TI Designs

Capacitive Touch Thermostat User Interface With CapTIvate™ Technology

TI Designs

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

TIDM-CAPTIVATE-THERMOSTAT-UI	Tool Folder Containing Design Files
MSP430FR2633	Product Folder
TIDM-FRAM-THERMOSTAT	Design Folder
CapTIvate Design Center	Tool Folder

TI E2E™ Community

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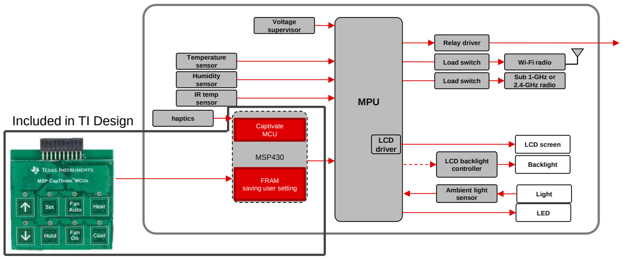
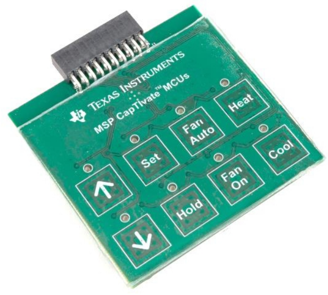
Design Features

- MSP430™ CapTIvate™ MCU for Capacitive Touch Sensing
- CapTIvate Design Center Support Enabling Real-Time Customization of Response Time, Sensitivity, and Other Parameters from a Host PC
- Multiple Modes of Operation, Including a Battery-Powered Mode for Increased Battery Life and a Line-Powered Mode for Increased Noise Immunity
- Less Than 50 µA Average Current in Battery-Powered Mode, Allowing for 2 Years of Battery Life on AAA Batteries
- Conducted Noise Immunity at the Commercial Product Level (IEC 61000-4-6 Class A at 3 Vrms) in Line-Powered Mode
- Mutual Capacitance Technology Enables 8 Buttons With Only 6 MCU Pins
- Maintained State and Momentary Capacitive Switch Implementations
- Ferroelectric Random Access Memory (FRAM) Enables Button State and Configuration Retention Through Power Loss

Featured Applications

- Capacitive Touch Thermostat User Interface





1 Key System Specifications

Table 1 lists the key system specifications of the TIDM-CAPTIVATE-THERMOSTAT-UI.

Table 1. Key System Specifications

FEATURE	SPECIFICATION	ADDITIONAL DETAILS
Button Count	8 mutual capacitance buttons	Section 4
Touch Panel Size	2.5 inch × 2.5 inch	Section 8
Response Time	Battery-power configuration: **100 ms typical**	Section 7.3
	Wall-power configuration: **110 ms typical**	
Power Consumption	Battery-power configuration: **44 µA**	Section 7.2
	Wall-power configuration: **1.33 mA**	
Noise Immunity Performance	Pass IEC 61000–4–6 Class A at 3 Vrms	Section 7.1
Featured MCU–MSP430FR2633	The MSP430FR2633 is a low-power, FRAM MCU with integrated CapTIvate Technology for capacitive sensing	Section 2.2
MSP430FR2633 Memory Footprint	Battery-power configuration: 824 B of RAM, 4.1 KB of FRAM	For more information, refer to (SLAS942)
	Wall-power configuration: 976 B of RAM, 5.2 KB of FRAM	

2 System Description

2.1 Introduction

A thermostat is a device that measures and controls the temperature of an indoor environment to a chosen set-point. Thermostats control temperature by managing the activity of various HVAC subsystems, such as heating and cooling units, and fans. A key component of a thermostat is the user interface, which includes a small collection of buttons.

The TIDM-CAPTIVATE-THERMOSTAT-UI is a reference design for a low-power, capacitive touch, thermostat user interface. The simple interface is comprised of eight buttons formed by a mutual capacitance sensor matrix. The use of a matrix enables all eight buttons to be measured using only six inputs on an MSP430FR2633 CapTIvate device. MSP430FR2633 enables the design to provide robust capacitive touch sensing, low-power operation, and high immunity to noise with low response time.

2.2 MSP430FR2633 CapTIvate MCU

The MSP430FR2633 is an ultra-low-power, FRAM-based MSP430 MCU featuring CapTIvate Technology. CapTIvate Technology is TI’s new, robust capacitive sensing solution. The integration of this technology with the strong MSP430 peripheral set makes the MSP430FR2633 an ideal MCU for user interface development.

Features:

- 16 CapTIvate inputs that can support up to 64 electrodes in mutual-capacitance mode
- Parallel scanning of up to four electrodes at a time
- CapTIvate Software Library included in a preprogrammed 12KB of ROM
- Four 16-bit timers and a 16-bit counter-only real-time clock (RTC)
- Three Enhanced Serial Communications peripherals for UART, IrDA, SPI, and I^{2}C
- 19 I/Os with 16 interrupt pins for wakeup from low-power modes
- High-performance, 8-channel, 10-bit analog-to-digital (ADC) converter
- Clock system with an operating speed of up to 16 MHz

3 Block Diagram

3.1 Thermostat Block Diagram

Figure 1 shows how the TIDM-CAPTIVATE-THERMOSTAT-UI is used in a thermostat design.

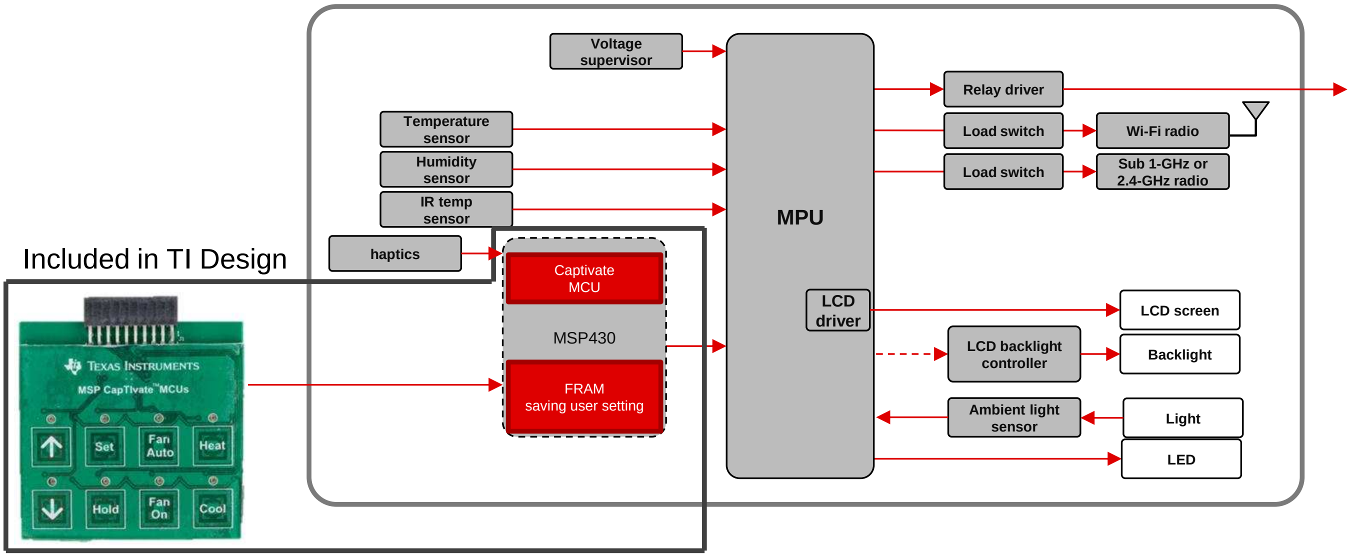


Figure 1. Example Thermostat Block Diagram

3.2 MSP430FR2633 MCU Block Diagram

MSP430FR2633 MCUs feature a diverse peripheral set that makes them ideal for use in many capacitive sensing applications. Figure 2 shows the block diagram of the MSP430FR2633 MCU.

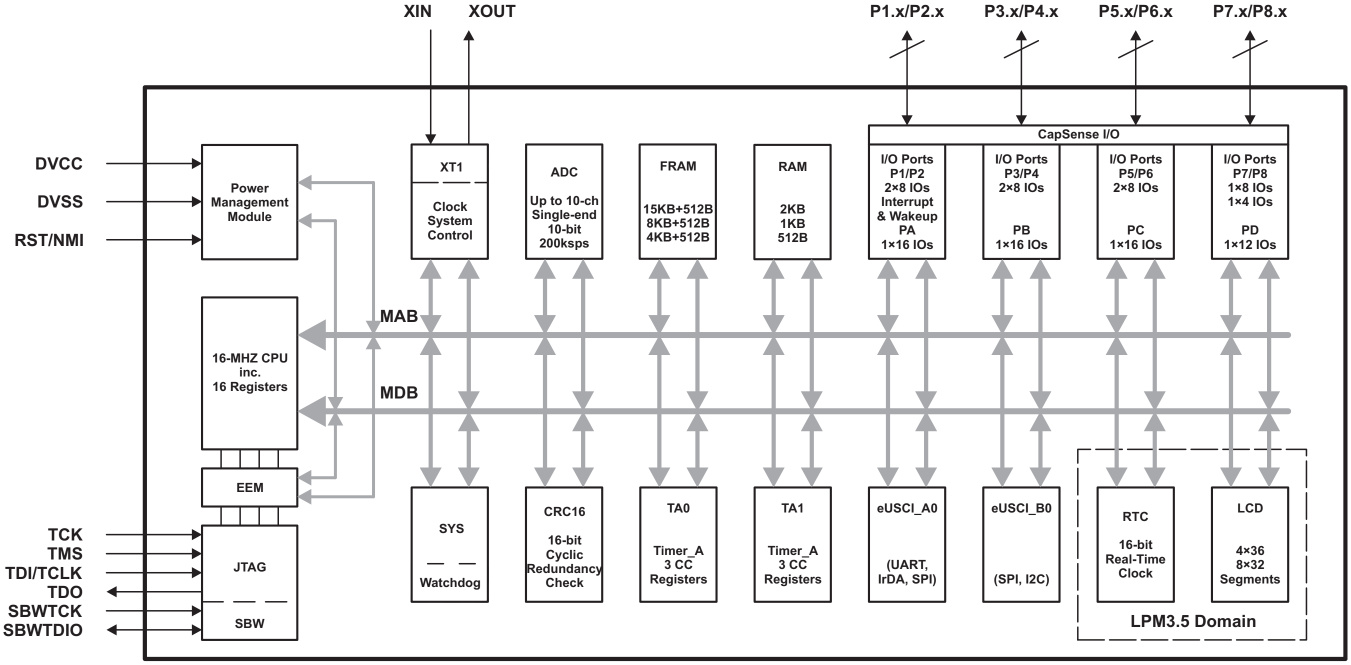


Figure 2. Block Diagram of MSP430FR2633

3.3 CapTIvate Technology Block Diagram

CapTIvate Technolagy enables capacitive sensing on the TIDM-CAPTIVATE-THERMOSTAT-UI. CapTIvate Technology is an MSP peripheral dedicated to providing robust capacitive sensing measurements. Figure 3 shows the block diagram of the CapTIvate peripheral.

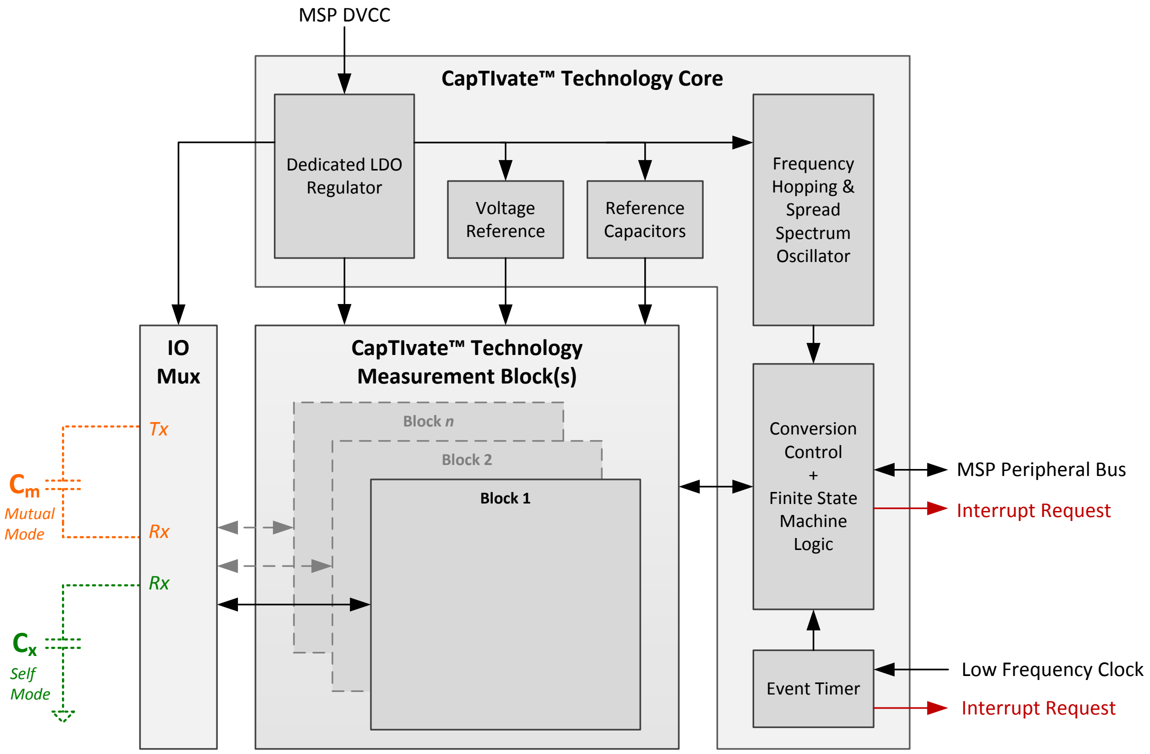


Figure 3. CapTIvate Technology Block Diagram

4 System Design Theory

4.1 Functional Design Overview

The TIDM-CAPTIVATE-THERMOSTAT-UI reference design uses eight mutual-capacitance sensors to implement its 8-button thermostat user interface. A benefit of capacitive sensing in this design is that the capacitive sensor elements in the thermostat interface require no mechanical parts, which allows for a slimmer product. The user can also use the same physical button layout for all buttons on the interface, which can act as both momentary and maintained switches. Figure 4 shows the TIDM-CAPTIVATE-THERMOSTAT-UI fully assembled with a 2.5 mm polycarbonate overlay.

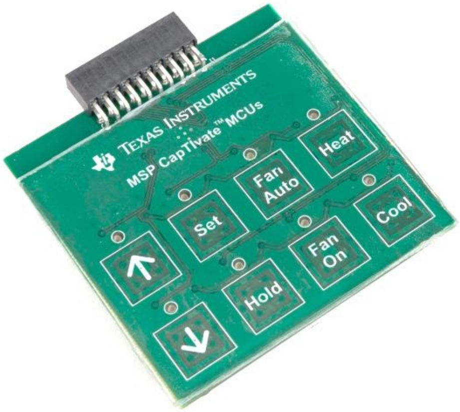


Figure 4. TIDM-CAPTIVATE-THERMOSTAT-UI

The TIDM-CAPTIVATE-THERMOSTAT-UI is designed for an onboard MSP430FR2633 CapTIvate MCU with FRAM. FRAM, also known as FeRAM, is a memory technology that combines the best of flash and static random-access memory (SRAM). FRAM is a nonvolatile memory that offers fast, low-power writes with an endurance of 10^{15} cycles. The FRAM is used in this design to retain the configuration and state of the thermostat through power loss, while maintaining a low-power profile. Figure 5 shows how the MCU and the LEDs are mounted on the back of the design.

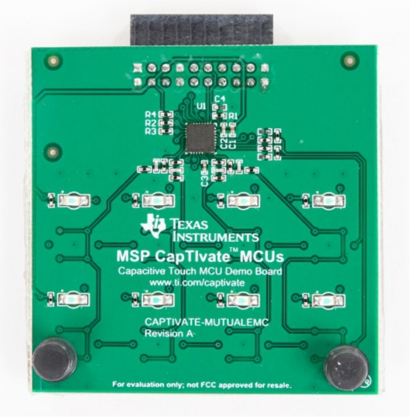


Figure 5. Bottom View of the Thermostat UI

4.2 Capacitive Touch and Mutual Capacitance Theory

Capacitive sensing is the ability to measure and detect the change in the capacitance of a sensor. When this change is due to human interaction, the technique is referred to as capacitive touch sensing. There are two distinct implementations of capacitive sensors, self and mutual. Buttons in the thermostat interface are designed as mutual-capacitance sensors. Mutual capacitance sensors are composed of two separate electrode structures, each acting as a plate in a capacitor. One electrode is referred to as a transmit electrode (Tx) and the other is a receive (Rx) electrode.

User interaction with a mutual capacitance sensor is identified by detecting a change in the electric field between a Tx and Rx electrode. Because a person is coupled to earth ground and the human body is a conductor, a touch between the electrodes has roughly the same effect as placing a ground between them. It reduces the electric field coupling between the electrodes and reduces the overall capacitance. A touch is identified when this change in capacitance is above a specified threshold.

4.2.1 CapTIvate Technology

CapTIvate Technology performs capacitive sensing measurements using a unique charge transfer technique. This technique is based on the principle that a capacitor is a charge storage device. A capacitive touch electrode holds a certain amount of charge when a specific voltage is applied to it.

CapTIvate Technology measures the amount of charge stored on an external capacitor (electrode or sensor) by charging it at a DC voltage, then transferring the stored charge into a “charge bucket” much larger than the external capacitor. The “charge bucket” is implemented as a large, internal sampling capacitor. By repeating the charge and transfer process until the sampling capacitor is full, CapTIvate Technology provides a relative measurement of the size of the external capacitor.

CapTIvate Technology can support up to 16 self-capacitance electrodes or 64 mutual-capacitance electrodes at the same time. CapTIvate Technology also provides a set of hardware tools for accommodating a wide range of external capacitances. For more information on CapTIvate, see the *CapTIvate Technology Guide*, www.ti.com/CapTIvateTechGuide.

4.3 Noise Immunity

A major advantage of this thermostat user interface is that it is designed for increased noise immunity. Noise immunity is especially important in capacitive touch sensing applications because they must be able to measure very small changes in capacitance. Changes in capacitance measured on a capacitive sensing electrode are often on the order of 1 pF or less. Capacitive touch circuits that might be exposed to electrically noisy environments must be designed with noise immunity in mind to ensure they can consistently resolve a measurement of this size.

4.3.1 Conducted RF Noise Introduction

Conducted RF interference is interference that couples with a system or device by direct contact with a conductive body, such as through cables, wires, and PCB traces. A common way for conducted noise to couple with a system that uses capacitive touch sensing is through its power supply.

Be aware of conducted RF noise when designing capacitive touch systems because it can cause the injection of noise currents into capacitive touch I/Os. These currents can make the capacitances on the I/Os appear larger or smaller than they actually are. If a capacitive I/O is measured when this happens, a failure to detect a touch or false touch detection may occur.

4.3.2 EMC With CapTIvate Technology

When capacitive sensors are measured by an MCU, they are generally measured at a specific scan frequency. Scanning sensors at a single frequency results in high susceptibility to conducted noise that propagates near the scan frequency or its harmonics. To prevent this from happening, the CapTIvate Technology enables frequency hopping, which is the ability to scan capacitive sensors at up to four different frequencies. Each scan frequency used results in a separate measurement of the sensor. When conducted noise impacts data from one of the measurements, data from the other measurements can be used to detect the noise and resolve a proper measurement with a multi-frequency processing (MFP) algorithm.

Frequency hopping is just one of the EMC features provided by the CapTIvate peripheral. For more information on the EMC features provided by the CapTIvate Technology, see the *CapTIvate Technology Guide*, www.ti.com/CapTIvateTechGuide.

4.3.3 Filter Elements

The TIDM-CAPTIVATE-THERMOSTAT-UI uses 68 pF capacitors to ground on the CapTIvate I/O Rx lines to further increase noise immunity. These capacitors provide stability to Rx lines by providing a shunt path to circuit return for noise currents. The observed effect of adding the capacitors is a reduction in the width of the band of frequencies, around each scan frequency, in which noise can impact sensor measurements. For mutual capacitance designs with CapTIvate Technology, it is recommended to include provisions for a 33 pF to 68 pF capacitor to circuit ground in case they are required during development. Using a capacitor closer to 68 pF provides the most reduction in width, but it also contributes more to parasitic capacitance.

4.3.4 Electrode Geometry

The sensors on the TIDM-CAPTIVATE-THERMOSTAT-UI are designed to increase the coupling between the Tx and Rx electrodes and reduce parasitic capacitances. Figure 6 shows the layout of a single sensor.

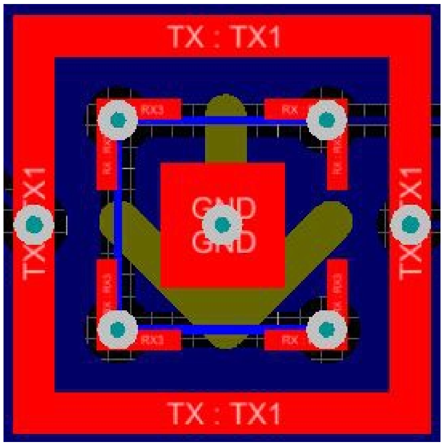


Figure 6. Down Button Electrode Geometry

The electric field coupling between the Tx and Rx electrodes is strongest near their corners. This section of the electric field is the part that a user interacts with the most during a touch. As a result, the coupling contributed by the edges of the senor acts mostly as parasitic capacitance. In this design, the edges of the Rx electrodes are removed to reduce parasitic capacitance. A ground plane is placed in the center of the sensor to keep the Rx and Tx electrode tightly coupled. The tight coupling that is forced between the two electrodes improves their resistance to external noise and allows for buttons which use this design to be spaced close together.

5 Getting Started With Hardware

The TIDM-CAPTIVATE-THERMOSTAT-UI will not be sold on the TI store. Hardware design files are provided with the TI Design so that it may be replicated. Alternatively, an MSP-CAPT-FR2633 Development Kit can be purchased to evaluate the CapTIvate Technology in a wide range of capacitive touch configurations. The kit includes a CapTIvate MCU EVM and multiple touch panels that demonstrate the use of CapTIvate Technology in different capacitive touch applications. These touch panels interface directly into the EVM for easy plug-and-play use.

Unlike the touch panels included in the MSP-CAPT-FR2633, the TIDM-CAPTIVATE-THERMOSTAT-UI was designed with an onboard MSP430FR2633 instead of with an interface to the CapTIvate MCU EVM. This was done to improve noise immunity. A large connector between the panel and the EVM would have been a significant source of noise. To use the TIDM-CAPTIVATE-THERMOSTAT-UI, plug it directly into an CAPTIVATE-PGMR.

6 Getting Started With Firmware

The example firmware developed for the TIDM-CAPTIVATE-THERMOSTAT-UI was developed using CCS v6.1.0.00104 and TI Compiler version 4.4.3. To evaluate the example firmware, download the latest version of CCS. The example projects can be imported into a CCS workspace from [TI Design Software Install Root]/Firmware/Source/*.

6.1 Thermostat Application–Stand-alone

The source code of the demo application for the thermostat is organized in multiple files, listed in Table 2.

Table 2. Source Code Files for Demo Application

NAME	DESCRIPTION
main.c	Application main function
Thermostat_UI_Demo.h	Demo initialization and typdefs header file
Thermostat_UI_Demo.c	Demo initialization and touch event handler file
Thermostat_UI_LEDs.h	LED definitions and macros header file
Thermostat_UI_LEDs.c	LED update function file

The demo application simulates a programmable thermostat with control over temperature, a fan unit, and a heating and cooling unit. The states of the units that the thermostat controls are displayed through the LEDs on the touch panel. Although the TIDM-CAPTIVATE-THERMOSTAT-UI cannot display the selected temperature, it is maintained as a variable in FRAM for debug purposes. Each time the UP and DOWN buttons are pressed, the temperature variable increases or decreases by one degree, respectively.

NOTE: Tuning of the keypad in the examples was set for a TIDM-CAPTIVATE-THERMOSTAT-UI assembled with a 2.54-mm polycarbonate cover over the buttons.

Two example CCS projects are provided that run the stand-alone thermostat demo application using different sensor configurations.

6.1.1 Wall-power Example

The wall-power example project runs the thermostat demo application with the conducted noise immunity feature of the CapTIvate Software Library enabled. The wall-power example also uses heavy debouncing and filtering to ensure that noisy samples have a smaller impact on performance. A small scan delay is used to ensure the design responds quickly to touch even with the increased requirements for measurement time and post-processing.

6.1.2 Battery-power Example

The battery-power example keeps noise immunity off and uses an extended scan delay to reduce CPU activity. No debounce and minimal filtering is used in the battery-power example to keep response time low with higher scan delay. The battery-power configuration uses significantly less power, but it provides less protection against noise. The trade off between power and noise immunity is made in an application such as a battery-powered thermostat remote.

6.2 Thermostat Application–With TIDM-FRAM-THERMOSTAT

A capacitive touch microcontroller may act as a main application processor, or it could simply be used as a dedicated human-machine interface (HMI). An example project is provided with the TIDM-CAPTIVATE-THERMOSTAT-UI that demonstrates how it could be used as a dedicated HMI for TIDM-FRAM-THERMOSTAT. Separate source code is provided for the TIDM-FRAM-THERMOSTAT that includes master I^{2}C drivers for interfacing with the touch panel.

When using the two together, the LCD of the TIDM-FRAM-THERMOSTAT can be controlled with the TIDM-CAPTIVATE-THERMOSTAT-UI. Figure 7 shows the application running using the designs.

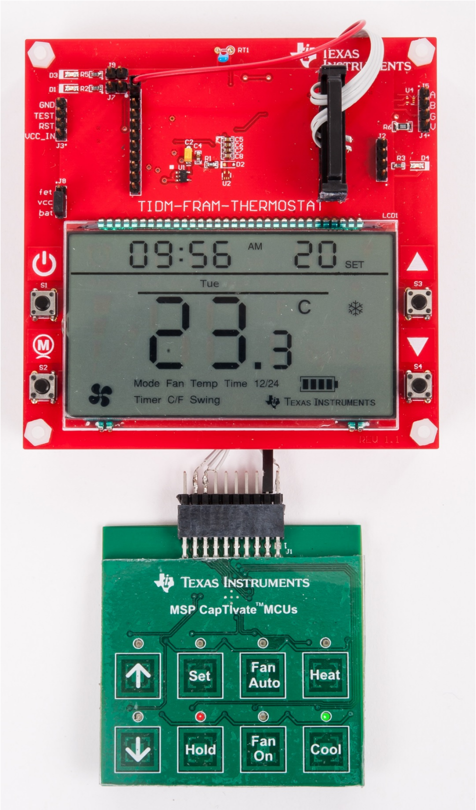


Figure 7. TIDM-CAPTIVATE-THERMOSTAT-UI With TIDM-FRAM-THERMOSTAT

The application requires the powering of the TIDM-CAPTIVATE-THERMOSTAT-UI by the TIDM-FRAM-THERMOSTAT. Power the TIDM-CAPTIVATE-THERMOSTAT with the TIDM-FRAM-THERMOSTAT by connecting the designs using female-to-male jumper wires. Table 3 shows a complete list of connections that are required to interface the designs.

Table 3. Required Device Connections

TIDM-FRAM-THERMOSTAT	TIDM-CAPTIVATE-THERMOSTAT-UI
VCC	VCC
GND	GND
SDA/SIMO (P5.2)	SDA (P1.2)
SCL/SOMI (P5.3)	SCL (P1.3)
GPIO 0 (P1.2)	IRQ (P1.1)

7 Testing

This section describes the testing that was performed on the TIDM-CAPTIVATE-THERMOSTAT-UI. It includes descriptions of test setups and results for conducted RF immunity testing, power profiling, and response time measurement.

7.1 Conducted RF Immunity Testing (IEC 61000-4-6)

IEC 61000-4-6 specifies constraints for a conducted noise immunity test over a range of 150 kHz to 80 MHz. The TIDM-CAPTIVATE-THERMOSTAT-UI was tested for conducted noise in the range of 300 kHz to 80 MHz.

7.1.1 Pass/Fail Criteria

A class B pass for the IEC 61000-4-6 requires no false detects by the capacitive touch system during the test and no unintentional resets by the MCU. Unintentional resets include unintentional MCU lockup. A class A pass requires no false detects allowed at any time during the test while the system detects all valid touches. The same restrictions for unintentional resets as for class B apply for class A.

7.1.2 Setup and Test Procedure

Figure 8 shows the setup used to test the TIDM-CAPTIVATE-THERMOSTAT-UI according to IEC 61000-4-6.

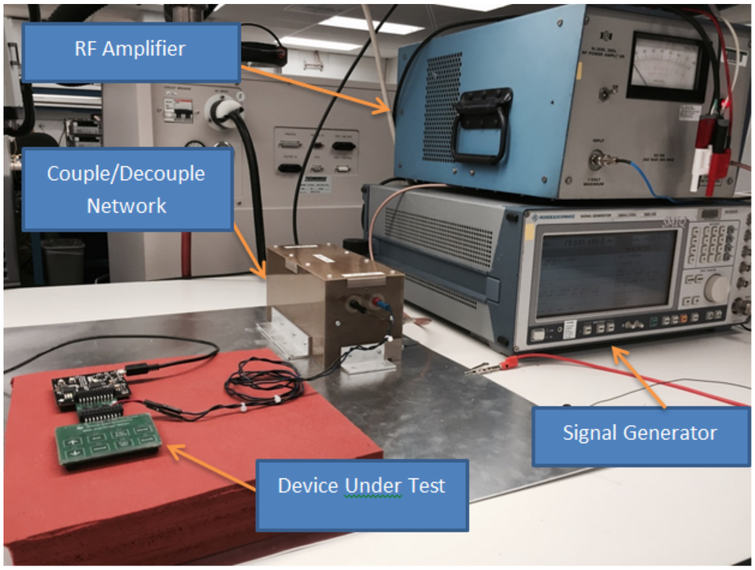


Figure 8. IEC 61000-4-6 Test Setup

In the setup, the board is approximately 10 cm above earth ground and is powered from a couple/decouple network that couples noise to the output of the power supply (power supply is not shown in Figure 8). A signal generator was used to generate a sinusoidal noise sweep from 300 kHz to 80 MHz, amplitude modulated on a 1 kHz sinusoidal carrier frequency at 80% depth. An RF amplifier was used to bring the noise signal up to a 3 Vrms stress level.

Data from the sensors on the touch panel was collected using the CapTIvate Design Center. The touch panel was connected to the Design Center GUI through the back channel UART through an CAPTIVATE-PGMR. The CAPTIVATE-PGMR was independently powered and isolated from the touch panel power supply with a CAPTIVATE-ISO isolation board during testing.

In the first test, measurements of an untouched button on the touch panel were recorded at four scan frequencies while noise was injected into the power supply. The measurements were continuously recorded while a frequency sweep was performed on the noise across the range of 300 kHz to 80 MHz. During the test, no false touches were recorded on any of the buttons. Figure 9 shows the raw data collected at each scan frequency.

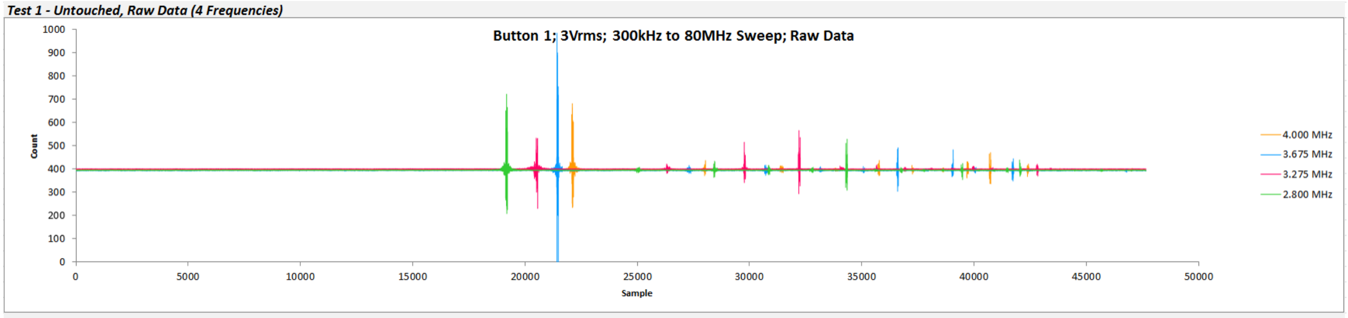


Figure 9. Untouched, Raw Data (Counts vs Time)

Disruptions in the raw data can be seen at various points during the frequency sweep. The first four peaks can be identified as points when the noise coupled with the power supply was at a fundamental scan frequency. The smaller peaks that occur in later samples can be understood to be points when the noise was at harmonics of the four scan frequencies. Though measurements from each individual scan frequency were disrupted by the noise, the processed measurement remained consistent throughout the sweep, as shown in Figure 10.

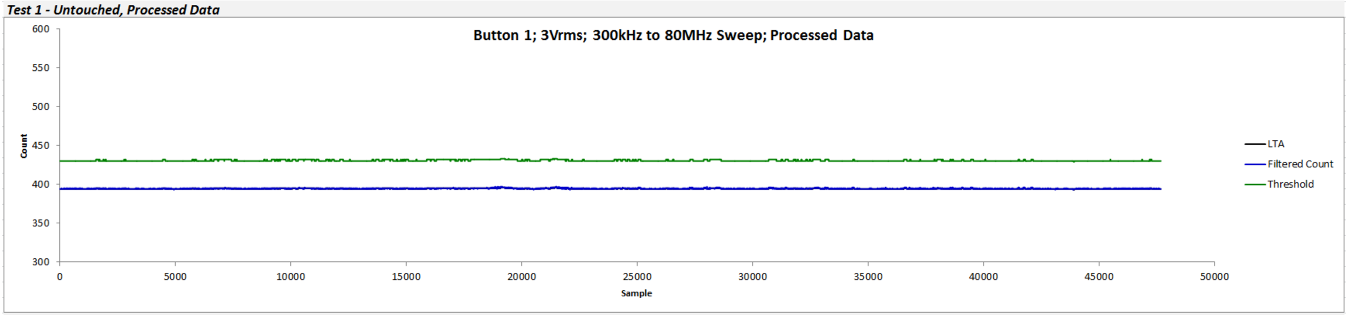


Figure 10. Untouched, Processed Data (Counts vs Time)

Throughout the frequency sweep, the filtered count value was steady and below the threshold value. The sensor constantly recorded **no touch** throughout the test, as expected.

The second test was conducted in the same manner as the first, except that a metal probe was applied to the button to simulate a touch during the frequency sweep. The TIDM-CAPTIVATE-THERMOSTAT-UI correctly identified a touch for the entire duration of the test. Figure 11 shows the raw data recorded on each scan frequency.

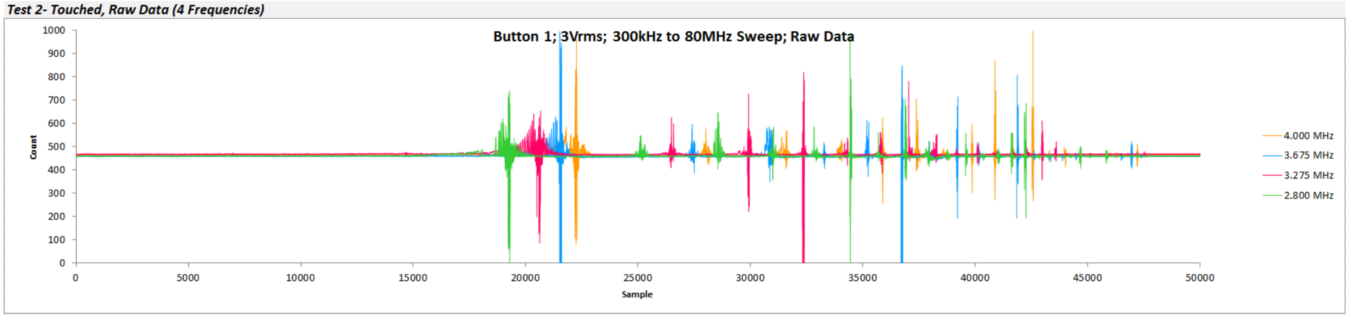


Figure 11. Touched, Raw Data (Count vs Time)

The raw data shows that the measurements were disrupted in wider bands around the four scan frequencies than in the untouched case. However, the filtered output of the CapTIvate Technology is consistently in the touch range as expected. Some noise appears in the filtered output when it is stressed to this degree, but the performance of the interface is not impacted. These results meet the IEC 61000-4-6 Class A requirements. Figure 12 shows the processed data from the test.

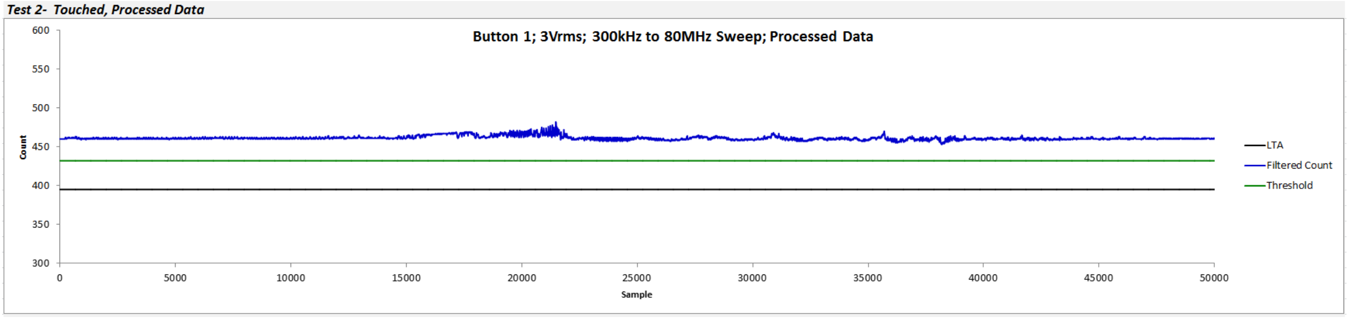
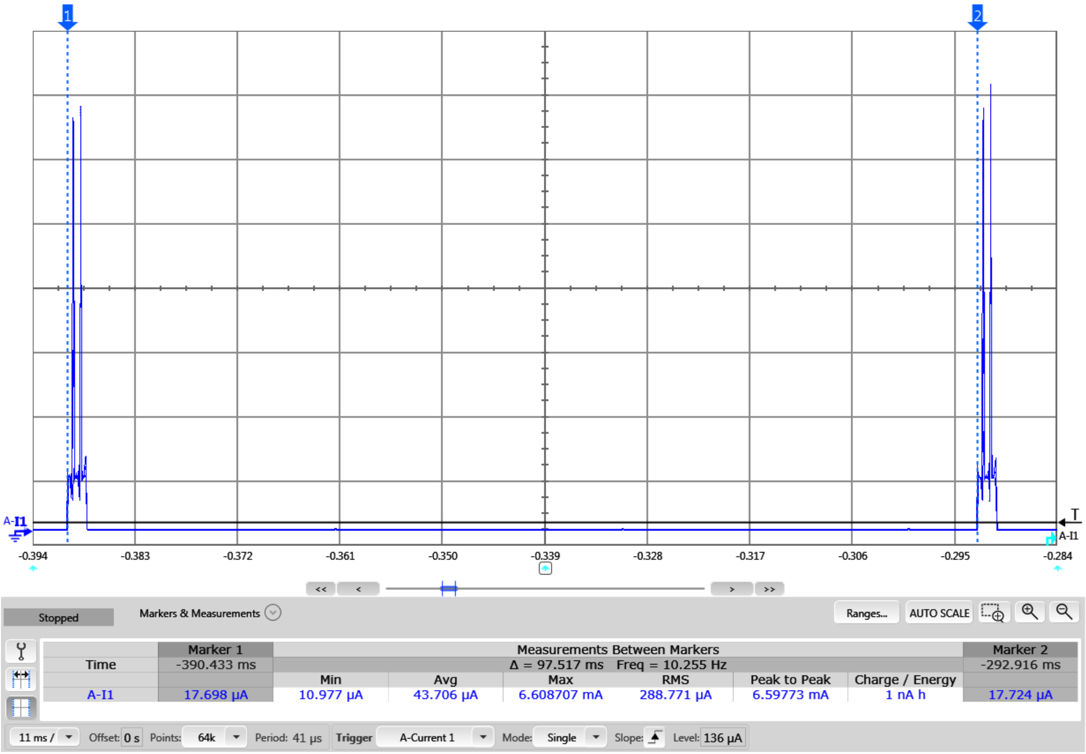


Figure 12. Touched, Processed Data (Counts vs Time)

7.2 *Power Profile*

Power profiles for the TIDM-CAPTIVATE-THERMOSTAT-UI in each provided example application were collected using a DC Power Analyzer. The DC Power Analyzer was used to supply a 3.3-V input voltage to the touch panel and measure current consumption. For the power testing, the LEDs that are normally used to indicate touch on the design were kept off. The example software can be run in the power testing mode by uncommenting the POWER_TESTING symbol in the Thermostat_UI_Demo.h file. The LEDs were kept off while testing to provide a better representation of the power consumption of the MSP430FR2633 CapTIvate MCU with the different configurations. The LEDs were also kept off because they are not an integral part of the design and could be removed in an end-product. Figure 13 shows the current consumption for the design while running the battery-powered example.

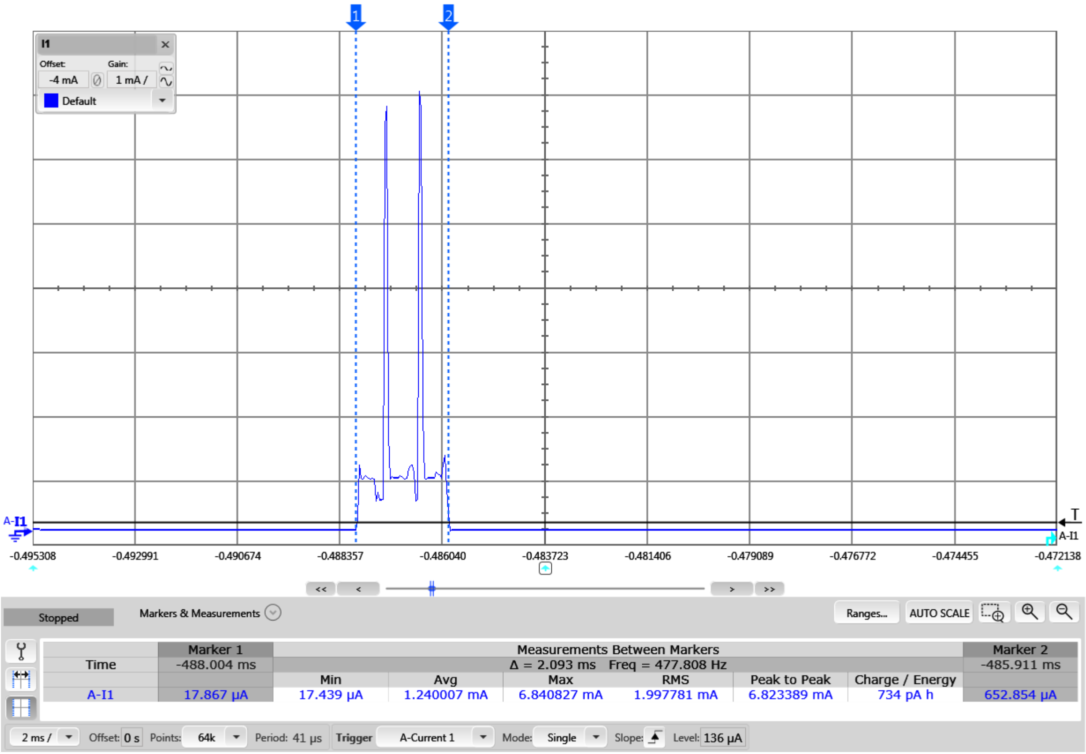


	Marker 1	Measurements Between Markers						Marker 2
Time	-390.433 ms	Δ = 97.517 ms Freq = 10.255 Hz						-292.916 ms
		Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	
A-I1	17.698 µA	10.977 µA	43.706 µA	6.608707 mA	288.771 µA	6.59773 mA	1 nA h	17.724 µA

11 ms / Offset: 0 s Points: 64k Period: 41 µs Trigger A-Current 1 Mode: Single Slope: Level: 136 µA

Figure 13. Power Profile for Battery-powered Example, Two Measurements (Current vs Time)

Two measurement periods separated by a scan delay are represented in Figure 13. The average current consumption for a single measurement period and sleep cycle with the battery-power optimization is around 43.7 µA. Figure 14 shows a more detailed view of the current consumption during the measurement period.



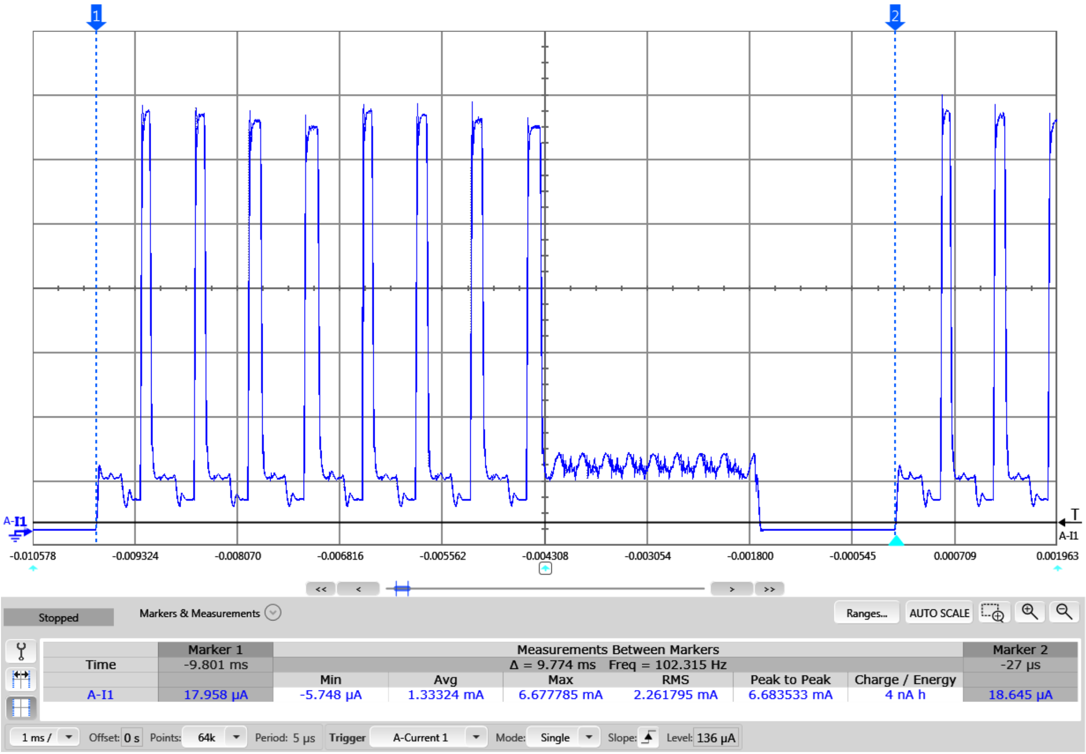
Offset: -4 mA Gain: 1 mA /

	Marker 1	Measurements Between Markers						Marker 2
Time	-488.004 ms	Δ = 2.093 ms Freq = 477.808 Hz						-485.911 ms
		Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	
A-I1	17.867 µA	17.439 µA	1.240007 mA	6.840827 mA	1.997781 mA	6.823389 mA	734 pA h	652.854 µA

2 ms / Offset: 0 s Points: 64k Period: 41 µs Trigger A-Current 1 Mode: Single Slope: Level: 136 µA

Figure 14. Power Profile for Battery-powered Example, Single Measurement (Current vs Time)

The maximum current consumption occurs while the device is measuring the buttons on the keypad sensor. Two distinct peaks in current occur during these times, because the buttons on the sensors are organized into two separate measurement cycles. Therefore, two measurement cycles are needed to update the status of the entire keypad. The amount of time required to measure the buttons in this battery-powered mode is much shorter than in the wall-powered mode because the buttons are scanned at only one frequency. Figure 15 shows the current consumption in the wall-powered mode.



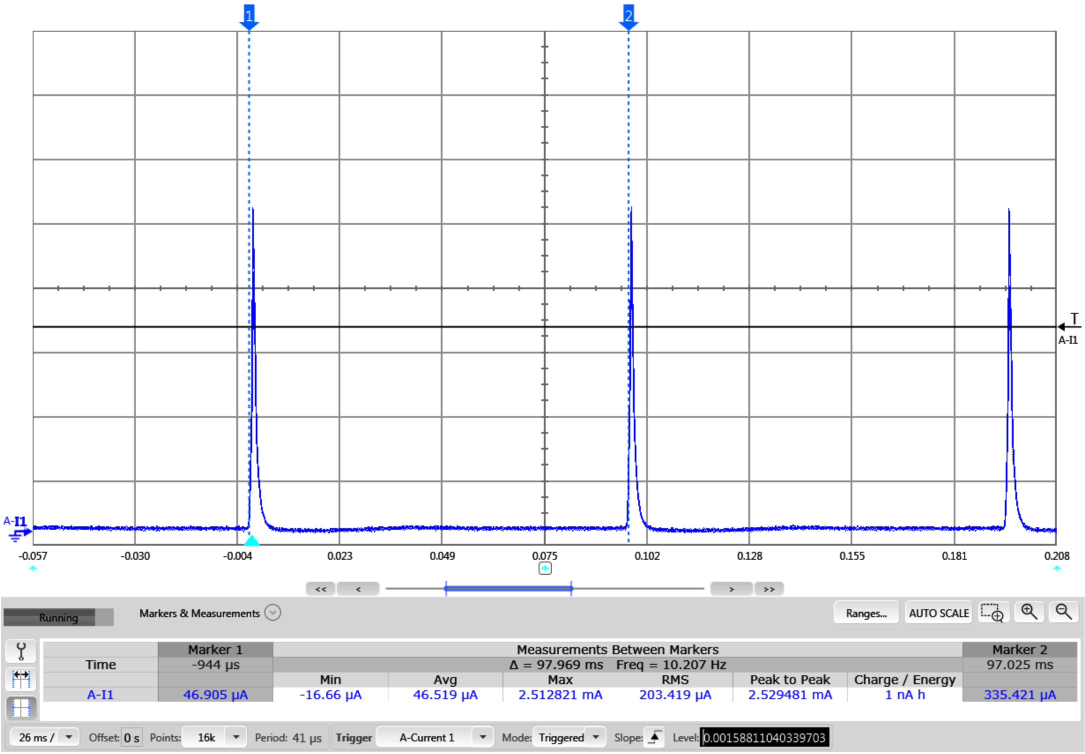
	Marker 1	Measurements Between Markers						Marker 2
Time	-9.801 ms	Δ = 9.774 ms Freq = 102.315 Hz						-27 µs
		Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	
A-I1	17.958 µA	-5.748 µA	1.33324 mA	6.677785 mA	2.261795 mA	6.683533 mA	4 nA h	18.645 µA

1 ms / Offset: 0 s Points: 64k Period: 5 µs Trigger A-Current 1 Mode: Single Slope: Level: 136 µA

Figure 15. Power Profile for Wall-Powered Example (Current vs Time)

With the wall-powered example, the current consumption is approximately 1.33 mA. The current consumption is significantly higher than in the battery-powered mode because each cycle is measured four times instead of once, for a total of eight measurement cycles. There is also more post-processing that is applied to the measurements than in the battery-powered example. To accommodate a low response time with the extended measurement time and additional post-processing, the scan delay is only 10 ms. As a result, the device spends most of its time out of low-power mode.

The example code provided for interfacing the TIDM-CAPTIVATE-THERMOSTAT-UI with the TIDM-FRAM-THERMOSTAT is based on the battery-power stand-alone example. The battery-power sensor configuration allows for the demo that combines the two designs to keep a low-power profile. Figure 16 shows the current consumption of the two designs together when running the combined demo.

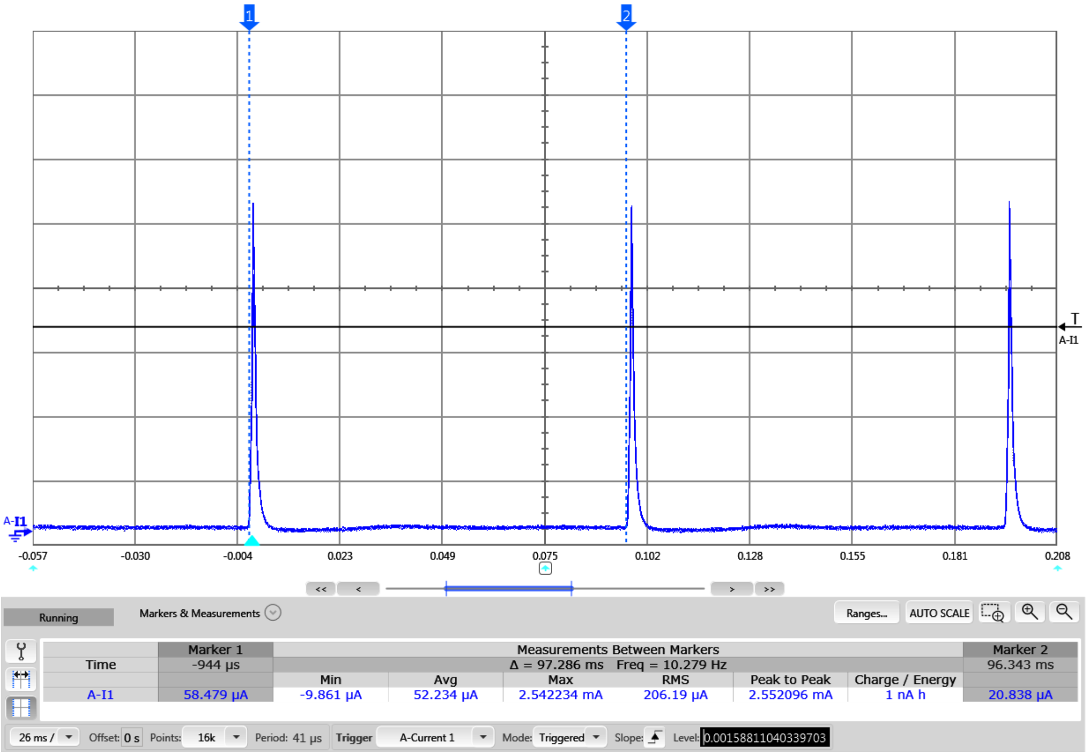


	Marker 1	Measurements Between Markers						Marker 2
Time	-944 µs	Δ = 97.969 ms Freq = 10.207 Hz						97.025 ms
		Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	
A-I1	46.905 µA	-16.66 µA	46.519 µA	2.512821 mA	203.419 µA	2.529481 mA	1 nA h	335.421 µA

26 ms / Offset: 0 s Points: 16k Period: 41 µs Trigger A-Current 1 Mode: Triggered Slope: Level: 0.00158811040339703

Figure 16. Power Profile for the TIDM-CAPTIVATE-THERMOSTAT-UI With the TIDM-FRAM-THERMOSTAT Example With LCD Off (Current vs Time)

As shown in Figure 16, the current consumption of the demo when the LCD is off is approximately 46.5 µA. The amount of current consumption is possible because the TIDM-FRAM-THERMOSTAT is only pulled out of its low-power mode (LPM3) when it must make a new temperature measurement or update the LCD. While in LPM3, the TIDM-FRAM-THERMOSTAT draws less than 3 µA on average. Figure 17 shows how the power consumption increases when the LCD is on.



	Marker 1	Measurements Between Markers						Marker 2
Time	-944 µs	Δ = 97.286 ms Freq = 10.279 Hz						96.343 ms
		Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	
A-I1	58.479 µA	-9.861 µA	52.234 µA	2.542234 mA	206.19 µA	2.552096 mA	1 nA h	20.838 µA

26 ms / Offset: 0 s Points: 16k Period: 41 µs Trigger A-Current 1 Mode: Triggered Slope: Level: 0.00158811040339703

Figure 17. Power Profile for the TIDM-CAPTIVATE-THERMOSTAT-UI With the TIDM-FRAM-THERMOSTAT Example With LCD On (Current vs Time)

The power profile of the demo when the LCD is turned on is identical to when it is off, except with an additional 5.7 µA of baseline current used to power the LCD. The total average current is 52.2 µA, which is low enough for approximately 2 years of lifetime on AAA batteries.

7.3 Response Time

Response time is the amount of delay between a touch on a user interface and the response to that touch. The response time of an interface often has a big impact on user experience. When developing capacitive touch interfaces, response time should be kept as low as possible.

The worst-case response time of the TIDM-CAPTIVATE-THERMOSTAT-UI was evaluated for the wall-power and battery-power applications. Worst-case response time is characterized by a touch on a button made immediately after a measurement of that button completes. The resulting worst-case delay can be estimated by adding the delay between proximity detection and touch detection to the scan period. The estimate is actually an overestimate of typical response time because proximity detection normally occurs before a touch occurs. It is also a worst-case response time because most touches would not occur a full scan period before measurement.

In the battery-power application, no delay was observed between proximity detection and a registered touch. No delay is observed because there are no debounce features and minimal filtering is performed on measurements in battery mode to keep power consumption low. The scan period is set to 0.1 second in the battery application. As a result, the worst-case response time is dominated by the scan period and is approximately 0.1 second.

In the wall-power application, heavy debouncing and filtering are used to decrease susceptibility to noisy measurements. The post-processing of measurements causes the delay between detecting proximity and registering a touch to vary according to the speed and nature of a touch. The delay is smaller when a finger approaches the panel quickly. The delay is also smaller when the surface area of a touch is larger.

The worst-case response time for the wall-power configuration was evaluated by measuring the response time for a set of 10 touches. Table 4 provides the data collected during the testing.

Table 4. Wall-Power Response Time Measurements

TOUCH NUMBER	PROXIMITY TO TOUCH DETECTION DELAY (SECONDS)	SCAN PERIOD (SECONDS)	APPROXIMATE TOTAL RESPONSE TIME (SECONDS)
1	.0880	.010	.0980
2	.0782		.0882
3	.0684		.0784
4	.0684		.0784
5	.1173		.1273
6	.1076		.1176
7	.0782		.0882
8	.0978		.1078
9	.2054		.2154
10	.0978		.1078
Avg	***0.1007***		***0.1107***

As seen in Table 4, the response time for the wall-power application was dominated by the measurement time and post-processing performed by the CapTIvate Technology. The result is an average approximate response time of 0.1107 seconds. Table 5 lists the response times in the battery-power application and wall-power application for comparison.

Table 5. Response Time Comparison

CONFIGURATION	APPROXIMATE RESPONSE TIME (SECONDS)
Battery-power application	0.10
Wall-power application	0.11 average

8 Design Files

8.1 Schematic

To download the schematic for the TIDM-CAPTIVATE-THERMOSTAT-UI, see the design files at http://www.ti.com/tool/TIDM-CAPTIVATE-THERMOSTAT-UI. Figure 18 shows the schematic for the design.

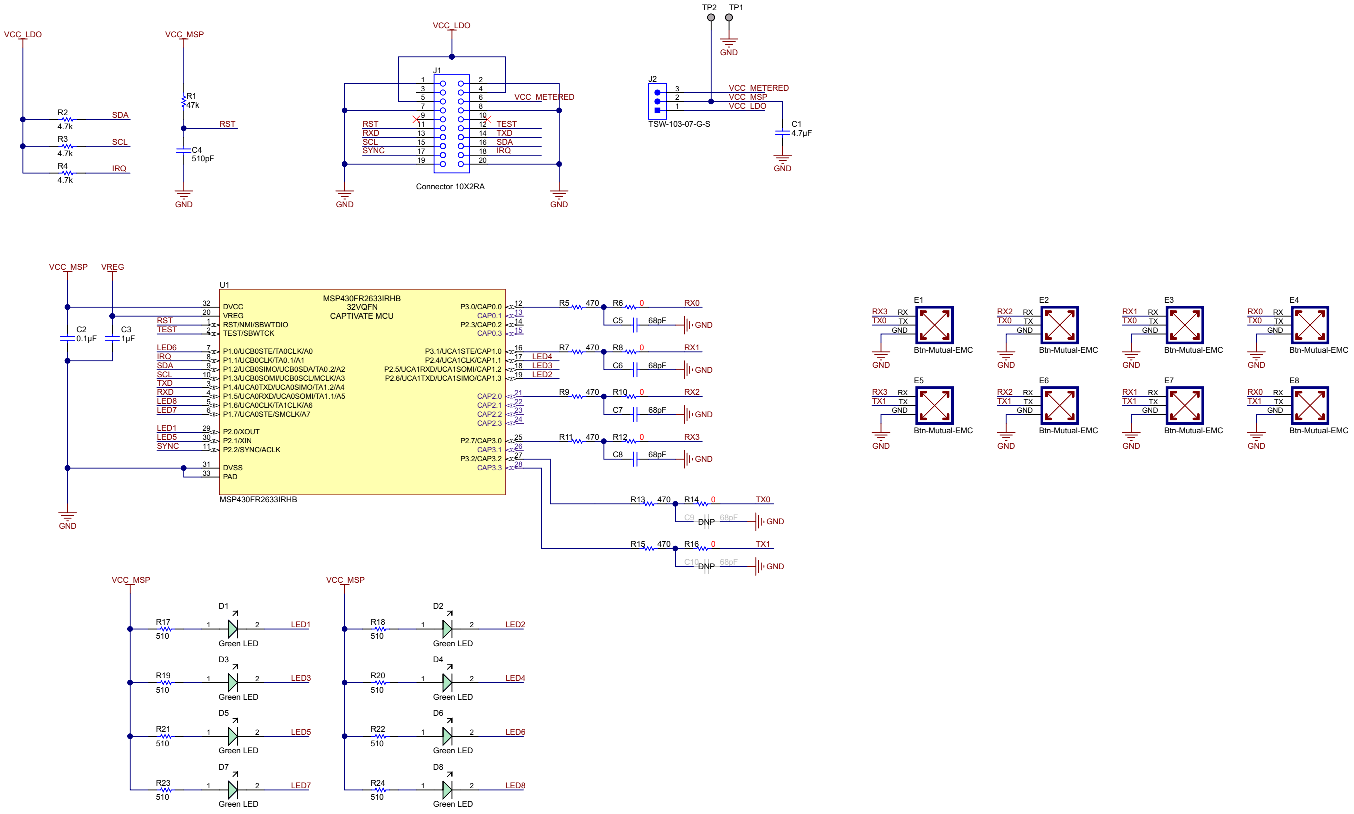


Figure 18. Schematic

8.2 Bill of Materials

To download the bill of materials for the TIDM-CAPTIVATE-THERMOSTAT-UI, see the design files at http://www.ti.com/tool/TIDM-CAPTIVATE-THERMOSTAT-UI.

Table 6. Bill of Materials

DESIGNATOR	QUANTITY	VALUE	DESCRIPTION	PACKAGE REFERENCE	PART NUMBER	MANUFACTURER
C1	1		CAP, CERM, 4.7 µF, 6.3 V, +/- 20%, X5R, 0402	0402	C1005X5R0J475M050BC	TDK
C2	1		CAP, CERM, 0.1 µF, 6.3 V, +/- 10%, X5R, 0402	0402	C1005X5R0J104K	TDK
C3	1		CAP, CERM, 1 µF, 6.3 V, +/- 20%, X5R, 0402	0402	C1005X5R0J105M	TDK
C4	1		CAP, CERM, 510 pF, 25 V, +/- 5%, C0G/NP0, 0402	0402	GRM1555C1E511JA01D	MuRata
C5, C6, C7, C8	4		CAP, CERM, 68 pF, 50 V, +/- 5%, C0G/NP0, 0402	0402	GRM1555C1H680JA01D	MuRata
D1, D2, D3, D4, D5, D6, D7, D8	8		LED, Green, SMD, Reverse Mount, 1206	1206	597-6301-607F	Dialight
FID1, FID2, FID3	3		Fiducial mark. There is nothing to buy or mount.	Fiducial	N/A	N/A
J1	1		Connector, Female, 10-Pin, 2 row, Right Angle		SSW-110-22-F-D-RA	Samtec
J2	1		Header, 100mil, 3x1, Gold, TH	3×1 Header	TSW-103-07-G-S	Samtec
R1	1		RES, 47 k, 5%, 0.063 W, 0402	0402	CRCW040247K0JNED	Vishay-Dale
R2, R3 R4	3		RES, 4.7 k, 5%, 0.063 W, 0402	0402	CRCW04024K70JNED	Vishay-Dale
R5, R7, R9, R11, R13, R15	6		RES, 470, 5%, 0.063 W, 0402	0402	CRCW0402470RJNED	Vishay-Dale
R6, R8, R10, R12, R14, R16	6		RES, 0, 5%, 0.063 W, 0402	0402	CRCW04020000Z0ED	Vishay-Dale
R17, R18, R19, R20, R21, R22, R23, R24	8		RES, 510, 5%, 0.063 W, 0402	0402	CRCW0402510RJNED	Vishay-Dale
TP1, TP2	2		PCB Pin, Swage Mount, TH	PCB Pin(2505-2)	2505-2-00-44-00-00-07-0	Mill-Max
U1	1		MSP430 Captivate Microcontroller	RHB (32VQFN)	MSP430FR2633IRHB	Texas Instruments

8.2.1 Layout Prints

To download the layout prints for the TIDM-CAPTIVATE_THERMOSTAT-UI, see the design files at http://www.ti.com/tool/TIDM-CAPTIVATE-THERMOSTAT-UI. Figure 19 shows the top silkscreen, Figure 20 shows the top layer, and Figure 21 shows the bottom layer of the MSP CapTIvate MCUs. Figure 22 shows the bottom silkscreen, and Figure 23 shows the mechanical dimensions of the MSP CapTIvate MCUs.

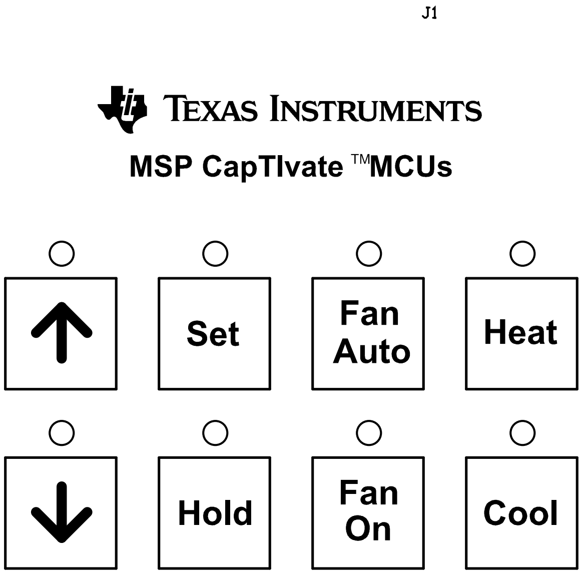


Figure 19. Top Silkscreen

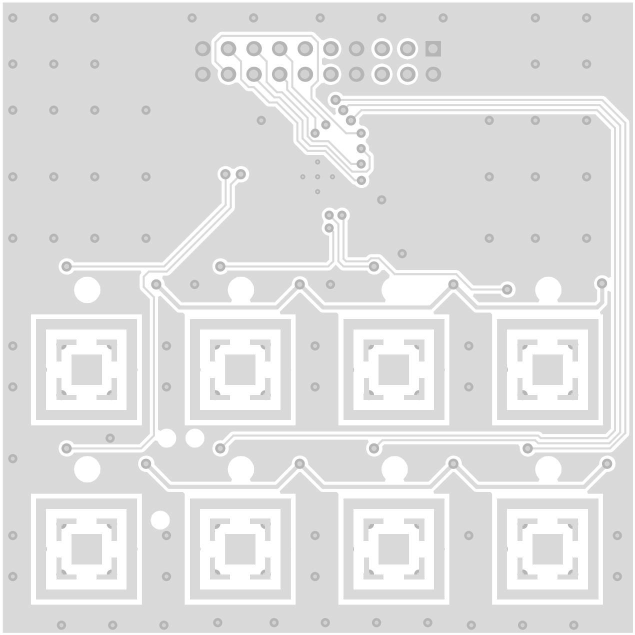


Figure 20. Top Layer

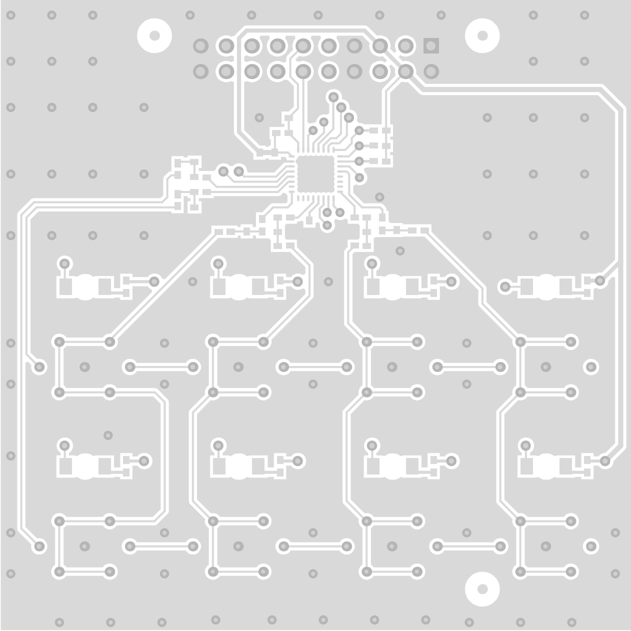


Figure 21. Bottom Layer

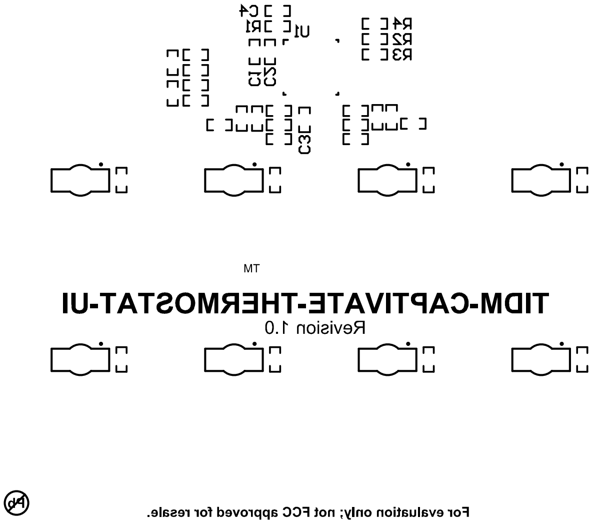


Figure 22. Bottom Silkscreen

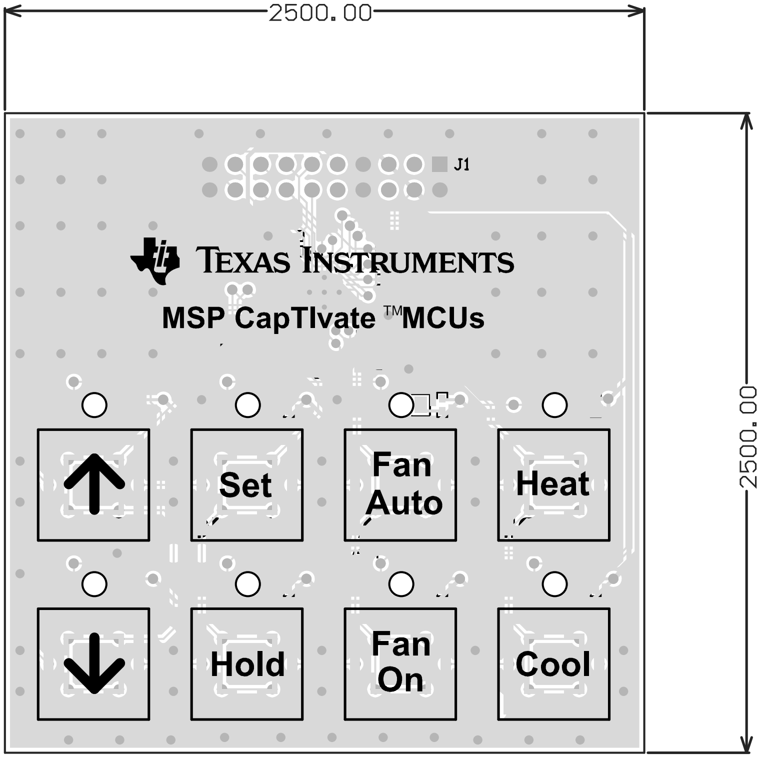


Figure 23. Mechanical Dimensions

8.3 Altium Project

To download the altium project files for the TIDM-CAPTIVATE-THERMOSTAT-UI, see the design files at http://www.ti.com/tool/TIDM-CAPTIVATE-THERMOSTAT-UI. Figure 24 shows the front of the layout, and Figure 25 shows the back of the layout of the MSP CapTIvate MCUs.

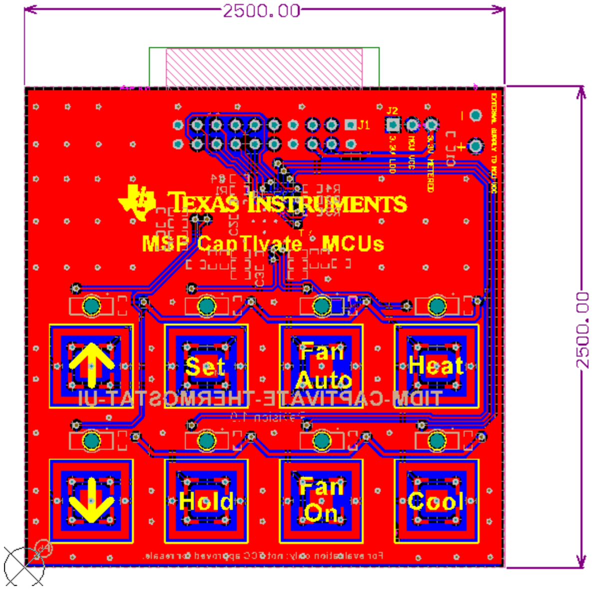


Figure 24. Front of Layout

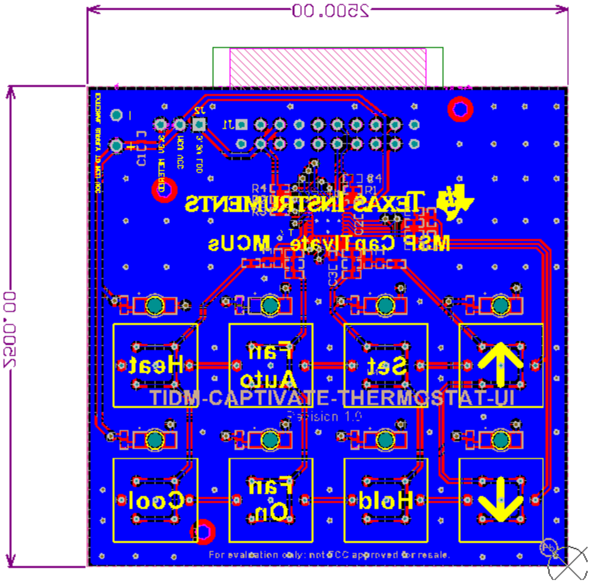


Figure 25. Back of Layout

9 Software Files

To download the software files for this reference design, see the link at http://www.ti.com/tool/TIDM-CAPTIVATE-THERMOSTAT-UI.

10 References

1. Texas Instruments CapTIvate Design Center, http://www.ti.com/captivate
2. Texas Instruments E2E Community, http://e2e.ti.com/

11 Terminology

- **Self capacitance**– The method of measuring changes in capacitance with respect to earth ground.
- **Mutual capacitance**– Involves measuring the change in capacitance on a sensor structure in which both plates of the capacitor are defined by electrode structures.
- **Noise Immunity**– The ability to maintain proper operation in an electrically noisy environment.

12 About the Author

BENJAMIN MOORE is an Applications Engineer at Texas Instruments on the MSP Microcontroller System Applications Team. Benjamin earned his Bachelor of Science in Electrical and Computer Engineering (BSECE) from The Ohio State University in Columbus, OH.

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