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Inductive Proximity Sensing

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Design Resources

TIDM-INDUCTIVEPROX	Tool Folder Containing Design Files
MSP-EXP430FR6989	Product Folder

TI E2E™ Community

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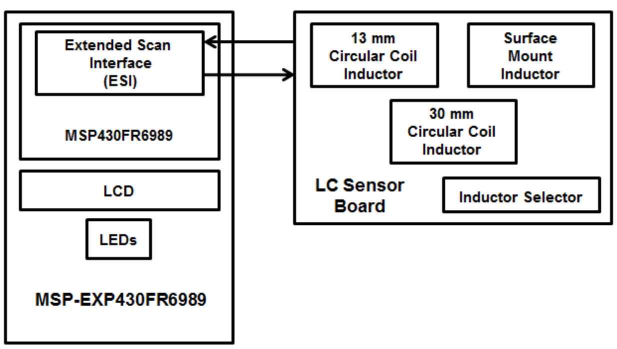
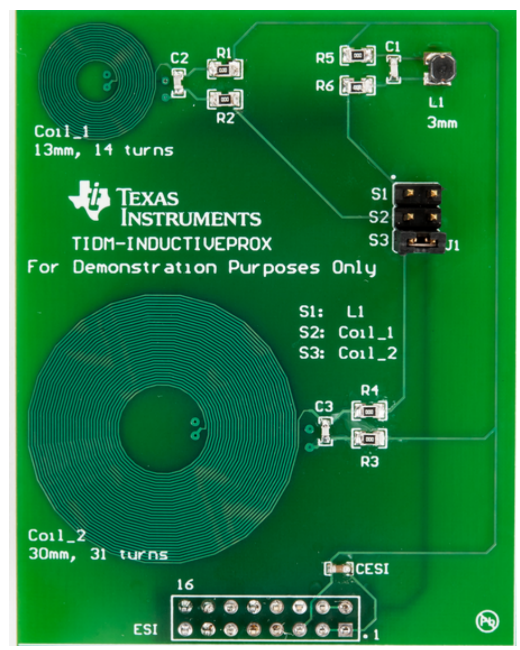
Design Features

- Ultra-Low Power
- Single-Chip Solution
- Noncontact Detection
- Insensitive to Environmental Contaminations
- Compatible With Different Types and Sizes of Inductors
- Onboard Inductor Selector for Two PCB Coil Inductors and One Surface-Mount Inductor

Featured Applications

- Factory and Home Automation
- Metal Detection Sensor
- Motor Position Detection
- Open and Close Switches
- Portable Instruments





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1 System Description

In many factory automation applications, the sensors supply the signal for counting tasks or the presence of metal objects. If the end-equipment system is deployed in a harsh environment that includes vibration, dust, dirt, oil, or moisture, the application will call for metal sensing. The contact and metal-free sensing of the MSP430FR6989 LaunchPad™, and its contamination-resistant and maintenance-free operation, make the MSP430FR6989 LaunchPad a great choice.

To provide a low-cost inductive sensing solution for designers, this reference design describes the implementation of the single-chip solution for inductive proximity sensor by using TI Extended Scan Interface module on MSP430 ™microcontrollers (MCUs). This reference design also uses three different LC sensors to demonstrate the compatibility of an Extended Scan Interface (ESI) module and calibration routine with different type and size of inductors.

1.1 MSP430FR6989 LaunchPad

The MSP430FR6986 LaunchPad Development Kit (see Figure 1) is an easy-to-use evaluation module (EVM) for the MSP40FR6989 MCU. The MSP430FR6989 onboard the LaunchPad is a 16-MHz FRAM-based ultra-low-power MCU with 128KB of FRAM, 2KB of SRAM. The segment LCD controller and ESI module on this LaunchPad provides a low-cost ultra-low power single-chip solution for inductive proximity sensing. To learn more about this device, visit http://www.ti.com/tool/MSP-EXP430FR6989.

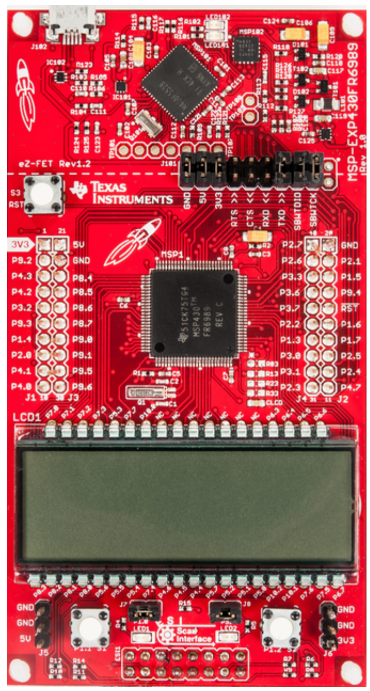

Figure 1. MSP430FR6989 LanchPad

2 Block Diagram

Figure 2 shows the system block diagram. Figure 3 shows the LC sensor board diagram.

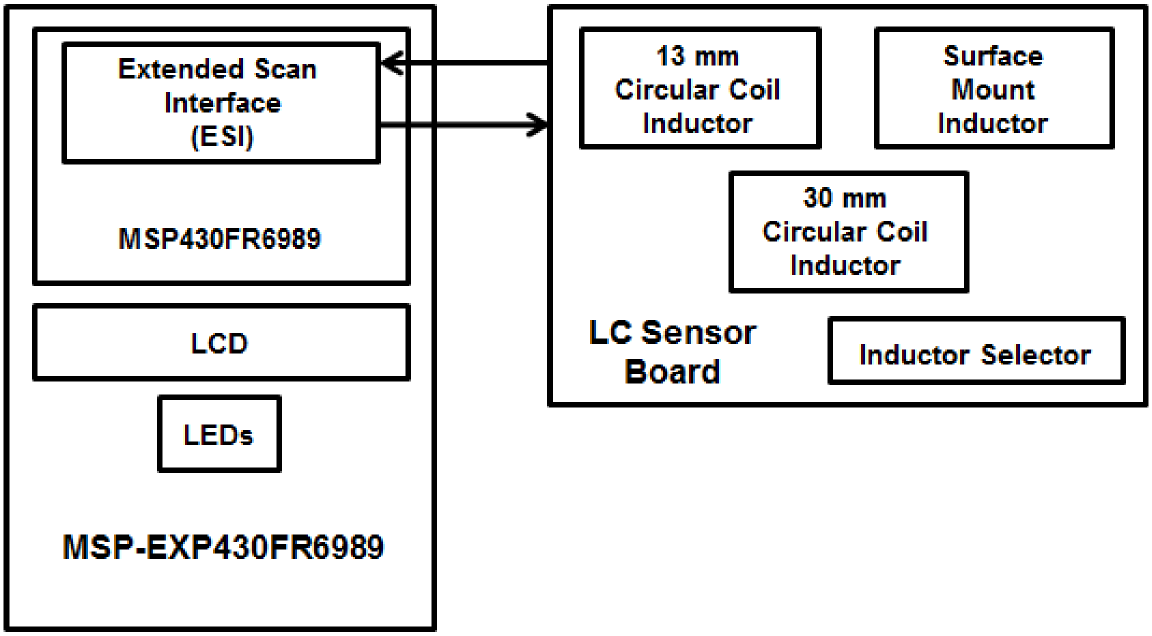

Figure 2. System Block Diagram

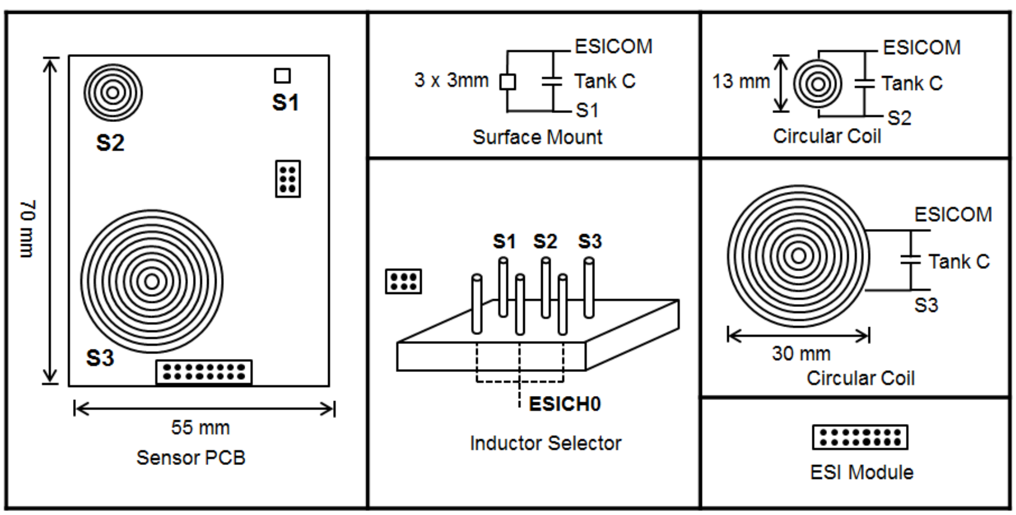

Figure 3. LC Sensor Board Diagram

2.1 Highlighted Products

For more information on each of these devices, see the respective product folders at www.TI.com.

2.1.1 MSP-EXP430FR6989

Key Features:

- MSP ULP FRAM technology-based MSP430FR6989 16-bit MCU
- EnergyTrace++ technology available for ultra-low-power debugging
- 40-pin LaunchPad standard leveraging the BoosterPack ecosystem
- Onboard eZ-FET emulation
- Two buttons and two LEDs for user interaction
- Pins for direct access to the ESI
- Available in TI eStore

3 System Design Theory

The TIDM-INDUCTIVEPROX design uses the MSP430R6989 device to demonstrate the function of the ESI with LC sensors. The following two subsections describe the operation theory for the ESI and LC sensors.

3.1 ESI

Figure 4 shows the block diagram of the Extended Scan Interface (ESI) and it consists of following blocks: the analog front-end (AFE1 and AFE2), the pre-processing unit (PPU), the processing state machine (PSM) with its associated RAM, the Timing State Machine (TSM), and the Timer_A output stage. The analog front end stimulates the LC sensors, senses the signal levels, and converts them into their digital representation. The digital representations of a measurement sequence are stored in the PPU. The stored digital signals are passed into the PSM. The PSM analyzes the changing of LC sensor oscillation. The TSM controls the analog front end, the PPU, and the PSM. There are three clock sources: ACLK of 32768 Hz, a built-in internal oscillator with an operating frequency of 2.3 MHz to 7.9 MHz (ESIOSC) of the ESI for a high-frequency clock source, and SMCLK using the DCO. In this design, ACLK and ESIOSC are used.

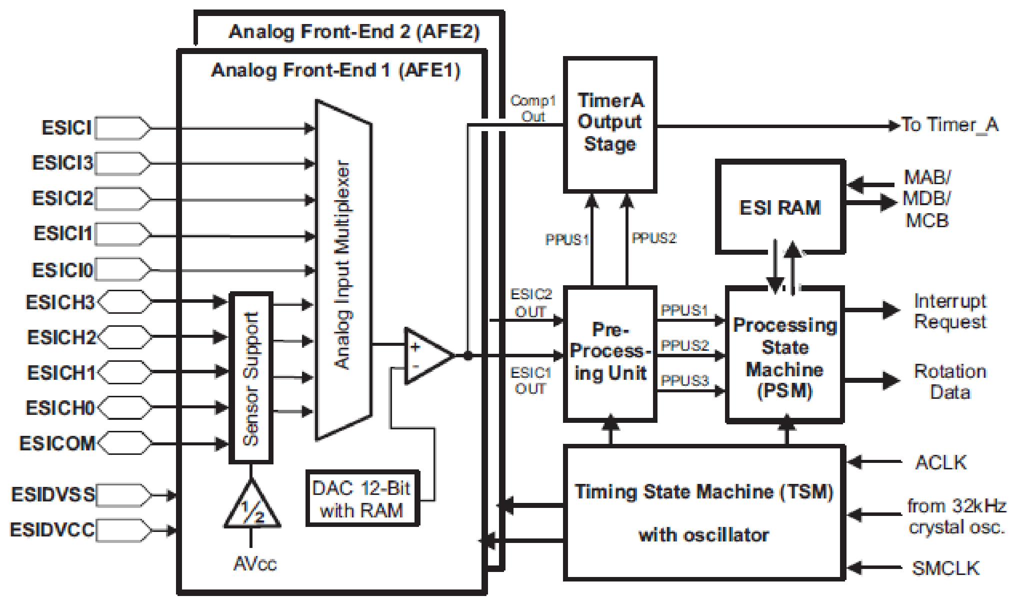

Figure 4. Block Diagram of the ESI

The flow chart shown in Figure 5 shows the basic operation process for the ESI. The AFE1 provides $V_{CC}/2$ as the AC ground of the LC signal and an excitation circuit to provide a short pulse in the range of microseconds for the excitation of LC oscillation. Up to four sensors can be connected to the four channels of the ESI. For each channel, the sensors are excited one by one.

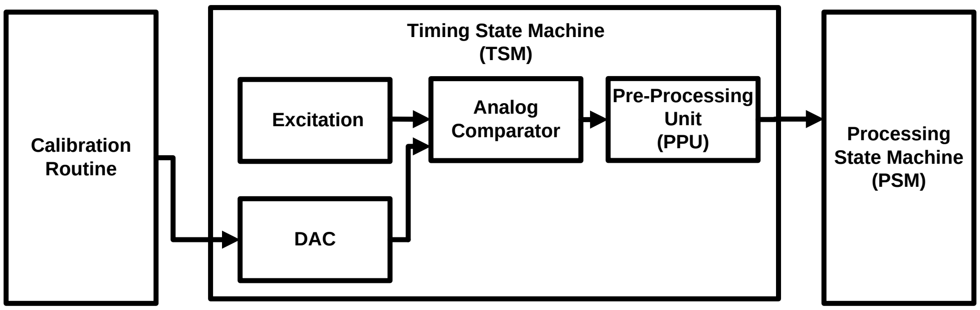

Figure 5. ESI Flow Chart

The input signal of a sensor is connected to the positive input of a comparator. The negative input is connected to the 12-bit digital-to-analog converter (DAC). Two registers of the DAC for each channel provide two reference levels to implement hysteresis, which avoids signal oscillation in the output of the comparator (see Table 1 and Figure 6). The values for these two reference levels are calculated by a calibration routine algorithm.

Table 1. DAC Registers

ANALOG FRONT END	SELECTED OUTPUT BIT, ESIOUT×	LAST VALUE OF ESIOUT×	DAC REGISTER USED
AFE1	ESIOUT0	0	ESIDAC1R0
		1	ESIDAC1R1
	ESIOUT1	0	ESIDAC1R2
		1	ESIDAC1R3
	ESIOUT2	0	ESIDAC1R4
		1	ESIDAC1R5
	ESIOUT3	0	ESIDAC1R6
		1	ESIDAC1R7
AFE2	ESIOUT4	0	ESIDAC2R0
		1	ESIDAC2R1
	ESIOUT5	0	ESIDAC2R2
		1	ESIDAC2R3
	ESIOUT6	0	ESIDAC2R4
		1	ESIDAC2R5
	ESIOUT7	0	ESIDAC2R6
		1	ESIDAC2R7

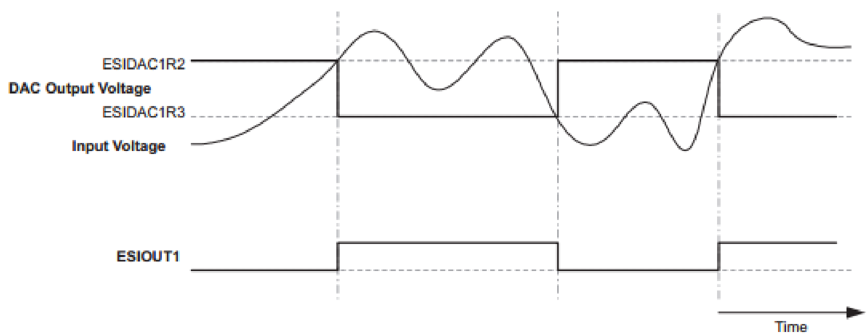

Figure 6. Analog Hysteresis With DAC Registers

The 32 registers of the TSM provide the timing sequence to control the on and off of the internal parts of the ESI module. The output of the comparator for each channel is stored in a register of the PPU. After one cycle of measurement completes, an ESISTOP signal is generated to trigger the operation of the PSM to analyze the status of the metal detection.

3.2 Working Principle of LC Sensors

The LC sensor consists of an inductor and a capacitor. In this TI Design, three different pairs of inductors and capacitors are used. After the capacitor is charged by a short pulse, the LC sensor begins to oscillate and the signal voltage level decays. The frequency and decay rate are dependent on the type of inductor and capacitor used and can vary according to the ambient environment. For example, the frequency and decay rate may be affected by temperature and humidity. In this design, room temperature is assumed.

When a metal object approaches the oscillating LC sensor, the signal decays faster due to the energy absorption by Eddy currents within the metal. As shown in Figure 7, this property allows the LC sensor to be used as inductive proximity sensor to identify metal (signal in red) or nonmetal part (signal in blue).

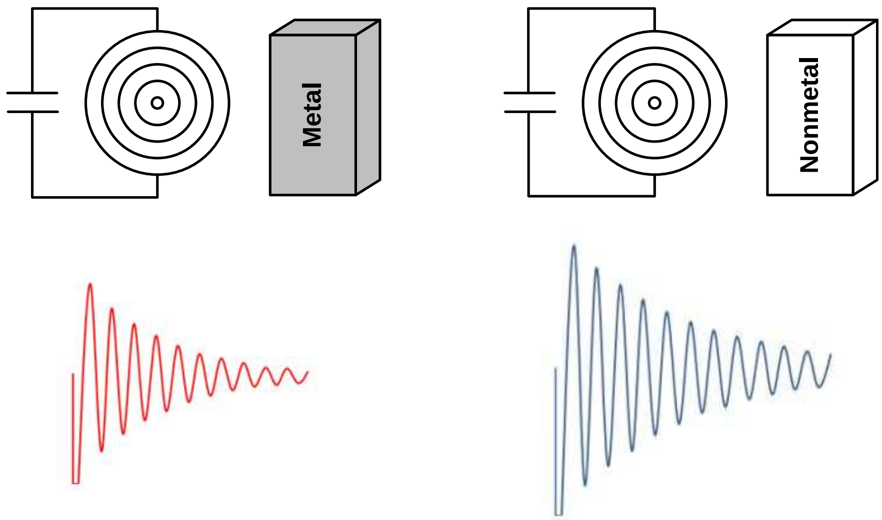

Figure 7. LC Oscillation Signal of Detection for Metal and Nonmetal

When overlapping these two oscillating signals of metal and nonmetal, the signal level difference is not constant. The difference starts small, becomes largest near the middle of the signal, and then returns to zero at the end. For a maximum detection distance, the portion of signals with maximum difference in signal level must be measured (see Figure 8). The measurement requires the TSM to control the timer to generate a time delay before comparing these two signals.

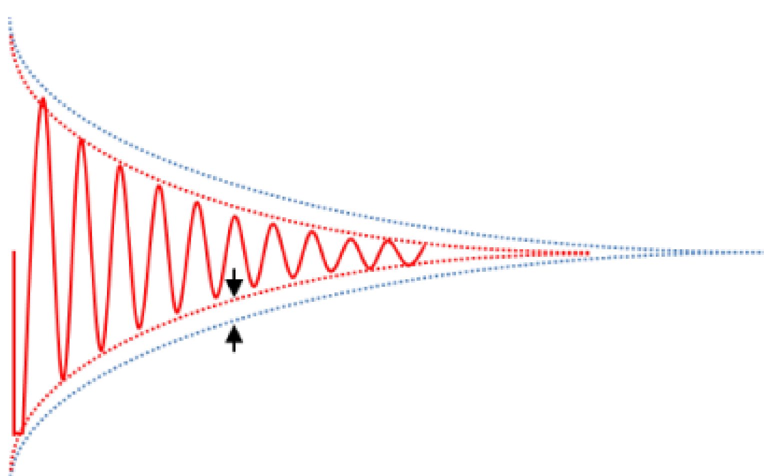

Figure 8. Maximum Difference Along the Decaying LC Signal

To detect the metal and nonmetal signals, set the reference voltage in between the "red" and "blue" of the LC signals. A DAC with 12-bit resolution is provided in the ESI module to create this reference voltage. For analog hysteresis, two voltage references are provided from the DAC module of the ESI (see Figure 9). A comparator is then used to identify the metal and nonmetal object.

The reference level can be placed in either the upper range or the lower range of the LC oscillation signal. In the ESI, the operating voltage for the comparator is from VSS to VCC – 1 V, and the operating voltage for the DAC is from VSS to 0.8 VCC. VCC is usually less than 3.3 V. With these electrical characteristics, if the measurement uses the upper range of the oscillating signal, a time delay is needed to wait until the LC signal has decayed to less than VCC – 1 V. However, when using the lower range of the signal, it can start functioning from VSS up. This eliminates the need for a long delay in the beginning part of the signals. In this TI Design, the lower range is used (see Figure 9). The signal level of a sensor is measured with the voltage level of the selected peak of its LC signal, which varies from metal to nonmetal. The reference voltages are calculated by a calibration algorithm.

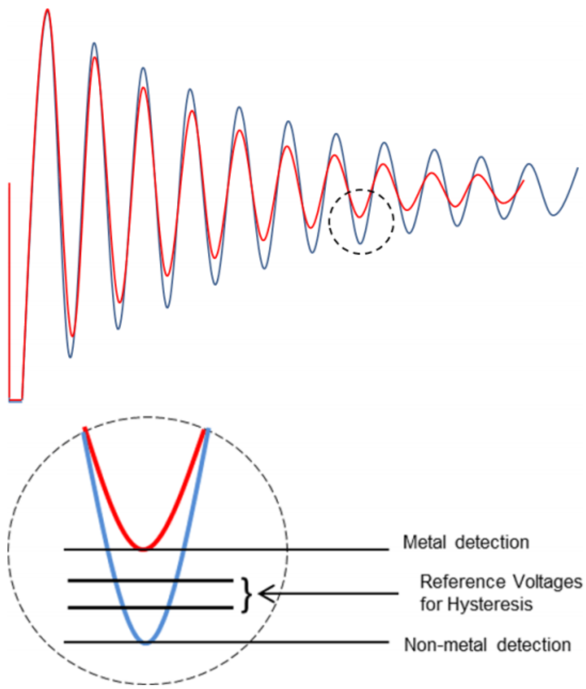

Figure 9. Reference Voltages for Detection of LC Signal to Identify Metal and Nonmetal Parts

4 Getting Started Hardware

This section of the document explains how to use the LC sensor board with MSP430FR6989 LaunchPad and the overview of the two PCB coils on the sensor board.

4.1 LC Sensor Board

This sensor board has three LC sensors include two coil inductors and one surface-mount inductor. If you use the MSP-EXP430FR6989 Rev. 1.0, you must connect the sensor board as shown in Figure 10. If you use the future revisions after Rev1.0 of MSP-EXP430FR6989 you must connect the sensor board as shown in Figure 11.

Figure 10. Sensor Board and LaunchPad Connection (Rev. 1.0)

Figure 11. Sensor Board and LaunchPad Connection (Future Revisions After Rev. 1.0)

4.2 LC Sensor Selector

The on-board sensor selector lets users switch between three different LC sensors by simply connecting the corresponding pins with the jumper as shown in Figure 12.

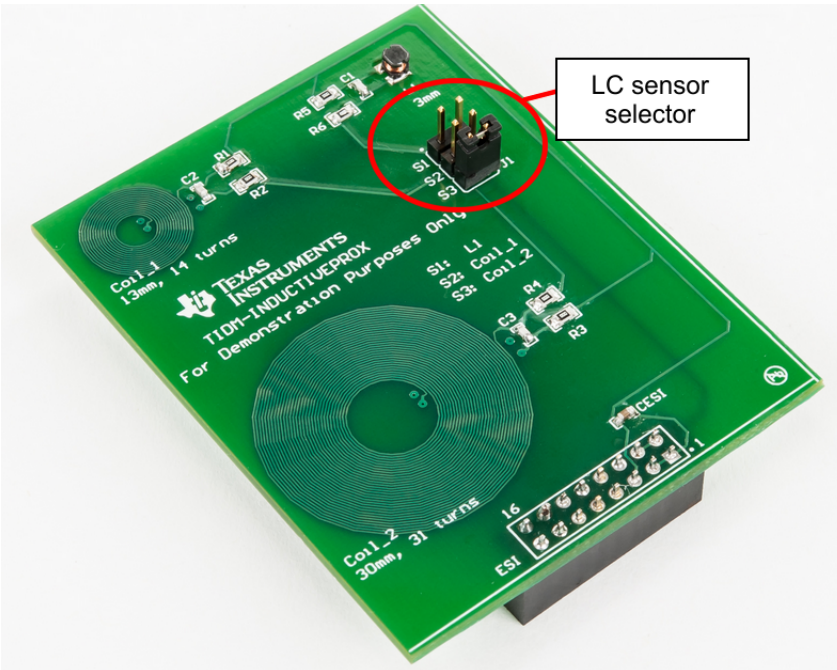

Figure 12. LC Sensor Selector

4.3 PCB Coil

WEBRENCH Design Center provides a great inductive PCB Coil designer for users to design their own PCB coils. This section provides the basic information for two coils used in this design.

As shown in Figure 13, Coil 1 is a 4-layer PCB coil with 14 turns and the outer diameter is 512 mils (13 mm), the inner diameter is 176 mils (4.5 mm), the trace width is 6 mils, and the trace spacing is 6 mils.

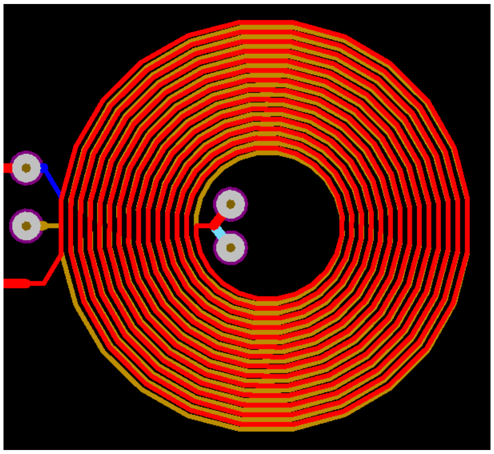

Figure 13. Coil 1 Layout

As shown in Figure 14, Coil 2 is a 4 layer PCB coil with 31 turns and the outer diameter is 1180 mils (30mm), the inner diameter is 374 mils (9.5 mm), the trace width is 7 mils, and the trace spacing is 6 mils.

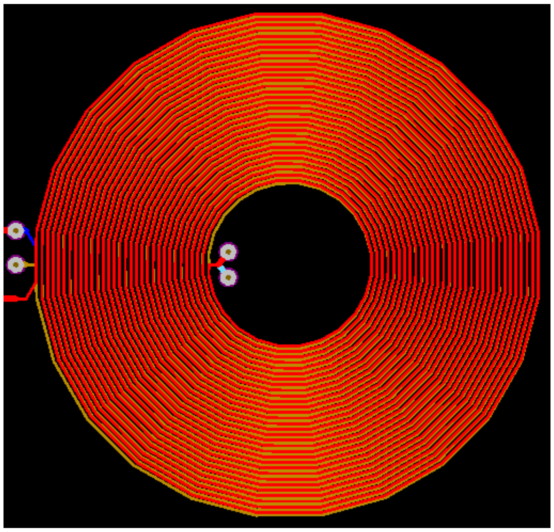

Figure 14. Coil 2 Layout

5 Getting Started Firmware

The software packaged with this design is intended to be sufficient for a full demonstration of the compatibility of the ESI module and the calibration routine with different LC sensors. However, the software is not optimized for each LC sensor and is not granted for the maximum sensing distance. Section 5.4 explains how to modify the code according to specific LC sensor to achieve the maximum sensing distance.

5.1 Operation of Software

The software is optimized to reduce power consumption of the system (see Figure 15). The software begins with initialization which includes ports setting for low current leakage, LCD, ESI internal oscillator calibration, ESI registers, sampling rate, TSM with auto-TSM calibration, optimal DAC level, and PSM table setting. After initialization, the design works well in low-power mode with the ESI as the only module that is active.

To avoid too many interrupts to wake up the CPU, the Q6 flag in PSM table is used. This flag is set only when there is a change between metal present and nonmetal. For more information about PSM, see Section 5.7. The system is in LPM2 mode when there is no metal present. To further lower the power consumption, the user can disable the LCD and add a key button to wake up the LCD when reading is necessary.

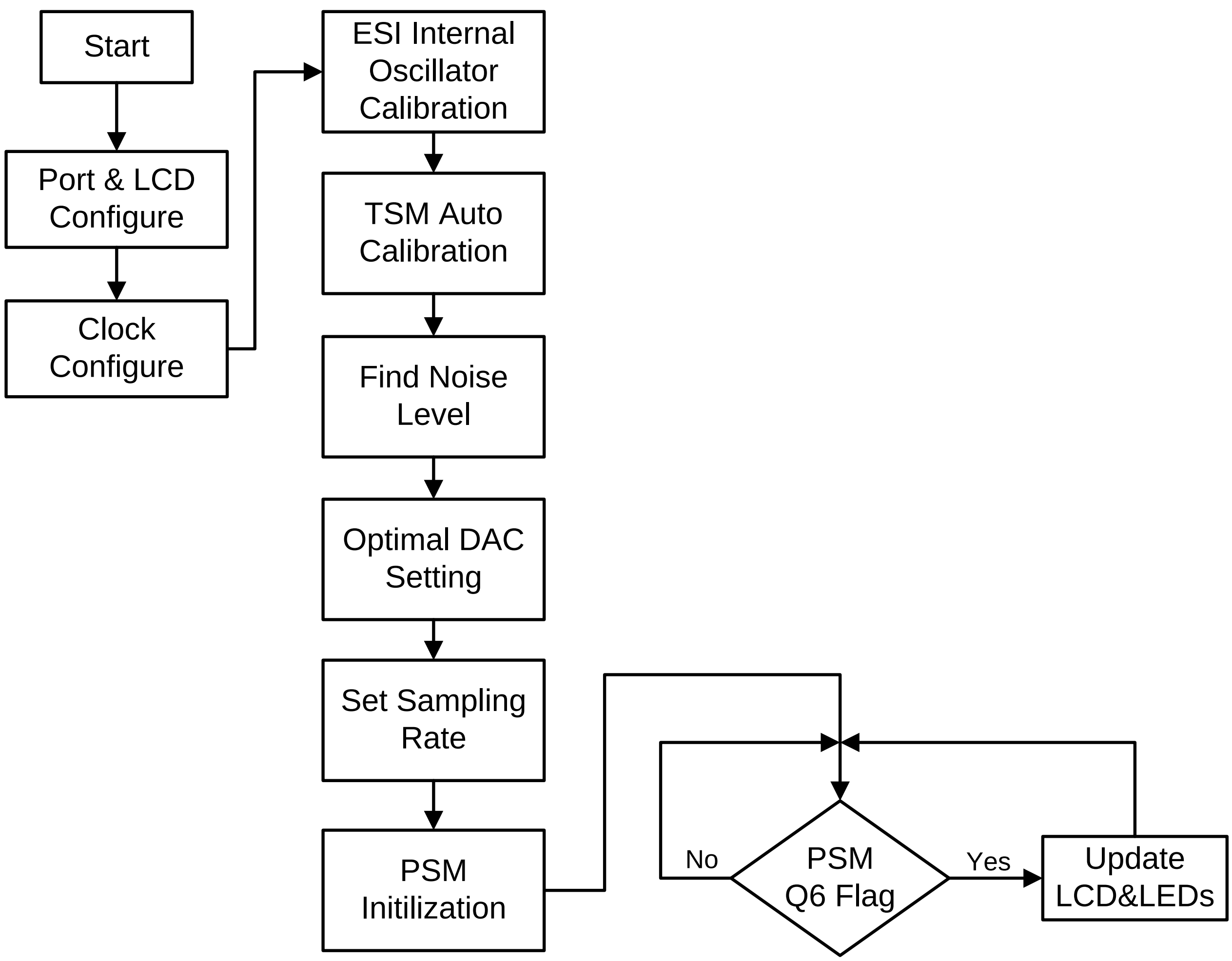

Figure 15. Flow Chart of the Software

5.2 Port and LCD Setting for Low-Power Operation

To enable low power consumption during ESI operation, the CPU wakes only on interrupts. Q6 of the PSM is the only interrupt flag that wakes the CPU. All ports must be set to minimize low-leakage. Unused pins must be set to an output of zero.

Port 1.2 is used as the analog-to-digital converter (ADC) input for the key pad. Port pin 1.2 is set to be the input mode with the pull-up resistor enabled. For port 9 pins that are multiplexed with ESICH0 to ESICH3, all P9SEL0 and P9SEL1 register bits must be set to 1 for the operation of the ESI function, even when working with two channels. At the same time, the peripheral comparator has pins multiplexed with ESI. The port disable register must be set to prevent parasitic current during the transition level of the gates in the port pins. To disable the port, CECTL3 must be set to 1.

5.3 ESI Internal Oscillator Calibration

Three clock sources are associated with the ESI: ACLK, SMCLK, and the internal oscillator of ESI. The internal oscillator and SMCLK are the sources of high-frequency clocks that must be used in the TSM timing control. For low-power and stand-alone operation of ESI, the internal oscillator is preferred. However, this clock frequency varies from device to device, so an initial calibration is required. The calibration code is found in esi.c from the MSP Driver Library.

5.4 Auto-TSM Calibration

The TSM controls the timing of each state, and the registers used are ESITSMx. Referring to the user guide, the 5 most significant bits (MSBs) of the register determine how long the corresponding state lasts. Afterwards, the TSM jumps to the next state. Repeat this process until the ESISTOP bit is set to complete one TSM cycle. An ESISTOP flag is asserted and the in this design the TSM is repeated after waiting until the next sampling period. However, the ESI module can also be configured to immediately start after ESISTOP flag is asserted.

The following shows the setting of TSM registers for this design.

```
ESITSM0 = 0x0400,                         // DAC=off, CA=off,  1xACLK
ESITSM1 = 0x482C + ESI_CHANNEL,     // DAC=off, CA=off,  10 x ESICLK, excitation
ESITSM2 = 0x0024 + ESI_CHANNEL,     // DAC=off, CA=off,  1xESIFCLK  , delay tunable
ESITSM3 = 0x0024 + ESI_CHANNEL,     // DAC=off, CA=off,  1xESIFCLK  , delay tunable
ESITSM4 = 0x0024 + ESI_CHANNEL,     // DAC=off, CA=off,  1xESIFCLK  , delay tunable
ESITSM5 = 0x0024 + ESI_CHANNEL,     // DAC=off, CA=off,  1xESIFCLK  , delay tunable
ESITSM6 = 0xF934 + ESI_CHANNEL,     // DAC=on,  CA=on,   32 x ESIFCLK,
ESITSM7 = 0x1934 + ESI_CHANNEL,     // DAC=on,  CA=on,   4 x ESIFCLK,
ESITSM8 = 0x5974 + ESI_CHANNEL,     // DAC=on,  CA=on,   OUTPUT LATCHES ENABLED,12 x ESICLK
ESITSM9 = 0x0200,                         // stop
```

First, the TSM starts with ESITSM0 of 0x0400, which is the beginning state of the TSM cycle. This state is to synchronizes with the rising edge of ACLK. The synchronization ensures the following timing of states to be the same for all TSM cycles. ESI_CHANNEL is to set the channel for ESI input; in this design use channel 1 so ESI_CHANNEL = 1.

Second, ESITSM1 makes an excitation pulse for the channel 1 with timing lasts for 10 clock cycles of ESI internal oscillation. The length of the pulse must be long enough to ensure the first shot of oscillation to reach the voltage of V_{CC} + V_{diode} (an internal protection diode of I/O). This makes every oscillation identical

Third, the LC sensor starts oscillating and the signal amplitude begins to decrease. A delay with the high-frequency clock from the ESI oscillator is turned on to fine tune the delay time. The time lasts for a period which is the sum of the time delay from ESITSM2 to ESITSM5. By using ESITSM2 to ESITSM5, an auto-TSM time delay function, "TIDM_INDUCTIVEPROX_autoCalibrateTSM" is constructed to tune the time delay of the LC signal, so as for calibration routine algorithm to find a lower peak of the oscillation signal level and timing to capture a signal. This function adds one high-frequency clock cycle delay every time. The captured signal is then measured by the function "TIDM_INDUCTIVEPROX_findDAC" to find its voltage level, by using the comparator and the DAC as reference voltage. With this setting, only the lower peak level is measured. In the reference design, an inverter is enabled to invert the output of the comparator so that the upper and lower reference level of the DAC must be swapped.

Fourth, ESITSM6 and ESITSM7 turn on the comparator and DAC output. A proper delay is taken for the settling time. The setting time for DAC is 2 µs and for the comparator, it is 3 µs.

Fifth, ESITSM8 is latched in the output of the comparator and stored in ESIPPU. One of function of high frequency clock delay from ESITSM2 to ESITSM5 is to select a lower peak of the signal for triggering the latch in function.

Finally, ESITSM9 ends the TSM sequence. The duration of this state is always one high-frequency clock period.

The TSM-Auto calibration routine is designed to demonstrate the ESI compatibility with different LC sensors, but does not ensure the location of the portion of signals with maximum difference. To achieve the maximum sensing distance, manually modify the TSM register to change the delay so the portion of signals can be located with maximum difference according to their specific LC sensors. To learn more about the TSM registers, see the device data sheet.

5.5 Find Noise Level and Optimal DAC Setting

The DAC in the ESI module generates a reference voltage for the comparator. To eliminate or reduce the oscillation when the voltage of input signal is close to voltage references of DAC, two DAC registers are used to provide two reference voltages for analog hysteresis. This is especially important when the sensor is on the border line of the maximum detection distance. The issue to determine the size of the separation of these two levels. If the separation is small, oscillation may frequently occur. If the separation is too large, it increases the voltage difference required between the maximum and minimum of sensor signals and, in turn, reduces the detection distance and creates a large hysteresis.

The noise level of the signal is then significant data for the optimal setting of analog hysteresis. The noise level is measured when there is no metal presented. The function “TIDM_INDUCTIVEPROX_findNoiseLevel" is responsible for the measurement, in which "TIDM_INDUCTIVEPROX_findDAC_Fast_Range" is the algorithm to search for the signal level. This function measures the variation of signal for 5000 iterations without metal presented. The noise level is then the difference between the maximum and minimum of the measured data. The Max_DAC_Ch0 and Min_DAC_Ch0 of channel 0 are, respectively, the maximum and minimum values of the sensor signal. Function “TIDM_INDUCTIVEPROX_setDACValues” is used to set the reference voltage levels.

In this design, an inverter is enabled to invert the output of comparator so that the upper and lower reference level of the DAC must be swapped. Thus, the upper voltage level is set to Max_DAC_Ch0 + DISTANCE_FACTOR. The lower voltage level is set to Max_DAC_Ch0 + NoiseLevel + DISTANCE_FACTOR (see Figure 16).

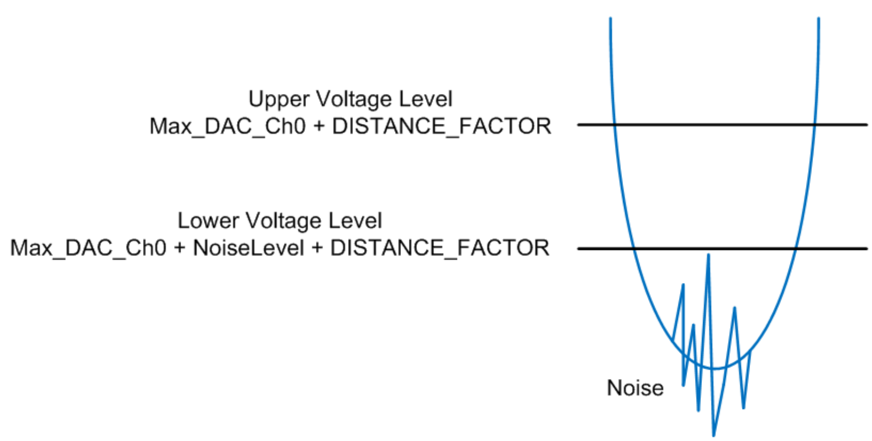

Figure 16. Optimal DAC Setting

The DISTANCE FACTOR lets the user adjust the metal detection range. Setting a DISTANCE_FACTOR of 0 returns the maximum range detection capable by the calibration algorithm.

5.6 Sample Rate Setting

For normal operation, the sampling rate of ESI is the frequency of triggering an LC oscillation so as to detect the metal present. The ESITSM register is used. In this design, we used ACLK as the start rigger for TSM, and the ACLK divider options are shown in Table 2.

Table 2. TSM ACLK Divider Options

ACLK DIVIDER	ESIDIV3Bx	ESIDIV3Ax		ACLK DIVIDER	ESIDIV3Bx	ESIDIV3Ax
2	000	000		126	011	100
6	000	001		130	010	110
10	000	010		150	010	111
14	000	011		154	011	101
18	000	100		162	100	100
22	000	101		182	011	110
26	000	110		198	100	101
30	000	111		210	011	111
42	001	011		234	100	110
50	010	010		242	101	101
54	001	100		270	100	111
66	001	101		286	101	110
70	010	011		330	101	111
78	001	110		338	110	110
90	001	111		390	110	111
98	011	011		450	111	111
110	010	101				

The software package included in this design uses a sample rate of approximately 72.8 Hz by default based on the equation:

$$SampleRate = \frac{\frac{ACLK}{ACLK\_Divider}}{StartTrigger\ ACLK\ Divider} = \frac{\frac{32768}{1}}{450} \approx 72.81 \quad (1)$$

Developers may modify the sample rate by changing the following definitions in TIDM_INDUCTIVEPROX.h:

- ESI_TSM_ACLK_DIVIDER
- ESI_TSM_STARTTRIGGER_ACLK_DIVIDER

5.7 PSM Operation

The PSM is a programmable state machine that determines the presence of metallic objects with its state table stored within the ESI RAM. The PSM controls interrupt generation based on the inputs from the TSM and the analog front-end.

In this design, only channel 0 of the PSM is used. However, a minimum of two input signals are required to set up the PSM because the ESI allows selecting either two or three signals for the PSM processing.

Channel 0 is only used so that all the input change from channel 1 is detected as an error. The input change from channel 0 will be detected as a metal present. In the PSM table (see Table 3), Q0 to Q7 represent the bit number of the register. The next state is represented by Q3 and Q0; the output is set by Q1. Q7 is set when there is an error input, indicated by red highlight in Table 3. Q6 is set when the system detects the change from metal to nonmetal or nonmetal to metal, indicated by blue in Table 3. Q2, Q4 and Q5 are not used in the application code. The Q6 is another interrupt flag of the PSM table. In the application code, when Q6 is set, it triggers an interrupt code to update the LCD display.

Table 3. PSM Table

PRESENT STATE	CH1/CH0 INPUT	DESCRIPTION	Q1	NEXT STATE (Q3/Q4)	Q7 (ERROR)	Q6 (CHANGE)	BYTE CODE
00	00	No change	0	00	0	0	0x00
00	01	Change	1	01	0	1	0x43
00	10	Error	0	00	1	0	0x80
00	11	Error	0	00	1	0	0x80
01	00	Change	1	00	0	1	0x42
01	01	No change	0	01	0	0	0x01
01	10	Error	0	00	1	0	0x80
01	11	Error	0	01	1	0	0x81

This design only uses CH0 for input so Q7 (error flag) is set if there is an input change from CH1. If there is any change from CH0 then Q6 (change flag) is set.

5.8 Header File Modification

In the TIDM_INDUCTIVEPROX.h header file, users can change the number of iterations for finding noise level time; they can also change the detection distance and enable the power consumption measurement mode.

- **NOISE_LEVEL_DETECTION_TIME** is a variable that lets the user modify the number of noise search iterations in the calibration routine. For power supplies that have an inconsistent noise level, use a value of at least 5000. For cleaner power supplies that have a consistent noise level, reduce the number of iterations to reduce the calibration time. If you notice false metal detection triggers, then increase the value of NOISE_LEVEL_DETECTION_TIME.
- **SEPARATION_FACTOR** is a variable that lets the user adjust the metal detection range. Setting this value to 0 provides the maximum detection range provided by this application code.
- **ENABLE_CURRENT_CONSUMPTION_MEASUREMENT** lets the user enable the power consumption measurement mode by uncomment this define in the header file.

6 Test Setup

This section demonstrates the test setups for sensing the distance test and the power consumption test.

6.1 Distance Test

For this design we performed the distance test for all three inductors (30-mm coil, 13-mm coil, and SMD) and used three different metal materials (steel, aluminum, and copper). We also used three different power supplies for the distance test to show how noise level can affect the sensing distance.

6.1.1 DC Power Analyzer 3.0 V

The KEYSIGHT N6705B DC Power Analyzer as the power supply and the input voltage is 3 V. We first program the LaunchPad and connect the sensor board to the LaunchPad. Because we are using an external power supply, we must remove all the connections from the eZ-FET as shown in Figure 17.

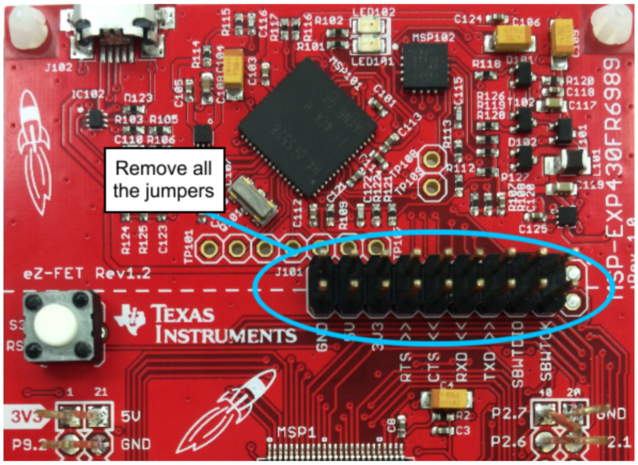

Figure 17. External Power Supply Jumper Configuration

Connect the DC Power Analyzer to the header J6 on the LaunchPad as shown in Figure 18. After the calibration routine, slowly move the metal material close to the sensor until the LED is steadily on for 30 seconds. Next, measure the distance from the metal to the sensor board. It is important to only measure the distance when you see the LED is steadily on. Once is the LED is on, reset the device and repeat the process ten times and take the average for measured distances. Repeat the process using three different metal materials for all three inductors.

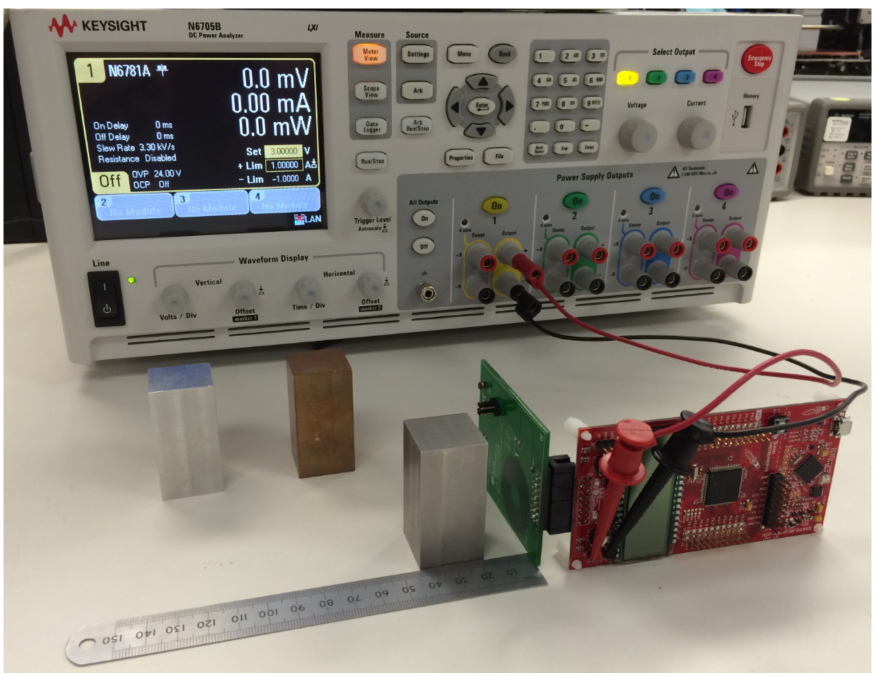

Figure 18. DC Power Analyzer Distance Test Configuration

6.1.2 Source Meter 3.0 V

The KEITHLEY 2400 Source Meter is used as the power supply and the input voltage is 3 V. First, program the LaunchPad and connect the sensor board to the LaunchPad. Because an external power supply is being used, remove all the connections from eZ-FET as shown in Figure 17

Next, connect the source meter to the header J6 on the LaunchPad (see Figure 19). After the calibration routine, slowly move the metal material close to sensor until the LED is steadily on for 30 seconds and measure the distance from the metal to the sensor board. It is important to only measure the distance once the LED is steadily on. Reset the device and repeat the process 10 times, and take the average for measured distances. Repeat this process using three different metal materials for all three inductors.

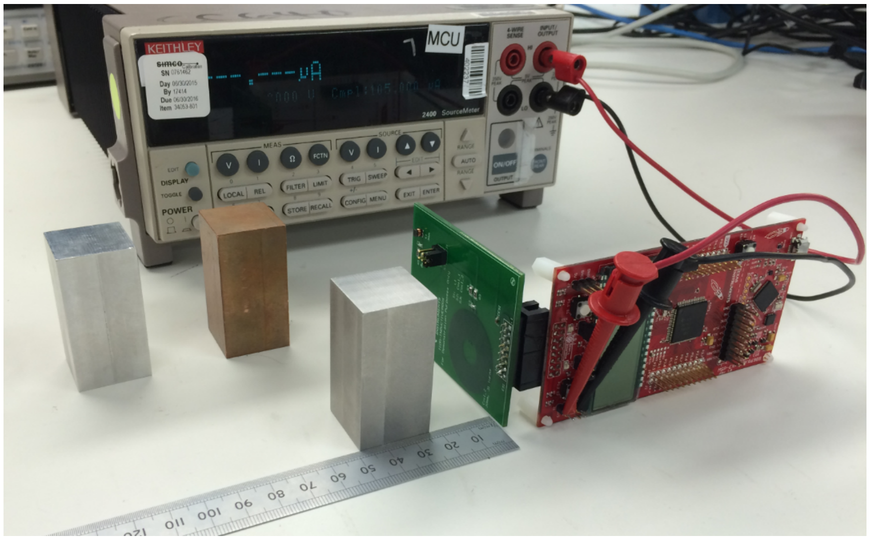

Figure 19. Source Meter Distance Test Configuration

6.1.3 USB 3.3 V

We also used the laptop USB port as the power supply, and the input voltage is 3.3 V. Collect the distance data for users who connect just the LaunchPad to their laptop, and the most common power-supply scenario is from USB through the eZ-FET debugger. This provides 5-V power from the USB and also regulates this power rail to 3.3 V for eZ-FET operation and 3.3 V to the target side of the LaunchPad. Connect the sensor board to the LaunchPad and make sure that a jumper is connected across the J101 3V3 terminal and also GND terminal, as shown in Figure 20

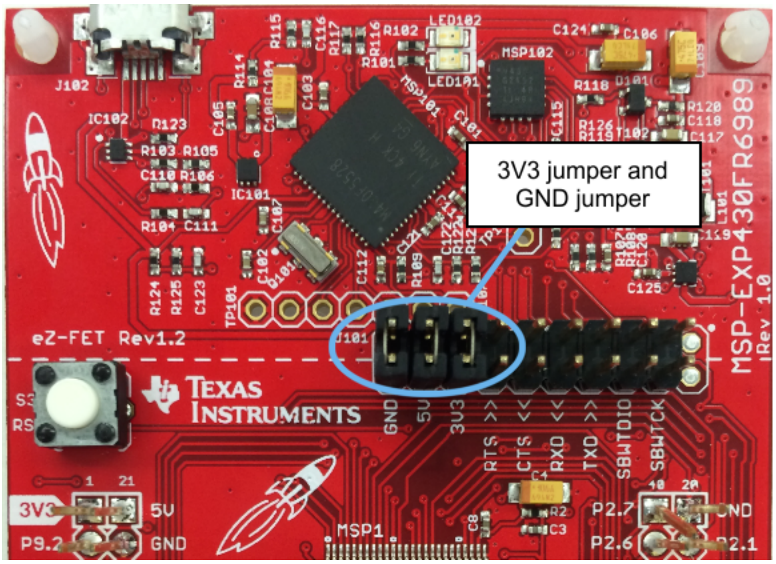

Figure 20. USB Power Supply Jumper Configuration

Next, connect the LaunchPad to a laptop (have the laptop plugged into the wall). Figure 21 shows the USB power supply jumper configuration. After the calibration routine, slowly move the metal material close to sensor until the LED is steadily on for 30 seconds. After the 30 seconds, measure the distance from the metal to the sensor board. Only measure the distance when you see the LED is steadily on. Reset the device and repeat the process 10 times, and compute the average for the measured distances. Repeat this process using three different metal materials for all three inductors.

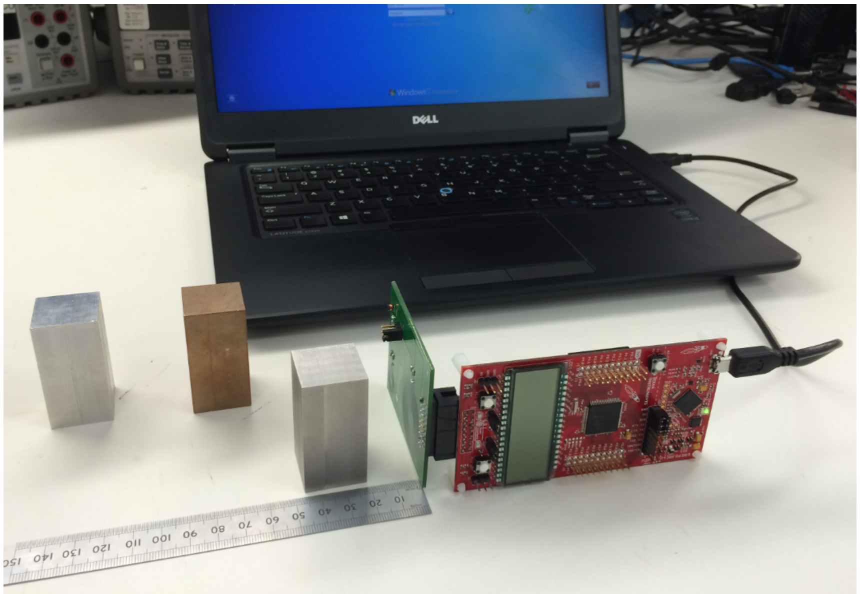

Figure 21. USB Distance Test Configuration

6.2 Power Consumption Test

For this design, the KEYSIGHT N6705B DC Power Analyzer was used to perform the power consumption test for all three inductors (30-mm coil, 13-mm coil, and SMD) with seven different sampling frequencies. First, program the LaunchPad as power consumption test mode; LED and LCDs are turned off in this mode. Connect the sensor board to the LaunchPad, and because an external power supply is being used, remove the connectionions from the eZ-FET, as shown in Figure 17. Figure 22 shows the power consumption test configuration.

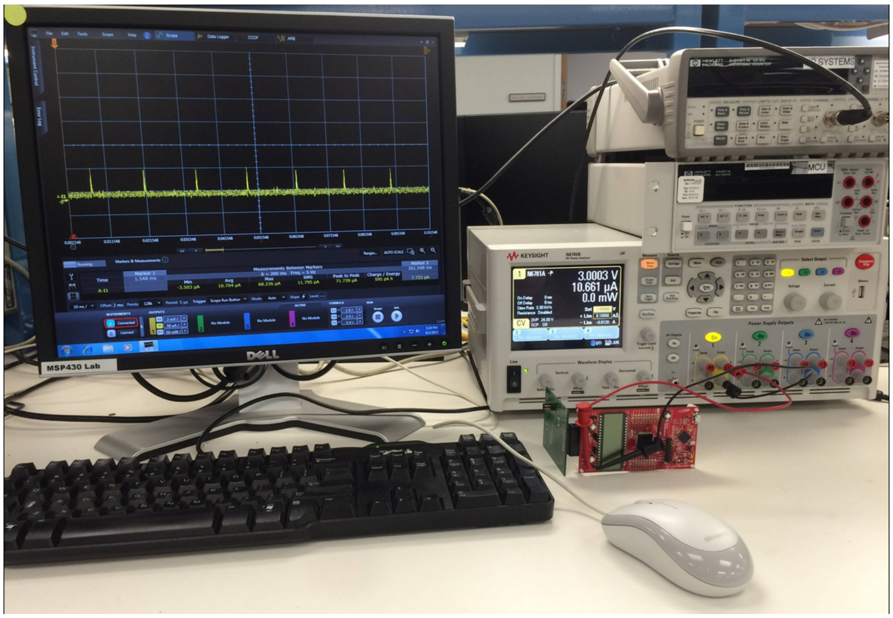

Figure 22. Power Consumption Test Configuration

Connect the DC Power Analyzer to the header J6 on the LaunchPad. After the calibration routine, use the DC power analyzer to log the current data for one minute, and collect the average current value. Repeat this process for all 7 sampling frequencies.

7 Test Data

7.1 Distance Test Data

The distance data provided is only the typical value for the test setup. Many factors can affect the sensing distance; for example, temperature, humility, voltage, power noise level, PCB coil thickness, and metal material.

7.1.1 DC Power Analyzer

For this test setup, the input power is 3.0 V and the average power noise level is 4 mV. The room temperature is 23 degrees Celsius, and the dimension for metal objects are 25 mm × 25 mm × 50 mm, and the thickness for the sensor board is 0.062 inch. Table 4 lists the results.

Table 4. DC Power Analyzer Distance Test

	STEEL	ALUMINUM	COPPER
Coil 1	13 mm	11 mm	10 mm
Coil 2	22 mm	16 mm	14.5 mm
SMD	3.5 mm	1.5 mm	< 1 mm

7.1.2 Source Meter

For this test setup, the input power is 3.0 V, the average power noise level is 13 mV, and the room temperature is 23 degrees Celsius. The dimensions for the metal object are 25 mm × 25 mm × 50 mm, and the thickness for the sensor board is 0.062 inch. Table 5 lists the results.

Table 5. Source Meter Distance Test

	STEEL	ALUMINUM	COPPER
Coil 1	9.5 mm	7.5 mm	6.5 mm
Coil 2	15 mm	10.5 mm	9.5 mm
SMD	2.5 mm	1 mm	< 0.5 mm

7.1.3 USB

For this test setup, the input power is 3.3 V, the average power noise level is 8 mV, room temperature is 23 degrees Celsius, and the dimension for the metal objects are 25 mm × 25 mm × 50 mm, and the thickness for this sensor board is 0.062inch. Table 6 lists the results.

Table 6. USB Distance Test

	STEEL	ALUMINUM	COPPER
Coil 1	8 mm	7 mm	6.5 mm
Coil 2	14 mm	9 mm	7.5 mm
SMD	1.5 mm	< 1 mm	< 0.5 mm

7.2 Power Consumption Test Data

Figure 23 shows the current consumption of the system when using each of the three sensors. The data is taken by measuring the current flowing into the MCU connected to each LC sensor, and varying the sampling rate of the ESI of MSP430FR6989. The power consumption depends on the sampling rate and the LC sensor; and Coil1 has the highest power consumption compared to the other LC sensors, due to the lower impedance of the coil.

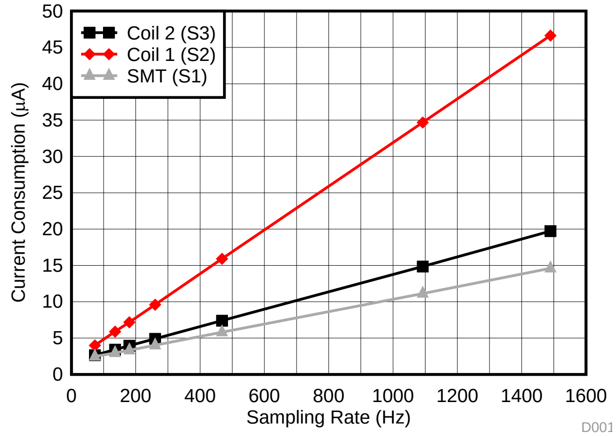

Figure 23. System Power Consumption With LPM2

7.3 LC Sensor Waveform

Figure 24 shows the 13 mm coil oscillation waveform captured on the oscilloscope. The oscillation frequency is about 520 kHz.

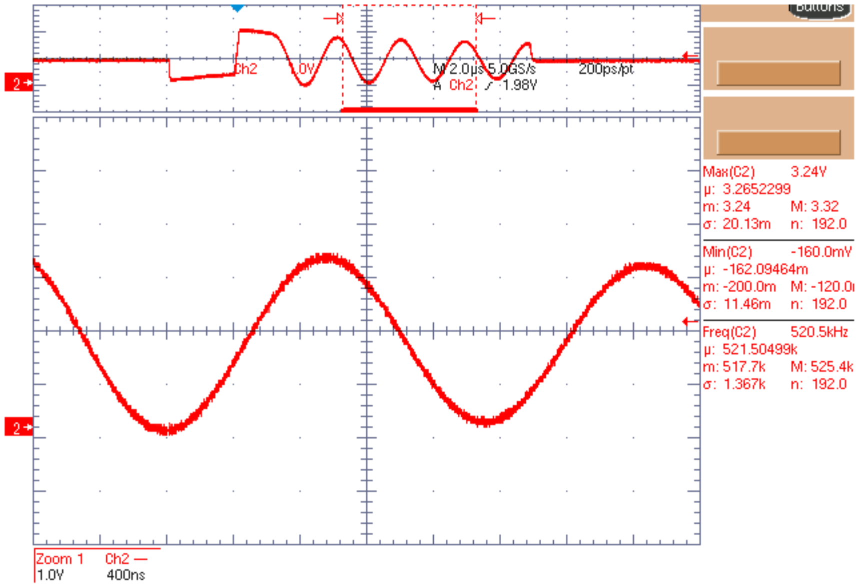

Figure 24. Coil 1 Oscillation Waveform

Figure 25 shows the 30 mm coil oscillation waveform captured on the oscilloscope. The oscillation frequency is about 648 kHz.

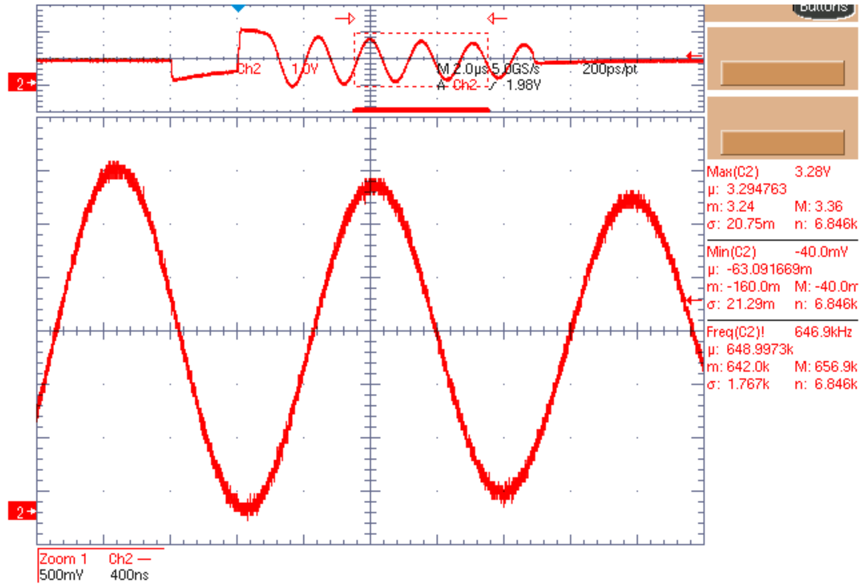

Figure 25. Coil 2 Oscillation Waveform

Figure 26 shows the SMD inductor oscillation waveform captured on the oscilloscope. The oscillation frequency is about 1.7 MHz.

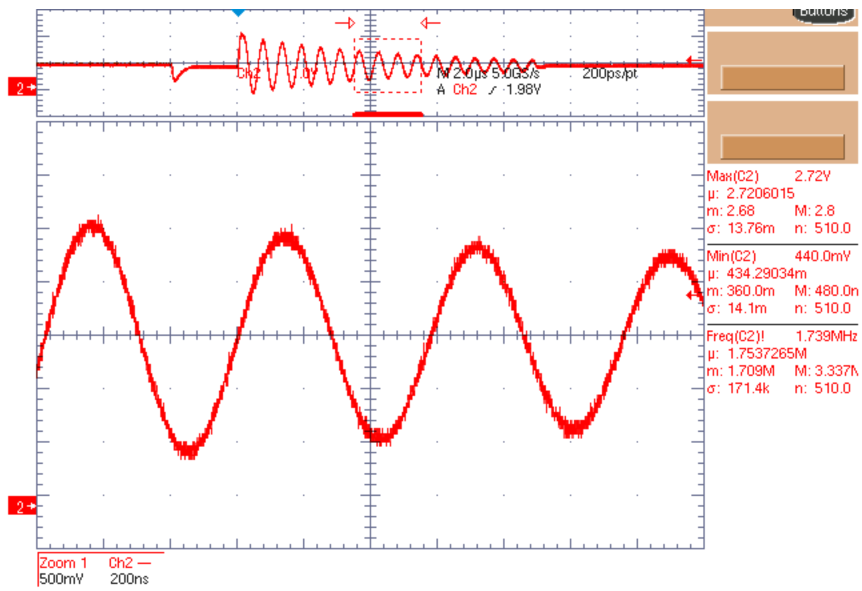

Figure 26. SMD Oscillation Waveform

8 Design Files

8.1 LC Sensor Board Schematics

To download the schematics for each board, see the design files at http://www.ti.com/tool/TIDM-INDUCTIVEPROX. Figure 27 shows the LC sensor board schematic.

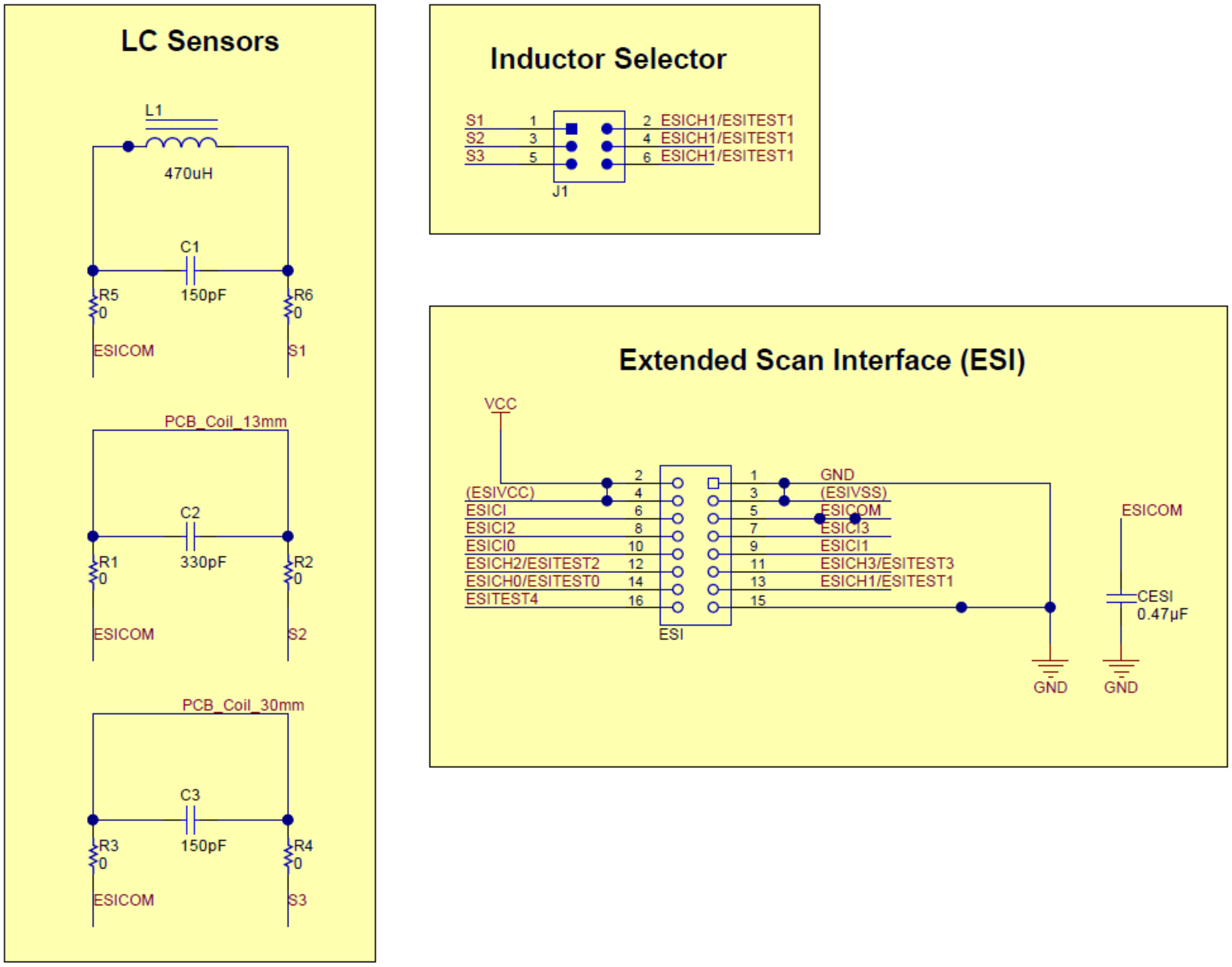

Figure 27. LC Sensor Board Schematic

8.2 Bill of Materials

To download the Bill of Materials for each board, see the design files at http://www.ti.com/tool/DESIGNNUMBER

Table 7. BOM: LC Sensor Board

DESIGNATOR	QUANTITY	VALUE	DESCRIPTION	PACKAGE REFERENCE	PART NUMBER	MANUFACTURER
PCB1	1		Printed Circuit Board		ISE 4002	Any
C1, C3	2	150 pF	CAP, CERM, 150 pF, 50 V, ±5%, C0G/NP0, 0603	0603	GRM1885C1H151JA01D	MuRata
C2	1	330 pF	CAP, CERM, 330 pF, 50 V, ± 1%, C0G/NP0, 0603	0603	C1608C0G1H331F080AA	TDK
CESI	1	0.47 µF	CAP, CERM, 0.47 µF, 10 V, ± 10%, X5R, 0603	0603	GRM188R61A474KA61D	MuRata
R1. R2, R3, R4, R5. R6	6	0 Ω	RES, 0, 5%, 0.125 W, 0805	0805	ERJ-6GEY0R00V	Panasonic
L1	1	470 µH	Inductor, Drum Core, Ferrite, 470 µH, 0.11 A, 14.3 Ω, SMD	SDR0302	SDR0302-471KL	Bourns
J1	1		Header, 100 mil, 3x2, Gold, TH		PBC03DAAN	Sullins Connector Solutions
ESI	1		Connector Header, 100 mil, 8x2, Gold, TH		SFH11-PBPC-D08-ST-BK	Sullins Connector Solutions

8.3 PCB Layout Recommendations

- Inner vias must be placed close to the traces and not in the absolute center of the inductor – this reduces the parasitic resistance.
- Keep the inner 30% of the sensor area unwound because the inner turns add resistance and do not contribute much to the inductance.
- The sensor capacitor should be placed as close as possible to the sensor to minimize the RS of the traces.
- Use thicker traces between the inductor and capacitor when possible, and 10 mil (0.25 mm) traces are sufficient.

8.3.1 Layout Prints

To download the Layout Prints for each board, see the design files at http://www.ti.com/tool/TIDM-INDUCTIVEPROX

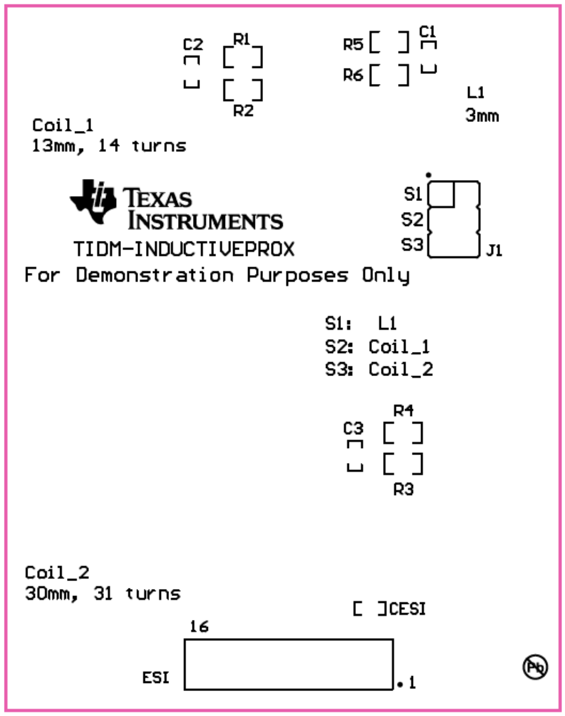

Figure 28. Top Silkscreen

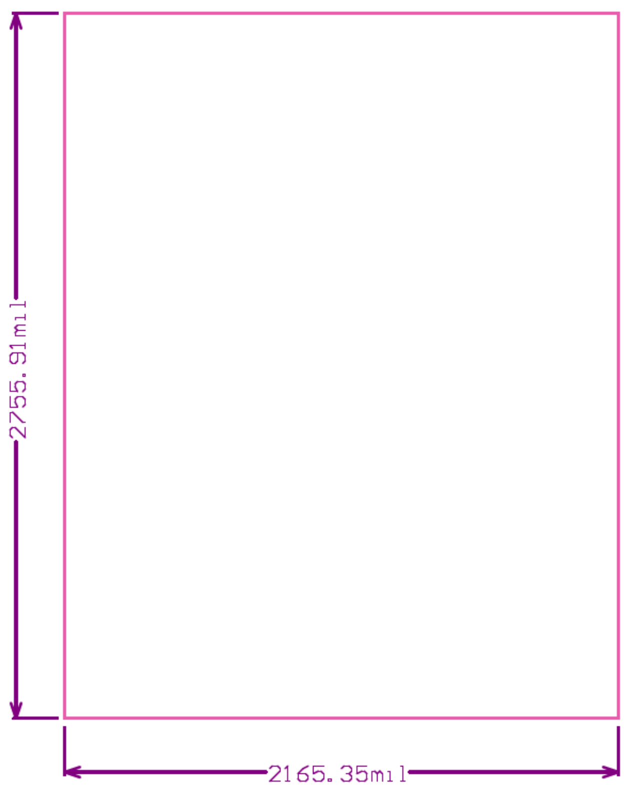

Figure 29. Mechanical Dimensions

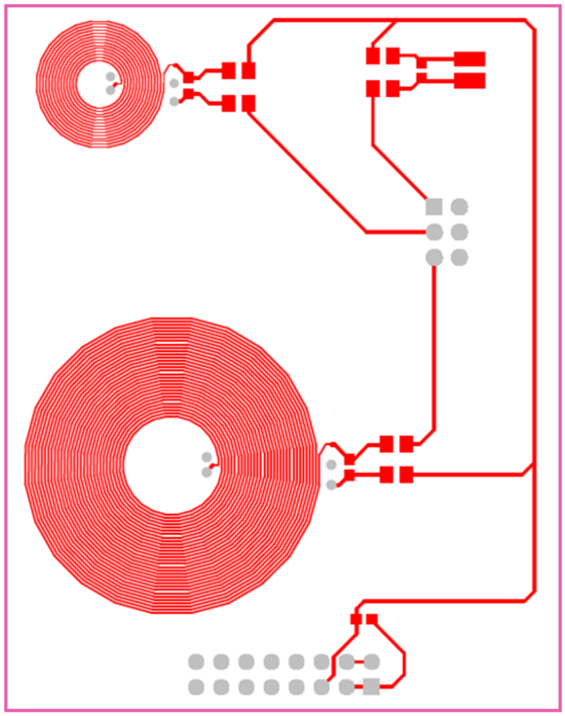

Figure 30. Top Layer

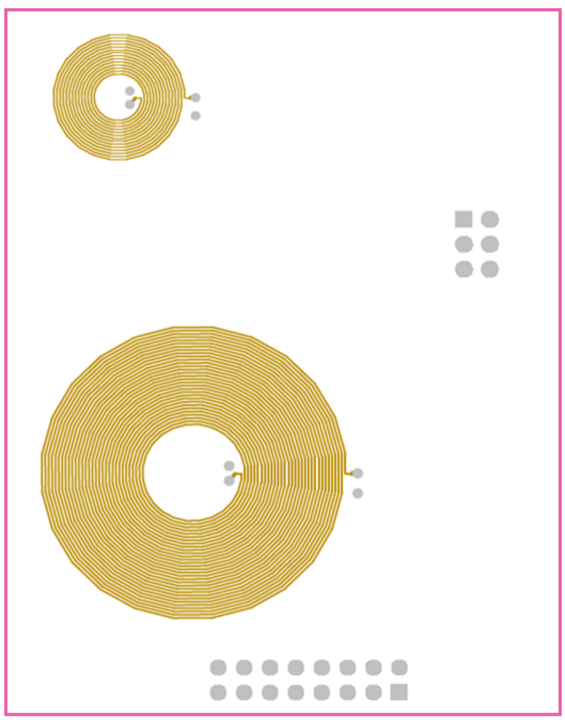

Figure 31. Mid-Layer 1

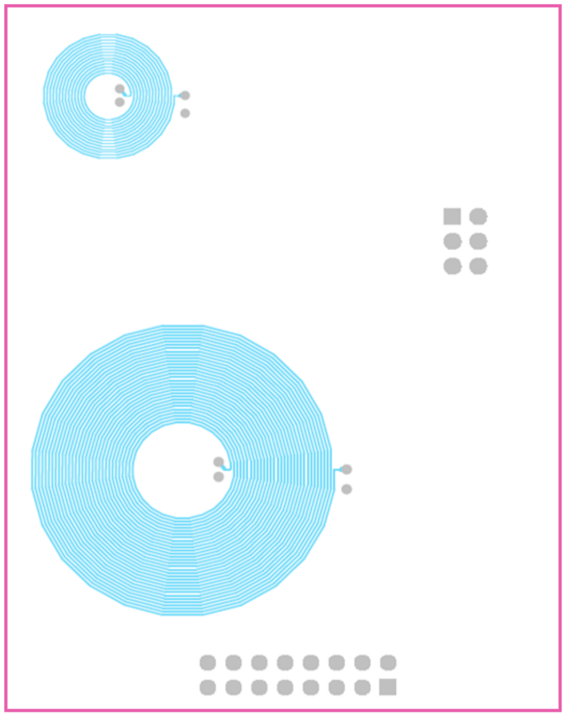

Figure 32. Mid-Layer 2

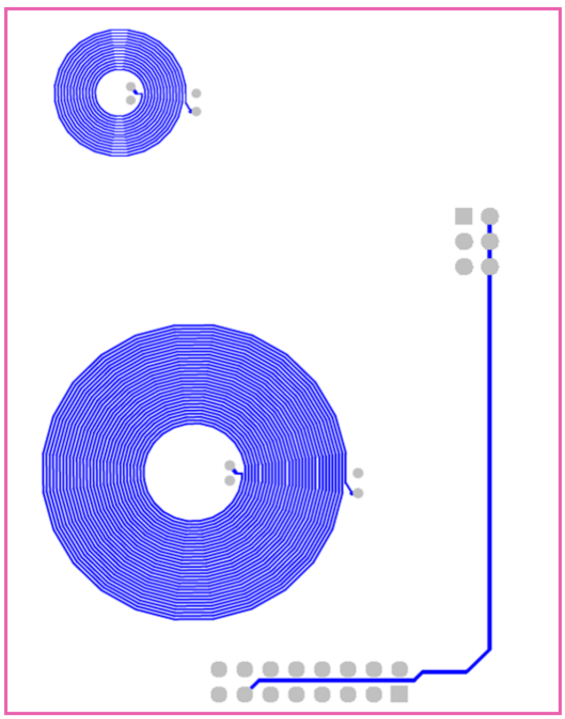

Figure 33. Bottom Layer

8.4 Altium Project

To download the Altium project files for each board, see the design files at TIDM-INDUCTIVEPROX

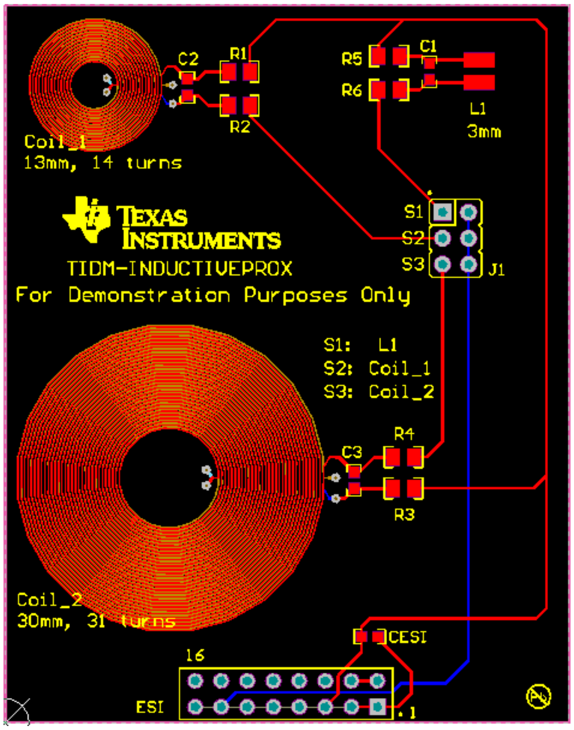

Figure 34. LC Sensor Board Layout

9 References

1. *MSP-EXP430FR6989 LaunchPad Development Kit User's Guide*, Texas Instruments (SLAU627A)
2. *LC Sensor Rotation Detection With MSP430™ Extended Scan Interface (ESI) Application Report*, Texas Instruments (SLAA639)
3. *Mechanical-to-Electronic Converter with Three LC Sensors for Gas or Water Meter User's Guide*, Texas Instruments (TIDU486)

10 About the Authors

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