-pF line capacitance makes it ideal for protecting interfaces such as USB 2.0, LVDS, Antenna, and I^2C.
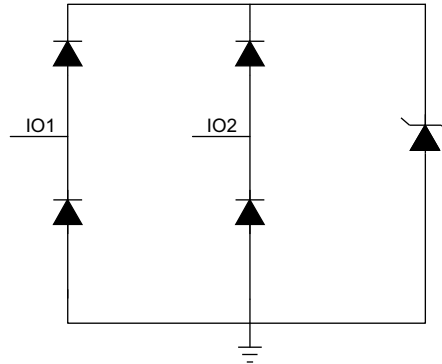
Figure 9. TPD2E2U06 Functional Block Diagram

- AEC-Q101 qualified
- IEC 61000-4-2 level 4
  - ±25-kV (contact discharge)
  - ±30-kV (air-gap discharge)
- I/O capacitance 1.5 pF (typ)
- DC breakdown voltage 6.5 V (min)
- Ultra-low leakage current 10 nA (max)
- Low ESD clamping voltage
- Industrial temperature range: –40°C to 125°C
- Small easy-to-route DBZ package

4 System Design Theory

4.1 Ambient Light Measurement

This reference design uses Texas Instruments' OPT3001 device to periodically measure the intensity of light shining on the screen and board. An adequate backlight brightness level is chosen by collecting ambient light data and correlating the lux level to a backlight level using linear interpolation. More discussion of software filters and algorithms are covered in Section 5.

4.1.1 OPT3001 Placement

The placement of any sensor is imperative for correct operation. To cut down on false readings, the OPT device was placed above the screen so the user's hand or body would have less of a chance to shade the sensor during use of the display. When the reference design is attached to a wall and approached by a person from the front, the light sensor has the smallest chance of being shaded by the hand of the user. The ideal location is in the top middle of the board to allow either a right- or left-handed person to approach the screen and not block light from coming in contact with the sensor.

In some of today's designs, the light sensor is positioned flush to the outside of the case to allow the most light into the sensor. Because this reference design was built using a regular four-layer PCB and was manufactured without the plan for using an enclosure, all components are mounted flush to the board. A problem arises when the OPT sensor cannot be mounted above the height of the LCD backlight. Extra light produced by the backlight could interfere with the lux reading collected by the OPT. A small light shield solves the problem of unintended light from the backlight adding to the lux reading. The shield was built using a 3D printer and black ABS plastic.
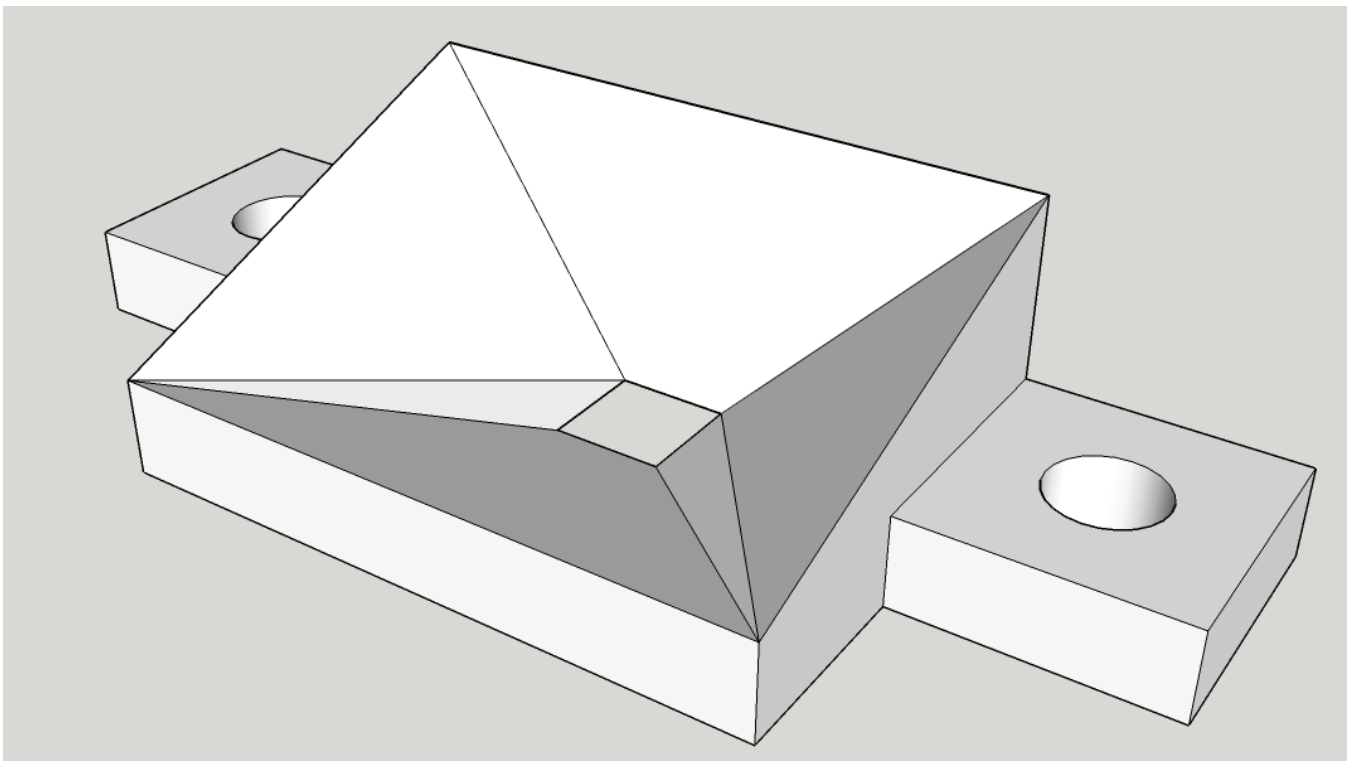
Figure 10. 6-mm Large Shield

NOTE: Not drawn to scale; actual: 6-mm tall × 26-mm long × 11-mm wide.

After further experiments, it was found that a shield was unnecessary. The top of the LCD backlight assembly is blacked out enough to block light; therefore, when active, the backlight does not contribute to the lux reading of the OPT device.
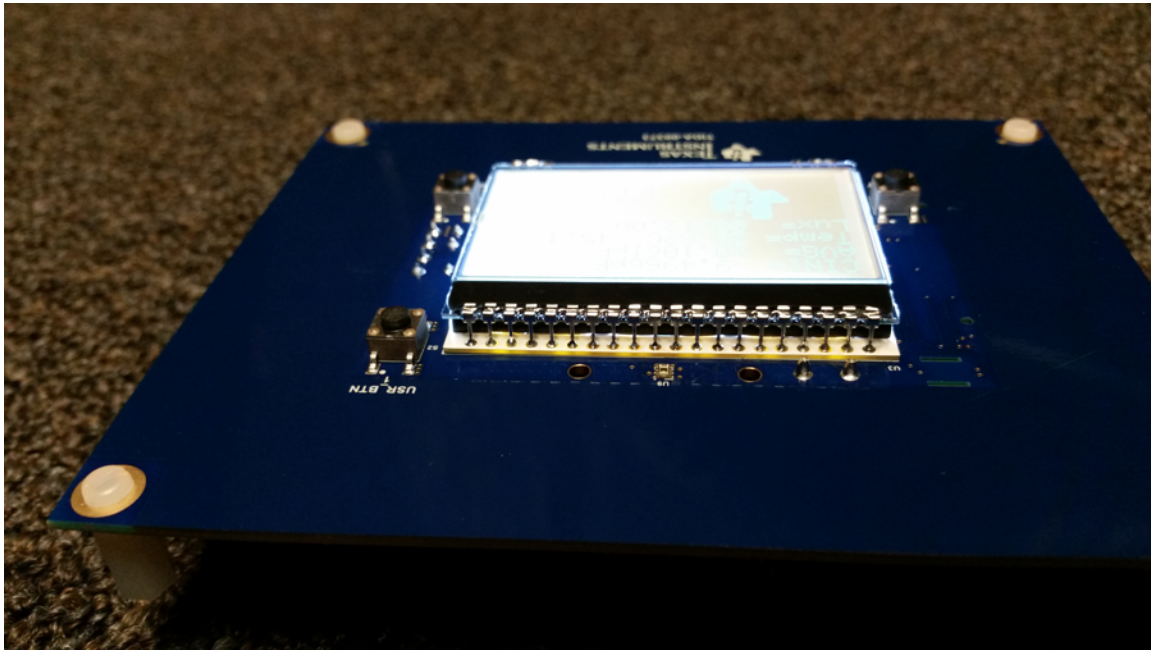
Figure 11. LCD Top Edge

However, if the light sensor was placed on either side of the LCD screen, extra light would be sensed by the OPT3001. In Figure 12, the edges of the LCD backlight does emit a good amount of extra light and a shield would be needed. Or the OPT3001 would need to be mounted slightly above the LCD height to avoid the extra light from adding to the lux reading.
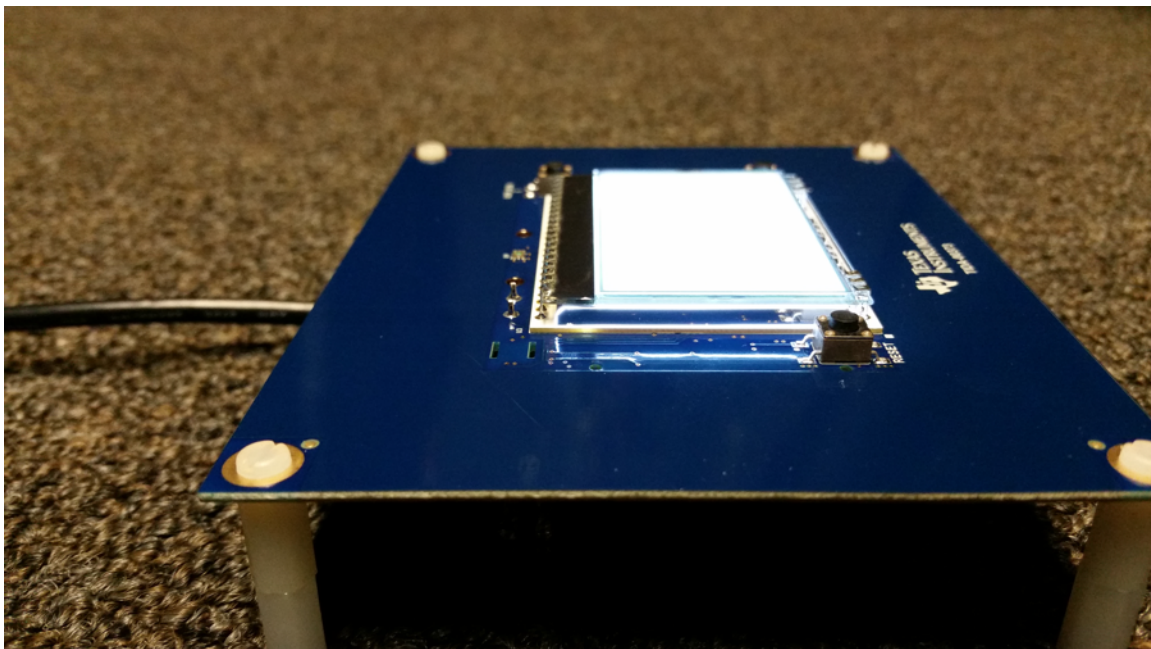
Figure 12. LCD Side Edge

4.2 Proximity Detection Theory of Operation

This TI Design detects proximity using capacitive sensing technology from TI. The FDC1004 device measures the capacitance on a proximity sensor plate, which in this TI Design is a rectangular bezel shape in a copper PCB trace. When no human presence is in front of the proximity sensor, the FDC1004 device measures some baseline capacitance. When a human moves in proximity to the sensor, the FDC1004 device measures an increased capacitance. At this time, the system turns on the LCD backlight for a set period of time. Depending on the end-system requirements, a different action can occur, such as a general system interrupt or wake-up signal.

One major concern about using capacitance-to-digital converter technology is how to deal with a fluctuating baseline capacitance. If any of the environmental conditions vary, the system likely has a baseline capacitance measurement that fluctuates, which either causes a false triggering of the system wake-up or prevents the system from ever triggering.

An active shield, as implemented in this design, greatly reduces baseline fluctuations due to temperature and humidity changes that cause the PCB to expand and contract. This TI Design also uses two main techniques to deal with this problem: a differential measurement using an environmental sensor, and a slow-moving average threshold for the proximity detection decision.

4.3 Environmental Sensor Measurements

This TI Design makes use of the multiple input feature of the FDC1004 device. A separate capacitive sensor, called the environmental sensor, is located on the backside of the TI Design hardware. Because both the proximity sensor and the environmental sensor have corresponding shields, they only "see" capacitive changes on the side of the PCB where they are located.

To clarify, the proximity sensor detects a hand when placed over top, but the environmental sensor, located on the opposite side of the PCB, does not detect that same hand. However, because the environmental sensor is still located close to the proximity sensor, both sensors are affected by environmental variations equally. In summary, the environmental sensor exists to zero out any changes due to environmental effects.

The FDC1004 device is configured in this TI Design to take a differential measurement between the proximity sensor and the environmental sensor. Therefore, whenever the difference between the two sensors rises above the baseline difference, the system can determine that there is a human or some other object present that was not previously there. By using the differential measurement, the system then does not need to rely on the absolute capacitance measured by each sensor, just the difference between the two.

4.4 Dynamic Threshold Proximity Detection

The other method that this TI Design uses to deal with a fluctuating baseline capacitance is a slow-moving average threshold. The differential measurement read by the FDC1004 device is averaged in firmware to reduce noise, and then this averaged value is compared against a threshold to determine if a proximate object is detected. However, this threshold is also an averaged value of the averaged values read by the FDC1004. Details on the specifics of this averaging scheme are found in Section 5.

The firmware adjusts to the new differential baseline measurement if a foreign object such as water drops or dust is placed on the proximity sensor but not the environmental sensor. In this case, the water drops have a short-term effect on the sensor that could activate the proximity threshold. However, once the water drops are stationary, the slow-moving average threshold changes to reflect the new capacitance. The differential measurement is altered with the contaminant present, but because the firmware is comparing the differential reading to a slow-moving average rather than a fixed value, the firmware eliminates the long-term effect from water drops, dust, or other contaminants on the proximity sensor.

The specific values of the slow-moving average threshold update rate, as well as the FDC1004 sample rate, can be adjusted, depending on end-product system requirements.

5 Software Overview

The MSP430 software was written in Code Composer Studio™ v6. A 14-pin JTAG debug interface is needed to program the reference design. The MSP-FET and the MSP-FET430UIF are suitable USB debuggers and programmers and were used during the development process. However, the MSP-FET is the only debugger that allows the EnergyTrace feature. A secondary board is necessary to program the reference design, called the JTAG Adaptor board. With limited board real estate, a smaller programming port was needed to save space. More information regarding the adaptor is covered in Section 6.2.

5.1 Software Filtering and Averaging

To improve the signal-to-noise ratio in the measurements of FDC1004, an IIR filter was implemented in software. The IIR filter implementation is similar to a moving average except that previous values do not have to be stored and shifted out of the summing order. This saves memory and calculation time, but some accuracy is lost.

A running total of 'N' values are kept. The current average, denoted by "Avg[m]" in Equation 1, is calculated by taking the previous average, "Avg[m – 1]", multiplying by N, and subtracting the previous average. Then, the new value is added to the sum to create a "new sum". Dividing by N creates a new average. Having N be a multiple of 2 allows bit shifting instead of actually dividing, further saving precious cycles.

$$Avg[m] = \frac{Avg[m-1] \times N - Avg[m-1] + val[m]}{N}$$

(1)

The long-term average is completed the same way but uses the average as the "val[m]", thus taking the average of the average to create a dynamic baseline reading. This enables the reference design to react to environment changes.

5.2 Backlight Brightness

Attempting to achieve the perfect brightness level for every environment is tough. The preferred brightness level can differ depending on the individual. The backlight levels of this design were based off a study completed by Microsoft® [1]. Further tests were completed in different environments and multiple opinions were collected. If a different LCD panel and backlight controller subsystem is used, the brightness levels may need to change; however, this is a good starting point to setting backlight brightness.

The LM3630 has 255 discrete backlight levels that can be set. During development, it was decided it would be easier and more efficient to set the brightness this way to avoid using PWM control that would have to be running anytime the backlight was on. A couple hundred levels allowed plenty of customization for the LCD and backlight devices selected for the reference design. Eleven values were correlated to ambient light levels and hard coded into arrays. Implementing linear interpolation between values in the arrays gives a suitable brightness leveling solution. The relationship between ambient light and backlight brightness is shown in Figure 13.
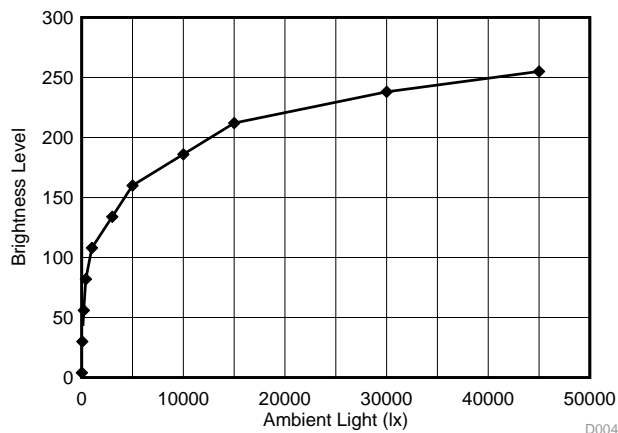
Figure 13. Backlight Brightness

5.3   Sensor Sampling and Update Frequency

All of the sensors communicate on the same I^{2}C line, but each have their own unique addresses. Simple register reads and writes are employed to configure and read data from each of the sensors. As discussed in Section 5.1, there is some filtering and averaging that occurs between outputting the capacitance readings. The equivalent sampling frequency for the FDC proximity detection is 10 Hz. The temperature, humidity, and lux data are collected and display on a 2-Hz frequency. A 2-Hz update frequency was chosen because the screen updates are hard to read when updated quickly, and temperature and humidity will not be changing that fast as well.

6 Getting Started

6.1 Hardware Overview

The TI Design is displayed in Figure 14. The capacitive bezel takes up one inch around the entire edge of the board on the first two layers. The environmental sensor is located on the bottom two layers and is about 75 percent smaller. A smaller environmental sensor picks up less noise from circuitry located on the back of the board.

The LCD, backlight panel, user, and reset buttons are located on the front of the board. The ambient light sensor is positioned at the top middle of LCD panel. The top of the LCD and backlight are blacked out to avoid an error in the light readings.
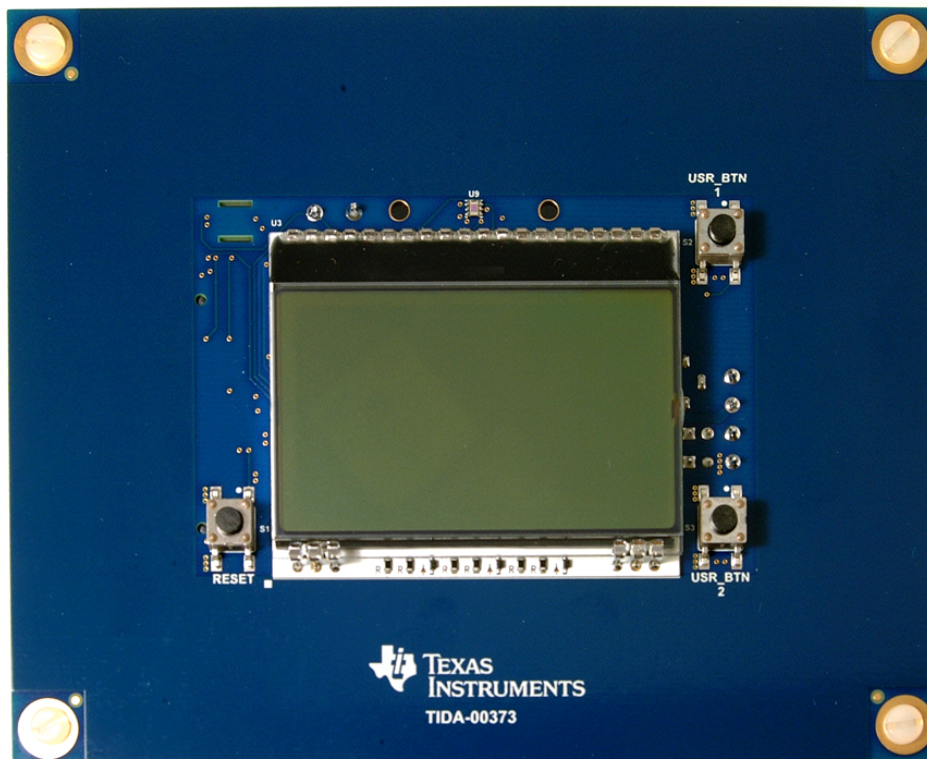
Figure 14. ISE4024 Front

Test points are located on the backside of the board to allow connection to the I^{2}C communication lines; these are the yellow test points. The GND, VBUS, V_INPUT, and 3v3 test points are positioned next to the right angle micro-USB connector.

Jumpers are positioned near the rear mounted USB connector as well. J1 should be put in place when powering off of USB power, 5 V. J1 can be removed when powering off a bench supply connected to V_Input and GND, 5 V. J3 allows the LDO to power the rest of the system using 3.3 V.
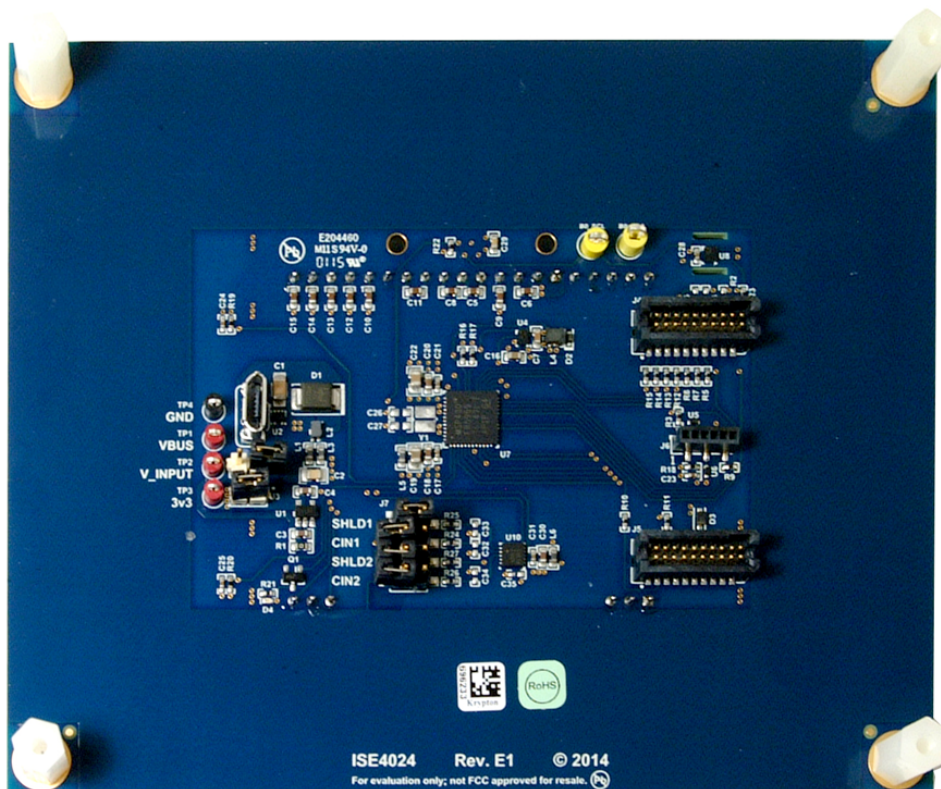
Figure 15. ISE4024 Back

CIN and SHLD selection headers near the bottom middle of the back of the board allow the user to add a different capacitive sensor to the board or select which onboard sensors are connected. Adding new and different geometries allow the user to try new sensor materials and geometries on the same platform.

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6.2 JTAG Adaptor Board

The ISE4020 hardware is an adaptor board that connects to the standard 14-pin JTAG ribbon connector on the MSP-FET Flash Emulation tool. Space requirements make fitting the standard JTAG programming connector onto the board difficult. By using the JTAG adaptor board, a six-pin 50-mil female header can be installed in place of the larger 14-pin JTAG connector.
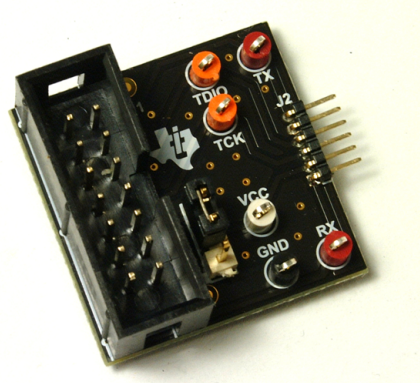
Figure 16. ISE4020 Front

This postage stamp-sized board contains two connectors, a jumper, and test points for the power, UART, and programming signals. The standard 14-pin JTAG header is shown on the left side of the board. The six-pin 50-mil output header is shown on the right edge of the board.

The schematic is shown in Figure 17. The jumper labeled J3 is used to select the power mode of the JTAG programmer. When jumper J3 is in position 1, connecting pins 1 and 2, the target is self-powered. With jumper J3 in position 2, connecting pins 2 and 3, the target board is powered from the debugger/programming adaptor. Take care to select the correct mode as the adaptor board does not use overvoltage protection.
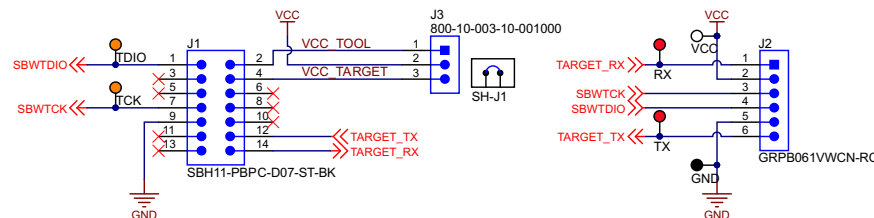
Figure 17. ISE4020 Schematic

To program the Proximity Ambient Light reference design, the programmer is set up in the orientation displayed in Figure 18. Check the jumper setting of the jumper labeled J3 before powering up and connecting to USB port on PC.
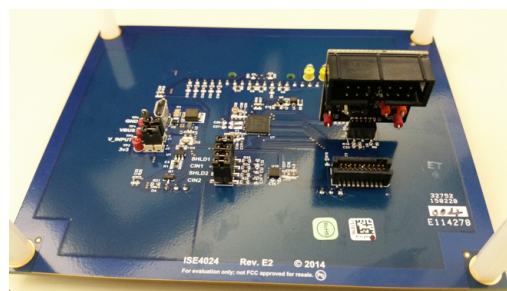
Figure 18. Programmer Connection

7 Test Setup

NOTE: Unless otherwise noted, the test data in the following sections was measured with the system at room temperature.

All of the measurements in this section were measured with calibrated lab equipment.

7.1 Overview

Testing of major sensing devices were completed. Temperature and humidity testing was also performed to verify how the reference design acts in different environments. The following subsections describe the test setup and procedures. Section 8 presents test data with some explanation.

7.2 Optical Light Sensing

Extensive testing of the optical sensor was completed in a similar method as the original device characterization. The results are comparable to the original data set collected from the OPT3001 EVM. The repeatability of the experiments and results demonstrates the ease of use of the ambient light sensor. The following section will outline the methods used, along with some of the theory involved in testing light sensors.

7.3 Equipment

A dark room equipped with various light testing equipment was used to test the reference design's ability to sense ambient light conditions. In a light testing setup, control as many test variables as possible. Controlling light can be a difficult process. The first piece of equipment used is a Thorlabs solid aluminum optical breadboard. Figure 19 shows a subsection of the board. Its matte black anodized finish reduces the amount of reflections and the standard hole patterns allow easy alignment of testing equipment.
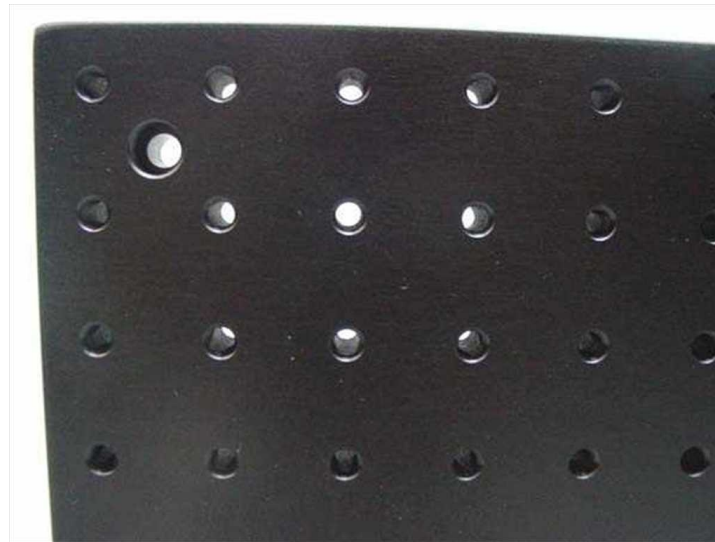
Figure 19. Thorlabs Optical Breadboard

When completing any light testing, any and all reflections should be minimized. The dark room used in testing had flat black paint on the walls and all reflective surfaces were covered from view. Almost all equipment was also painted a flat black color.

Testing cannot be achieved without a good reference value. Therefore, a Konica Minolta T-10MA Illuminance meter was used to know the "actual" value of lux being directed into the OPT3001 device.
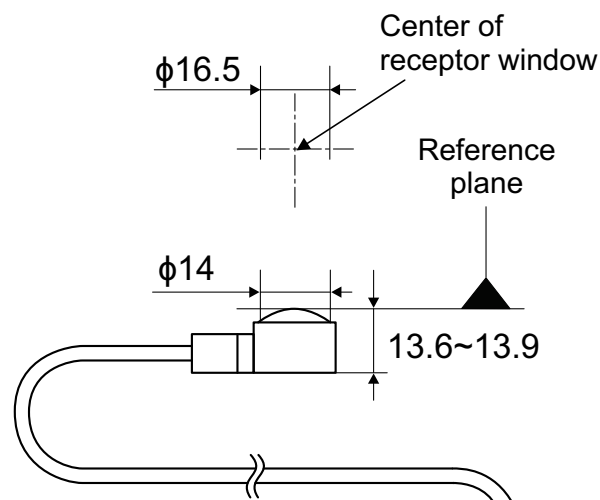
Figure 20. Lux Meter Mech

The accuracy is specified as 2% linearity and ±1 digit of display value. Additionally, its spectral response is specified to be within 6% of the CIE standard for illuminance.

To house the light source and to attempt to control light direction and reflections, a light box was manufactured. The light source enclosure is a custom-machined box designed to house various bulbs. The light box is intended to be sealed for non-darkroom testing, and it is compatible with Thorlabs components. Two back plates support different bulbs. The first back plate attaches to the large LED array, and the second back plate attaches to common threaded household bulbs. The back plates also allow an adjustable depth or distance to be set, and this distance can be fixed by tightening a set screw. The enclosure also has six fans to aid in the temperature stability of the bulb inside.

To test the full range of the OPT3001, an array of white LEDs were used to reach above 83 klux. It is the workhorse light source. It consists of an array of discrete LEDs wire-bonded together to produce a forward voltage drop of roughly 40 V at up to 0.5 A. It is the only light source available at the time of testing capable of reaching 100 klux, and it is also the only one that can exercise the maximum range of the OPT3001. When driven by Yokogowa or Keithley SMU in current source mode, it is also the quietest source, capable of 1 LSB of noise.

The aforementioned discrete LEDs create unique optical problems. If this light source is not well diffused, it will create hot spots in the illuminated intensity. This problem is especially noticeable if lens systems are used to focus the light. At the distances used for calibration, uniformity appears to be within the measurement capability of the Konica lux meter. The parts in Table 2 were put together to create a configurable light source.

Table 2. LED Light Source Parts

IMAGE	DIGIKEY PART NUMBER	MFG PART NUMBER	DESCRIPTION
	CXA2011-0000-000P00J050F-ND	CREE CXA2011-0000-000P00J050F	LED COOL WHITE 5000K SCREW MOUNT
	WM4779-ND	Molex 1802890000	HEATSINK BLACK ANODIZED HELIEON
	BER142-ND	Berqquist Q3-0.005-00-48	THERMAL PAD RECT .005" Q3
	WM4788-ND	Molex 1802200001	CXA20 LED ARRAY HOLDER W/COVER
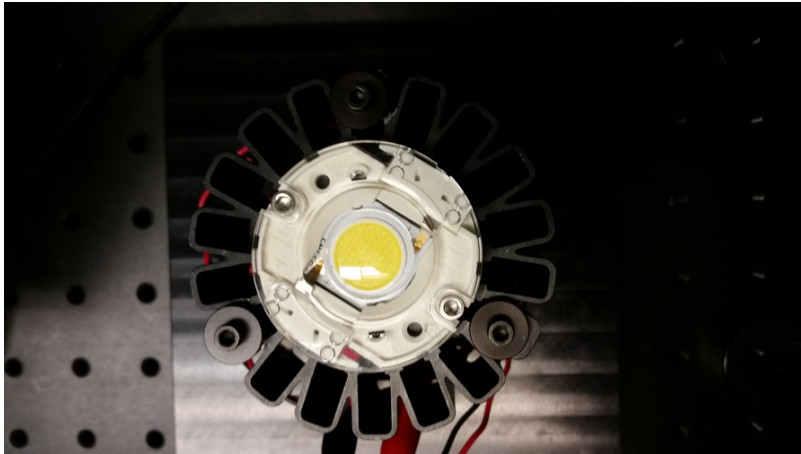
Figure 21. Assembled Light Source

To adjust the intensity of light projected onto each of the sensors, a gradient rotating neutral density filter was used. The rotating neutral density filter reduces the intensity of all wavelengths equally to effectively dim the light being emitted onto the sensor. The ND filter used is shown in Figure 22.
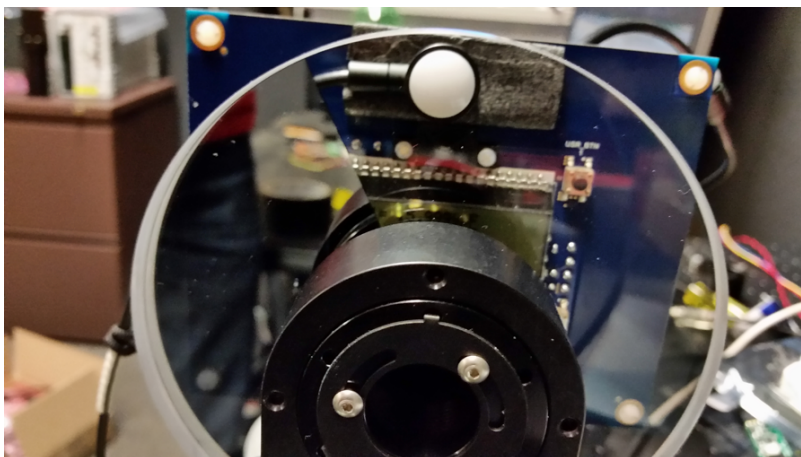
Figure 22. ND Filter Close Up

7.4 *Illuminance Testing Theory*

For reliable light testing, the reference reading needs to be taken from the exact location every time. Light is very hard to keep uniform unless more specialized equipment is used. The highly specialized equipment was not available to test this reference design. When the light output cannot be forced into uniformity, it is even more imperative to take measurements from the same position inside the emitted light field. When a bulb emits light, it is never perfectly uniform. The brightness or intensity can change from changes in relative distance from light source. Changes are also seen when moving a lux meter on an equidistance plane in front of the light source. A cone-shape light emission usually appears from the light source or the light box.

7.5   Test Platform

The test platform was created with on-hand parts to quickly come up with a solution for accurately testing the ambient light sensor. If more time was available, a more robust assembly would have been created.

The test platform was also created using parts from Thor Labs to make a rotating-type jig to position the lux meter receptor window in the same position as the reference design's. The underlying idea for the test platform was to create a type of machine that could position either the lux meter or the reference design's OPT sensor in the same location in the emitted field with repeatability. The tester could then rotate the jig one direction to align the OPT part to take a reading and then rotate the jig in the opposite direction to align the lux meter. This setup allowed repeatability throughout the entire test process. A 3D printed block was created to align the lux meter receptor window at the same height and depth as the OPT sensor.

Stop posts are located on either side of the jig to manage the maximum rotation of the jig (see Figure 24).
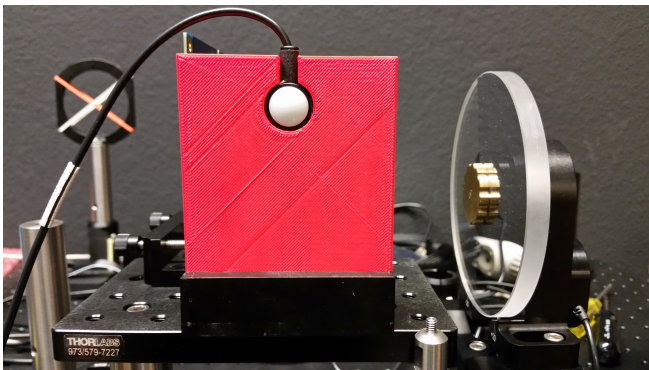
Figure 23. 3D Print Lux Holder
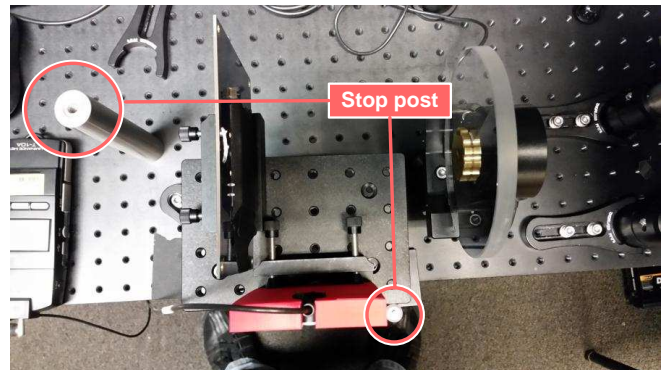
Figure 24. Jig Top View

Figure 25 demonstrates how this setup perfectly lines up each sensor in the same location for repeatability of readings. By aligning each board along its axis of rotation, the position is guaranteed to match.
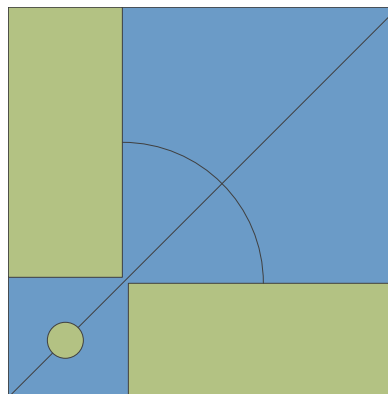
Figure 25. Jig Mounting Diagram

Carefully align both the ambient light sensor and the lux meter in exactly the same location in space; the same XYZ space is critical for accurate measurements. A laser pointer or some other method can be used to determine the same location for each board on the jig.

8 Test Results

8.1 *Light Testing Results*

Several important tests were completed to further the applicability of the OPT3001 device and its ability to sense the ambient light projected onto an LCD screen.

8.1.1 Multiple Light Sources

The first test completed compares the output response versus the input Illuminance of multiple light sources, or bulb types. Fluorescent, halogen, and incandescent light were tested.
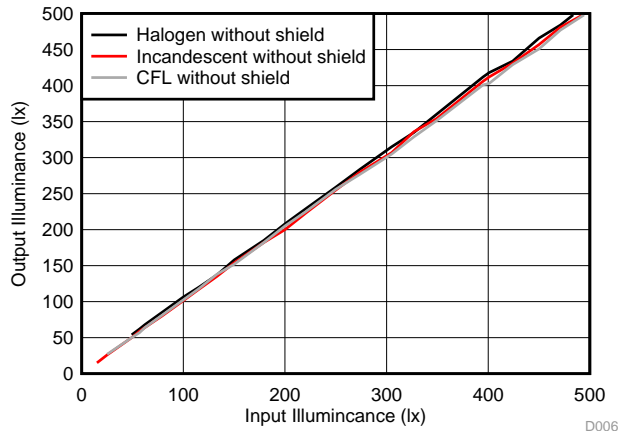
Figure 26. Output Response versus Input Illuminance — Multiple Light Sources

The test platform described in Section 7.5 was used to collect this data. The test platform was approximately 11 inches from the light box during each test. As demonstrated in the test data, various light sources have little effect on the output of the OPT3001. The ambient light sensor does a great job of sensing the intensity of light, no matter the type of light.

8.1.2   Output Response versus Input Illuminance

The next test showcases the OPT3001's ability to closely measure the intensity of light from 0 lux to 83 klux. There is less than a 4% error at any one point. The LED array mentioned in the test equipment section (Section 7.3) was used to produce the needed intensity.
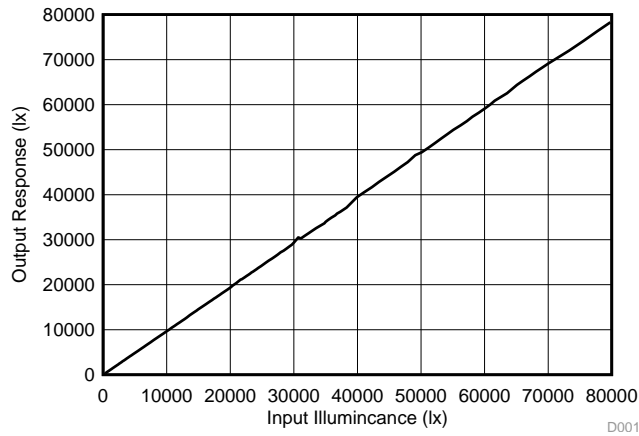
Figure 27. Output Response versus Input Illuminance — Full Range, White LEDs

The data demonstrated good accuracy and range, but this test was not completed with the more accurate rotating test setup. In fact, a hole was drilled into the capacitive sensor above the OPT3001 sensor to mount the lux meter close to the ambient light sensor. Even more accurate results could have been achieved with the lux meter and OPT3001 positioned in the same location. The rotating jig had not been designed before starting this test. The partially mutilated board is shown in Figure 28. It was difficult with the tools at hand to drill a hole next to the OPT sensor, and because of this, the hole for the lux meter is not perfectly centered above the OPT3001. This could also account for some of the error seen in the graph.
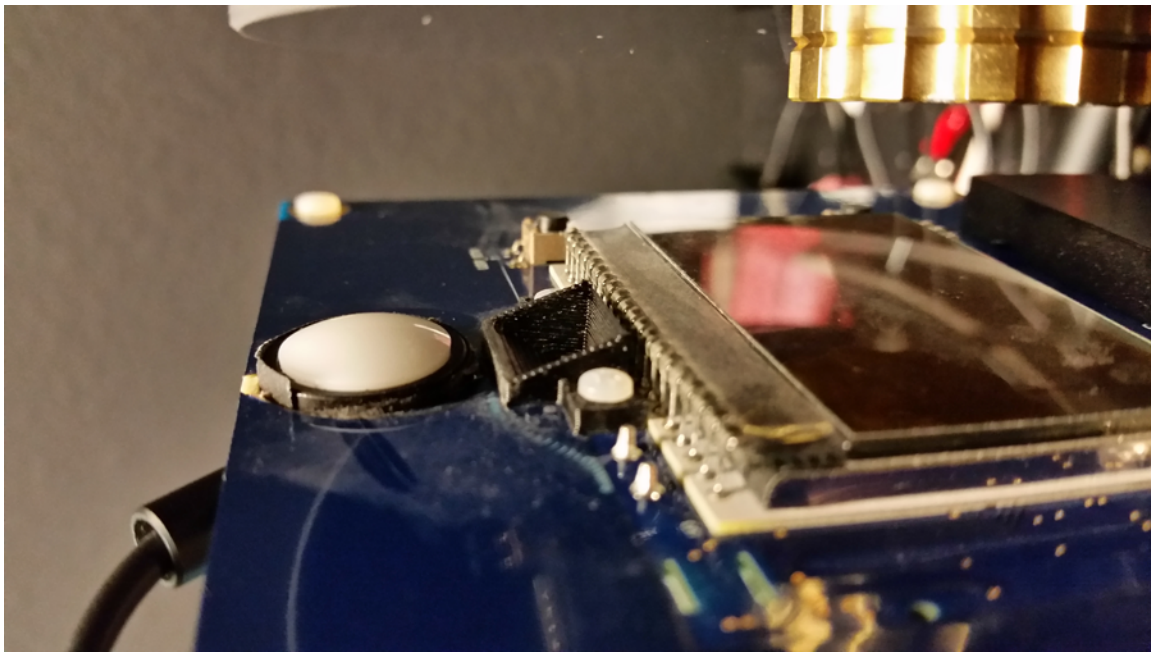
Figure 28. Reference Design Modified for Testing with Lux Meter (Non-Ideal)

Figure 28 is not ideal for many measurements. The setup featured in Figure 23 through Figure 25 is a more ideal and preferred method.

8.1.3   Normalized Response versus Illuminance Angle

The OPT3001 response can change depending on the illuminance angle. This test was originally done to compare how the light shield would change the response. However, the way the shield was designed does not affect the response too much. The extreme angles are greatly affected because the shield causes a shadow effect on itself at these positions. This test was completed by mounting the reference design vertically to a rotating mount and setting the LED array to emit 1000 lux of light. Then, data was taken at different degrees of rotation, both in the negative and positive direction. At zero degrees, the board is perfectly facing the emitted light. The results are shown in Figure 29.
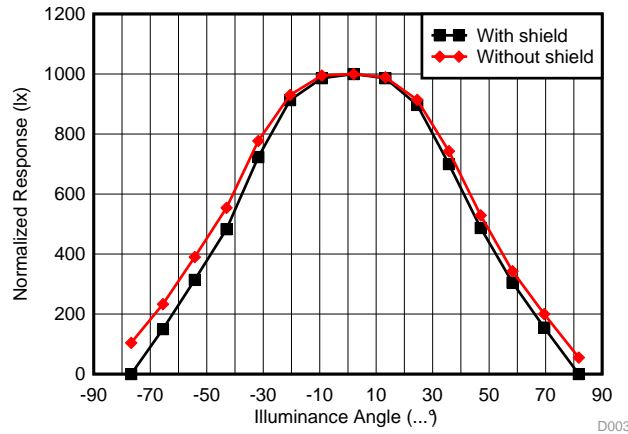
Figure 29. Normalized Response versus Illuminance Angle

8.2 *International Electrotechnical Commission*

This TI Design was characterized through pre-compliance and engineering tests for ESD and radiated immunity.

Table 3. Criteria and Performance as Per IEC61131-2

CRITERIA	PERFORMANCE (PASS) CRITERIA
A	The system shall continue to operate as intended with no loss of function or performance even during the test.
B	Temporary degradation of performance is accepted. After the test, the system shall continue to operate as intended without manual intervention.
C	During the test, loss of functions accepted, but no destruction of hardware or software. After the test, the system must continue to operate as intended automatically, after a manual restart, powering off, or powering on.

8.3 *IEC Testing*

8.3.1 **IEC 61000-4-2 (ESD)**

For IEC testing, the reference design was powered by a USB cable to 120-V USB wall wart.

Figure 30. ESD Test Setup

Table 4. IEC Test Results

IEC 61000-4-2 (ESD) TEST CONDITION	RESULT (SEE Table 3 FOR DETAILS)
±2-kV air discharge on USB power connector	Class A
±4-kV air discharge on USB power connector	Class A
−8-kV air discharge on USB power connector	Class A
±2-kV contact discharge on USB power connector	Class B
±4-kV contact discharge on USB power connector	Class B
±2-kV air discharge on copper PCB sensor	Class A
±4-kV air discharge on copper PCB sensor	Class A
±2-kV contact discharge on copper PCB sensor	Class A

8.3.2 **Radiated Immunity**

Because the FDC1004 device excites the capacitive sensor at approximately 25 kHz, engineering tests for radiated immunity were performed at low frequencies on the system. The system was powered and the differential proximity capacitance was recorded through UART stream before, during, and after test conditions were applied. The radiated interference was varied from 25 to 300 kHz at the harmonics of 25 kHz with a field strength of 3 V/m.

8.4 Temperature Testing

Environment temperature has some affect on the capacitance reading. A temperature chamber was used to control temperature during testing. At each temperature data point, the board was allowed to soak for five minutes after the chamber reached the intended temperature. After the five-minute soak, one minute of UART data was captured and averaged to obtain the average reading at each temperature. Figure 31 shows the differential measurement between the larger front facing sensor and the smaller back facing sensor.
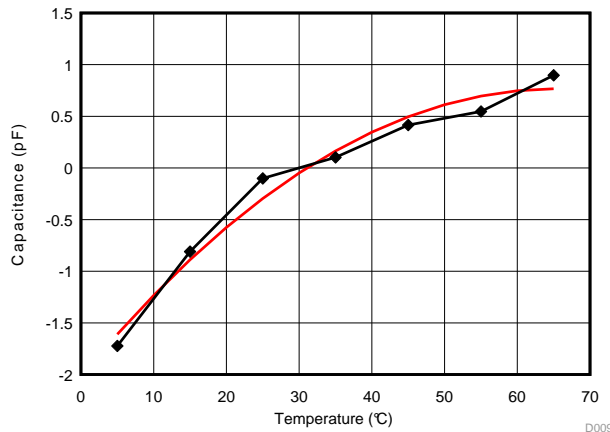
Figure 31. Output Capacitance versus Temperature

8.5 Humidity Testing

A humidity chamber with a blacked out window was used to complete these tests on the OPT sensor and capacitive proximity sensor. Humidity has no affect on the OPT output. However, humidity does change the capacitive output. This change was part of the reason for a slow moving baseline, to correct differences like the one seen on the FDC output graph in .

The humidity data was taken while the FDC was in differential mode. By using the humidity data and some calibration, the differences caused by humidity can easily be corrected.
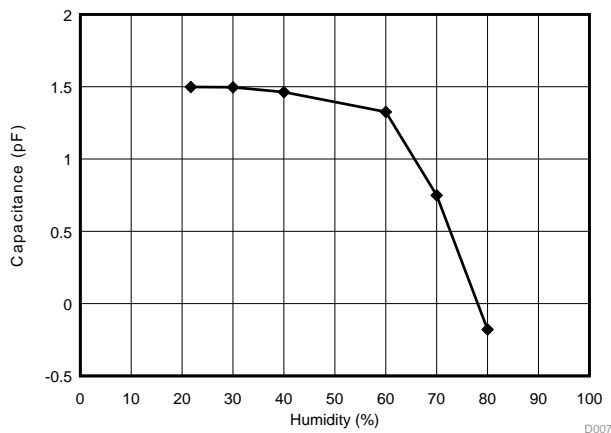
Figure 32. FDC Output versus Humidity
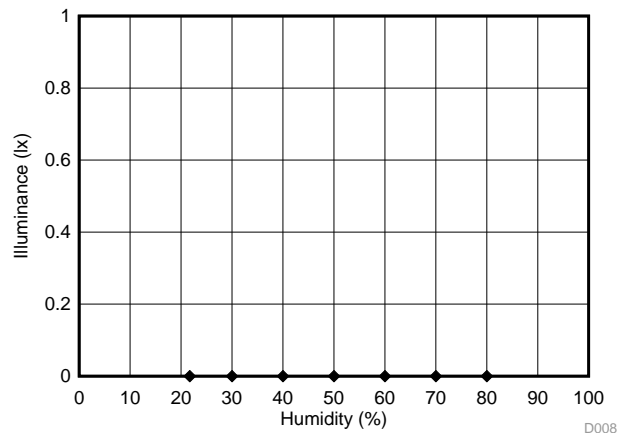
Figure 33. Darkness Response versus Humidity

9   Design Files

9.1   Schematics

To download the most recent schematics, see the design files at TIDA-00373.

9.2   Bill of Materials

To download the most recent bill of materials (BOM), see the design files at TIDA-00373.

9.3   Layer Plots

To download the most recent layer plots, see the design files at TIDA-00373.

9.4   Altium Project

To download the most recent Altium project files, see the design files at TIDA-00373.

9.5   Gerber Files

To download the most recent Gerber files, see the design files at TIDA-00373.

9.6   Software Files

To download the most recent software files, see the design files at TIDA-00373.

10   References

1. Microsoft, *Understanding and Interpreting Lux Values* (https://msdn.microsoft.com/en-us/library/windows/desktop/dd319008%28v=vs.85%29.aspx)

11   About the Author

JARROD KREBS is a systems designer at Texas Instruments, where he is responsible for developing reference designs in the industrial segment. Jarrod has experience with software and embedded applications implemented on ARM-based microcontrollers and TI's MSP430 platforms. Jarrod earned his bachelor of science in computer engineering from Kansas State University in Manhattan, KS. Jarrod is also a member of the Institute of Electrical and Electronics Engineers (IEEE).

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