ESI + LDC Inductive Linear Position Sensing

TEXAS INSTRUMENTS

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-INDUCTIVELINEAR	Tool Folder Containing Design Files
MSP-EXP430FR6989	Product Folder

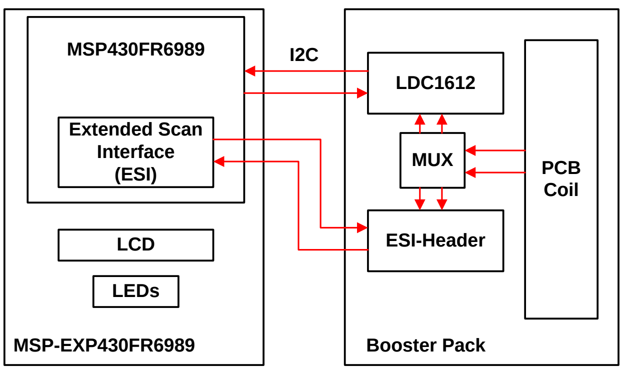
TI E2E™ Community ASK Our E2E Experts

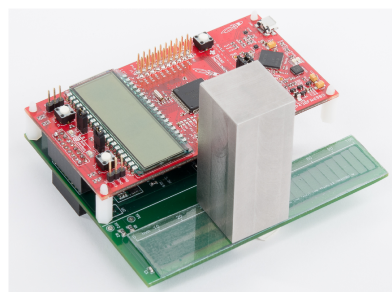
Design Features

- Ultra-Low Power
- Non-contact Detection and Measurement
- Highly Immune to Environmental Contaminations
- High Resolution and Accuracy
- Increased Flexibility and Performance Without Requiring Analog Trimming Techniques

Featured Applications

- Factory and Home Automation
- Sensors and Field Transmitters
- Portable Instruments





An IMPORTANT NOTICE at the end of this TI reference design addresses authorized use, intellectual property matters and other important disclaimers and information.

1 System Description

In many factory automation applications, the sensors supply the necessary signal for counting tasks or the present of metal objects. If the end-equipment system is deployed in harsh environment because of vibration, dust, dirt, oil and moisture and the application calls for metal sensing then the inductive sensing technology solution seems to be a natural choice due its contactless, magnet-free sensing, contamination-resistant, and maintenance free operation. The technology of inductive sensing has been around for decades. Historically, this technique has required complex, analog-only circuitry, making it a costly technique for applications outside of industrial controls or portable metal detectors.

Typical implementations of linear position measurements use expensive rare-earth magnets. To lower the overall system cost, this reference design describes the implementation of the industry's first inductance-to-digital converters (LDC) from TI for linear position sensing without the use of any expensive rare-earth magnets. This reference design also describes the implementation of the ultra-low power two chips solution for inductive linear position sensor by using TI Extended Scan Interface (ESI) module on MSP430 microcontrollers and LDC1612 chip. While LDC provides more accuracy and high resolution inductive measurement, ESI may be used in a stand-by mode to detect proximity of an object. In the approach used for this TID, ESI may reduce the power consumption of the system by more than an order of magnitude (see the power measurement results in Section 7.2) when in stand-by mode. By combining the ESI module on MSP430 and the LDC technology, the reference design provides designer a low cost and low power inductive linear position sensing solution.

1.1 MSP430FR6989 LaunchPad

The MSP430FR6989 LaunchPad™ Development Kit is an easy-to-use evaluation module (EVM) for the MSP40FR6989 microcontroller (MCU). The MSP430FR6989 on board the LaunchPad is a 16 MHz FRAM-based ultra-low-power MCU with 128 KB FRAM, 2 KB SRAM. The segment LCD controller and Extended Scan Interface (ESI) module on this LaunchPad provide a low cost ultra-low power solution for inductive proximity sensing. In this TI design, the MSP430FR6989 is also used to process the algorithm to analyze the raw data generated from the LDC1612 inductance to digital converter. To learn more about this device, see http://www.ti.com/tool/MSP-EXP430FR6989. Figure 1 shows the MSP430FR6989 LaunchPad.

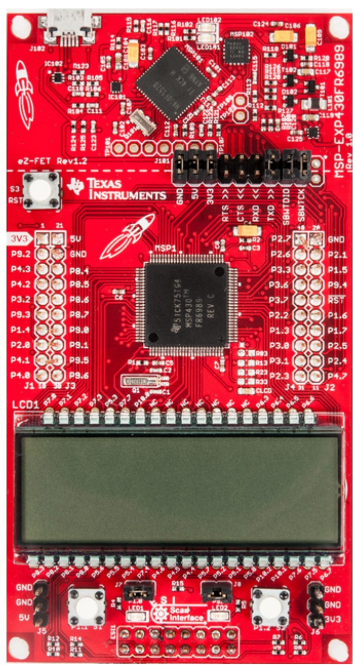


Figure 1. MSP430FR6989 LaunchPad

1.2 LDC1612

The LDC1612 and LDC1614 are 2 and 4-channel, 28-bit inductance to digital converters (LDCs) for inductive sensing solutions. With multiple channels and support for remote sensing, the LDC1612 and LDC1614 enable the performance and reliability benefits of inductive sensing at minimal cost. The high-resolution channels allow for a much larger sensing range, maintaining good performance beyond two coil diameters. Well-matched channels allow for differential and ratio metric measurements, which enable designers to use one channel to compensate their sensing for environmental and aging conditions. These conditions include temperature, humidity, and drift. Given their ease of use and low system cost, these products designers to greatly improve performance, reliability, and flexibility over existing sensing solutions. The products also introduce brand new sensing capabilities to products in all markets, especially consumer and industrial applications. These LDC1612 devices are easily configured via an I2C interface. The two-channel LDC1612 is available in a WSON-12 package and the four-channel LDC1614 is available in a WQFN-16 package. In this TI Design, only one channel is used on the LDC1612. To learn more about the LDC1612 device, see http://www.ti.com/product/LDC1612. Figure 2 shows the LDC1612 functional block diagram and Figure 3 shows the system block diagram.

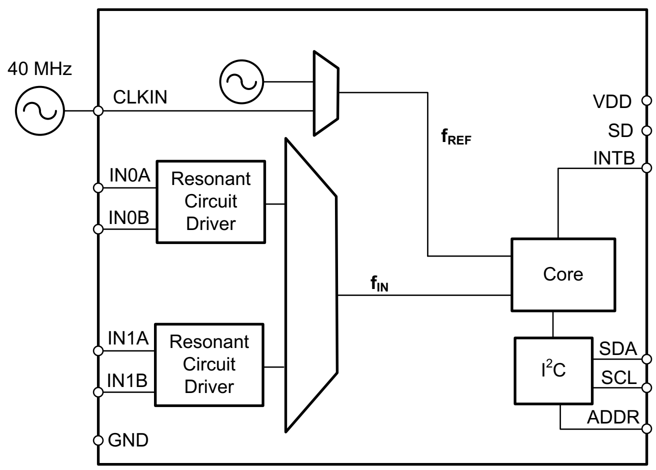


Figure 2. LDC1612 Block Diagram

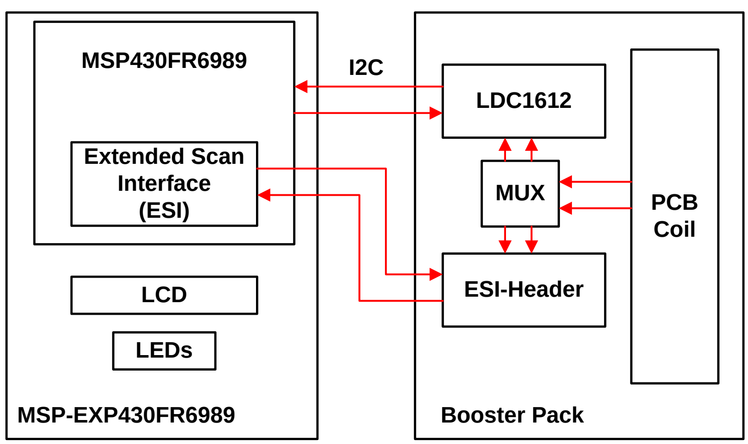


Figure 3. System Block Diagram

Figure 4 shows the BoosterPack™ diagram.

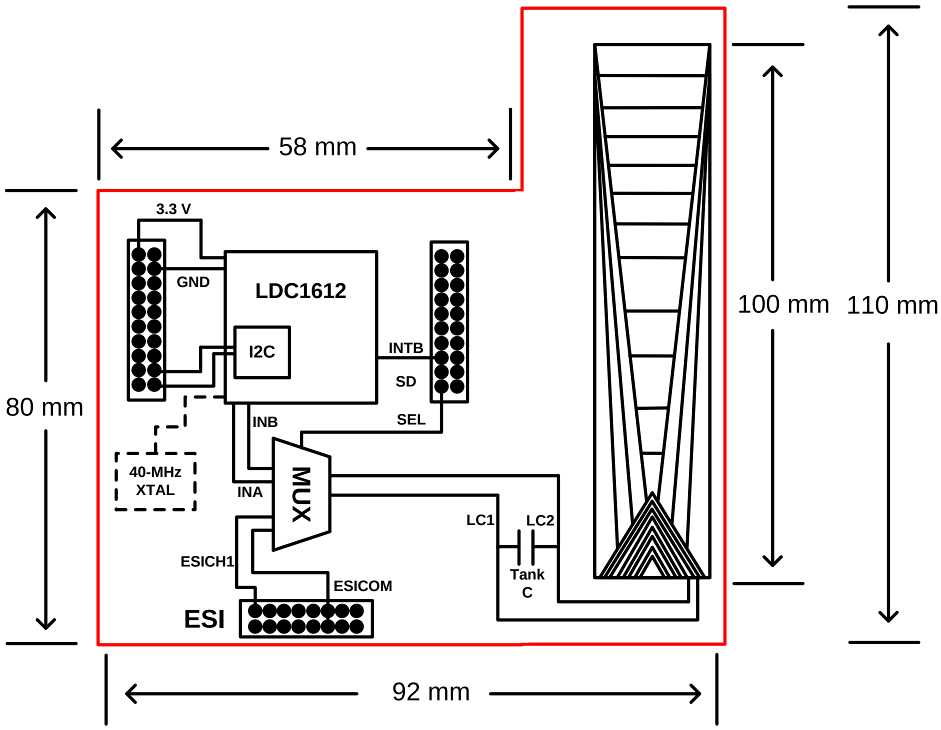


Figure 4. BoosterPack Diagram

2 Highlighted Products

2.1 MSP-EXP430FR6989

Key Features:

- MSP ULP FRAM technology based MSP430FR6989 16–bit MCU
  - 16-bit RISC architecture up to 16-MHz clock
  - 128 KB FRAM, 2 KB SRAM
  - Digital: HW MPY32, DMA, Five 16-bit Timers, AES256 or AES128
  - Analog: ESI, segment LCD controller, ADC12, 16-Ch Comparator
- 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 Extended Scan Interface (ESI)
- Available in the TI e Store

2.2 LDC1612

Key Features:

- Multiple channels support environmental and aging compensation
- Pin-compatible medium and high-resolution options
  - LDC1312/4: 2/4-ch 12-bit LDC
  - LDC1612/4: 2/4-ch 28-bit LDC
- Supports wide sensor frequency range of 1 KHz to 10 MHz
- Support internal or external reference clock
- Immune to DC magnetic fields and magnets
- Available in the TI eStore

3 System Design Theory

The TIDM-INDUCTIVELINEAR design demonstrates a low-power linear position sensing solution by combining the metal proximity function of the ESI module on the MSP430FR6989, and the inductance to digital converting function of the LDC1612. The following two subsections discuss the operation theory for ESI module and LDC1612.

3.1 Working Principle of the Extended Scan Interface (ESI)

For the working principle of ESI module, please refer to section 3.1 and 3.2 of the *Inductive Proximity* design guide (TIDUAK9).

3.2 Working Principle of the LDC1612

For LDC technology, the inductive sensing working principle is similar to ESI. An AC current flowing through a coil generates an AC magnetic field. If a user brings conductive material into the vicinity of the coil, such as a ferrous metal target, some of the energy from the oscillating magnetic field transfers to the metal target. This transferred energy induces tiny circulating electrical currents, known as eddy currents on the surface of the target. The flowing eddy currents encounter electrical resistance as they try to circulate, which creates a small amount of power loss in the form of heat. These losses are known as eddy current losses. These eddy currents are a function of the distance, size, composition, and orientation of the target to the magnetic field. The induced eddy currents in the metal target then generate their own magnetic field (counter field or secondary field) that reacts with the original field generated by the coil; this reaction changes the characteristics of the coil.

Conveniently, an inductor, along with a capacitor, can be used to construct an L-C resonator, also known as an L-C tank, which can be used to produce an EM field. In the case of an L-C tank, the effect of the field disturbance is an apparent shift in the inductance of the sensor, which can be observed as a shift in the resonant frequency. Using this principle, the LDC1612/1614 is an inductance-to-digital converter (LDC) that measures the oscillation frequency of an LC resonator. The device outputs a digital value that is proportional to frequency. This frequency measurement can be converted to an equivalent inductance.

As Figure 5 shows, the LDC1612/LDC1614 is composed of front-end resonant circuit drivers, followed by a multiplexer that sequences through the active channels, connecting them to the core that measures and digitizes the sensor frequency (f_{SENSOR}). The core uses a reference frequency (f_{REF}) to measure the sensor frequency. f_{REF} is derived from either an internal reference clock (oscillator), or an externally supplied clock. The digitized output for each channel is proportional to the ratio of f_{SENSOR}/f_{REF}. The I2C interface is used to support device configuration and to transmit the digitized frequency values to a host processor. The LDC can be placed in shutdown mode, saving current, using the SD pin. The INTB pin may be configured to notify the host of changes in system status.

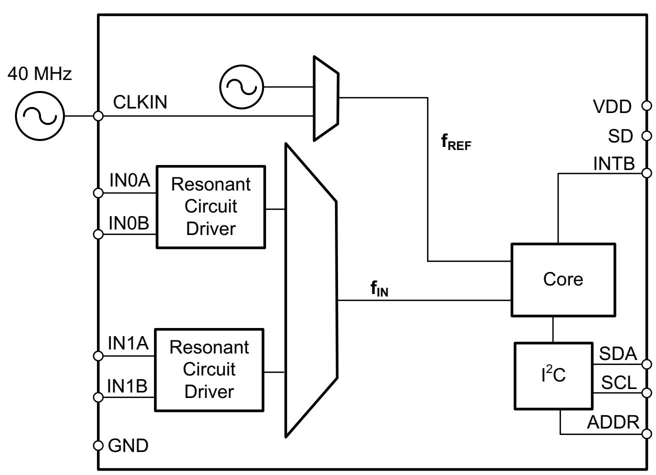


Figure 5. Functional Block Diagram of the LDC1612

3.3 Coil Design Principle

As an alternative to shaping the target to produce a varying output when moving a target over a coil, the user may instead shape the AC magnetic field that the coil produces. The idea is to generate a non-homogeneous magnetic field of the coil along the sensing range. Depending on the position x along the coil, the strength of the magnetic field is different. To use a rectangular target for linear position sensing, the coil must be shaped to produce a non-homogeneous AC magnetic field. This shaping can be achieved by *stretching* a coil, such that it produces a stronger AC magnetic field on one side than on the other.

Figure 6 shows an example of such a system, where a rectangular target kept at a constant air gap sliding over such a sensor coil along x-axis. The sliding produces an LDC output that can be used to determine the target position. The advantage of choosing a stretched coil (rectangular PCB coil with decreasing turns per section) with a rectangular target over a circular coil with a triangular target is that the target may be much smaller, and of a simpler shape. In many systems, where space for the moving target is restricted, a stretched coil design may be a more feasible approach.

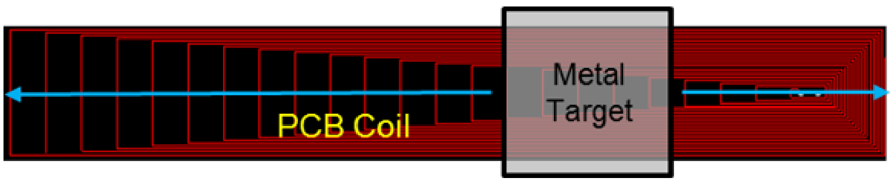


Figure 6. Lateral Movement of Rectangular Target on PCB Coil

The coil used in this reference design is a 100 mm×15 mm coil, has 23 turns per layer on four layers. The AC magnetic field that the coil produces is strongest at its innermost turn and decays towards the left hand side. Therefore, the peak strength of the AC magnetic field lies right of the geometric center of the coil. TI provides PCB layout scripts that generate stretched coils for linear position sensing applications. The *LDC Sensor Design* application report (SNOA930) contains additional information on LDC sensor design.

For demonstration purposes, to keep the metal target above the coil for a constant distance without touching the coil, place a 1-mm thick plastic sheet on top of the coil. This is so the user may place the metal target on top of the plastic sheet to keep a 1 mm gap between the target and the coil.

Figure 7, Figure 8, and Figure 9 show different target positions with respect to the sensor coil in different views.

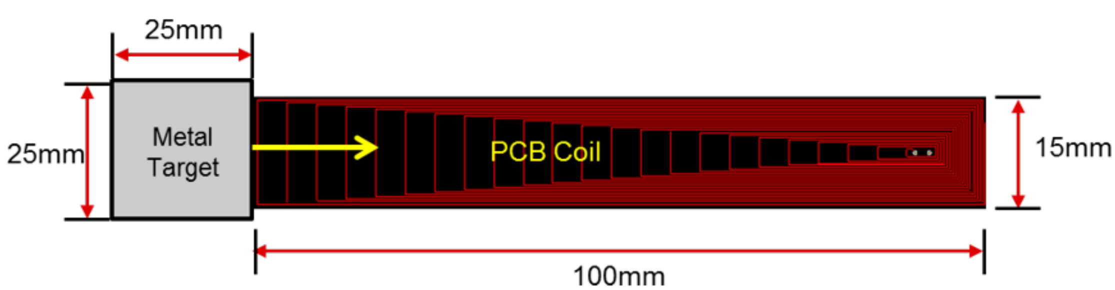


Figure 7. Starting Position: dx= 0 mm (Top View)

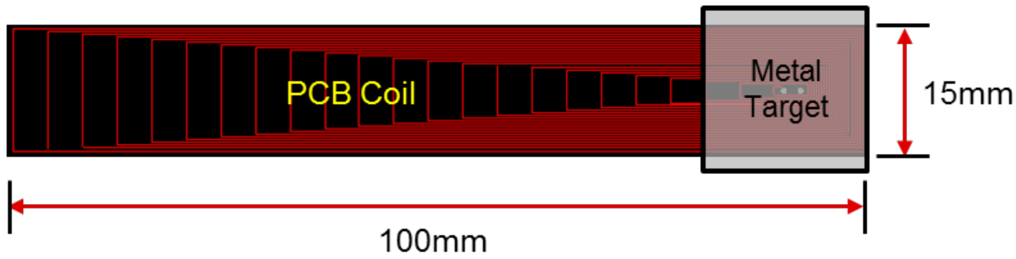


Figure 8. Final Position dx= 100 mm (Top View)

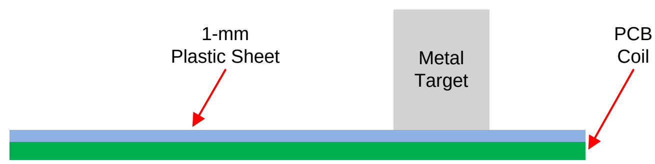


Figure 9. Moving Target With 1 mm Gap (Side View)

The target length impacts resolution and travel range. A longer target improves resolution, but limits the usable travel range. The target width must extend past the coil to ensure maximum metal exposure.

The wide range of oscillation frequency and the driving current of the LDC1612 device provides great flexibility to the user when selecting the dimensions of the coil that best suits his or her specific mechanical system configuration. However, certain rules must be followed to ensure the proper operation of the device.

- LC tank resonant frequency– The recommended sensor frequency range for LDC1612 devices is 1 kHz to 10 MHz
- Inductance of the sensor coil– There is no absolute requirement on the value of the inductance, as long as the range of the resonant frequency and RP (the parallel loss resistance) are not violated.

The capacitors must be placed as close to the sensor coil as possible to reduce the parasitic inductance of the PCB traces. The trace length from the LC tank to the IC is less critical, because they do not affect the resonance frequency.

TI recommends using high quality capacitors, such as the ceramic capacitors or film capacitors with a tolerance of 1% to 5%. The tank capacitor for this design is a 150-pF ceramic surface-mount device (SMD) part. These values make the tank oscillate at a resonant frequency below the 10-MHz operation limit. The sensor coil that works at the highest possible frequency in precision applications is advantageous because these sensor coils require less turns. Also, less turns help to reduce the temperature drift of the frequency due to the target’s resistance change.

4 Getting Started Hardware

This section of the document explains how to use the linear position sensing BoosterPack with the MSP430FR6989 LaunchPad.

4.1 BoosterPack

This BoosterPack, shown in Figure 10, includes one rectangular PCB coil, a LDC1612 device and a high-speed multiplexer and also the optional 40MHz XTAL for external clock. Before connecting the BoosterPack to the LaunchPad there are two modifications to the board according to the specific configuration, as shown in Table 1.To provide power to LDC1612, the user must connect the J8 pin.

Table 1. BoosterPack Configuration

	POPULATE	DO NOT POPULATE
Internal Clock	R17	R20, R16, C5, Y2
External Clock	R20, R16, C5, Y2	R17
12C Address 0x2A	R18	R19
12C Address 0x2B	R19	R18

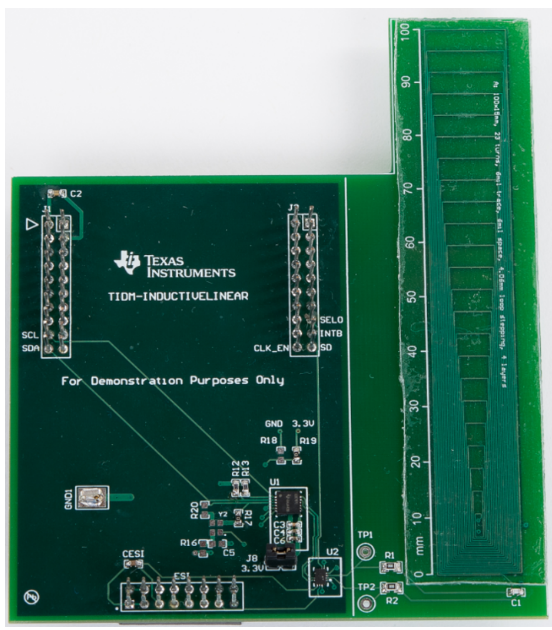


Figure 10. Inductive Linear Position BoosterPack

4.2 MSP430FR6989 LaunchPad

To use this BoosterPack, the user must connect it to a MSP430FR6989 LaunchPad from the bottom so it will have access to both the BoosterPack header and the ESI header, as shown in Figure 11.

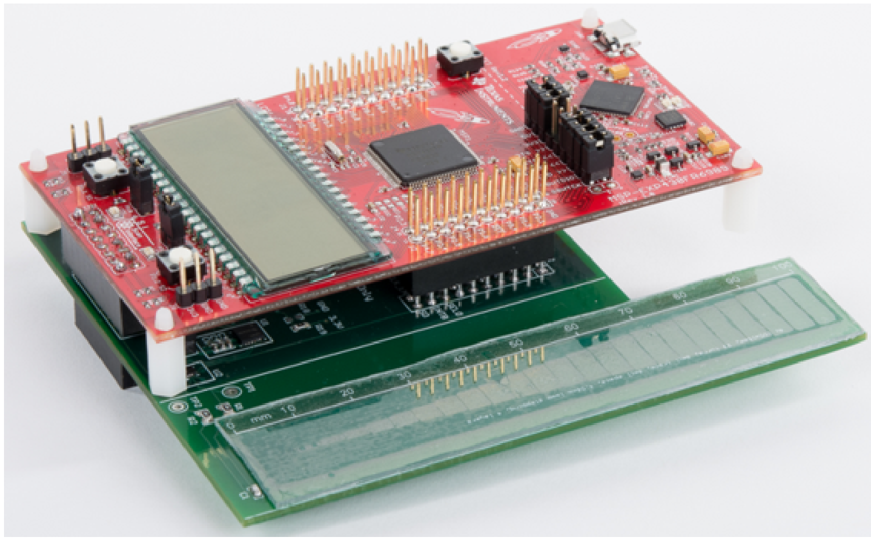


Figure 11. Inductive Linear Position Sensing Reference Design

To demonstrate this reference design, Figure 12 shows how the user may place the metal target on top of the plastic sheet and slide along with the coil. This system requires calibration process for different coils and metal targets and you can find the detail procedures in Section 5.3.3.

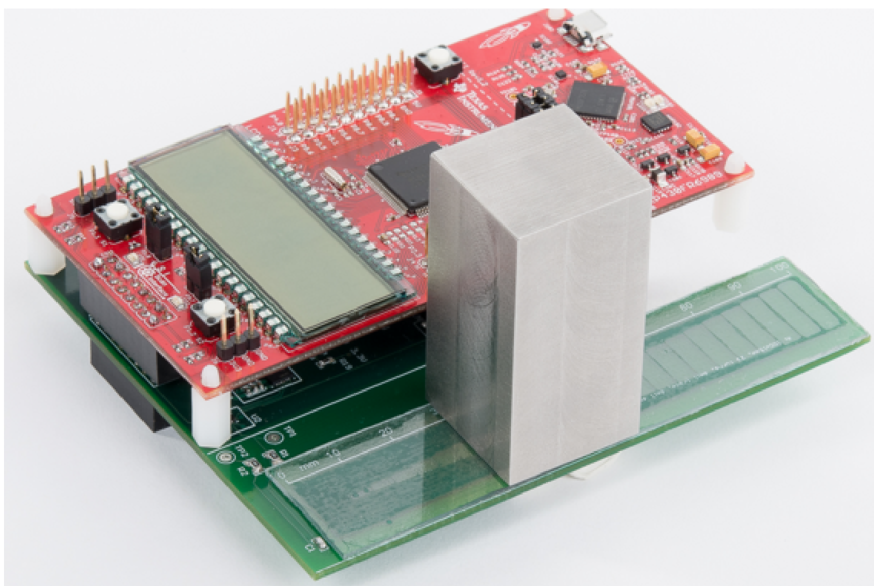


Figure 12. Inductive Linear Position Sensing Reference Design and Metal Target

5 Getting Started Firmware

Figure 13 shows the basic firmware flowchart. The software packaged with this design is intended to be sufficient for a full demonstration of the compatibility of ESI module and LDC1612 with a specific coil, but it is **not** optimized for all types of LC sensors and is not granted for best tuning. The optimization and tuning process are required if the user wants to use different coils.

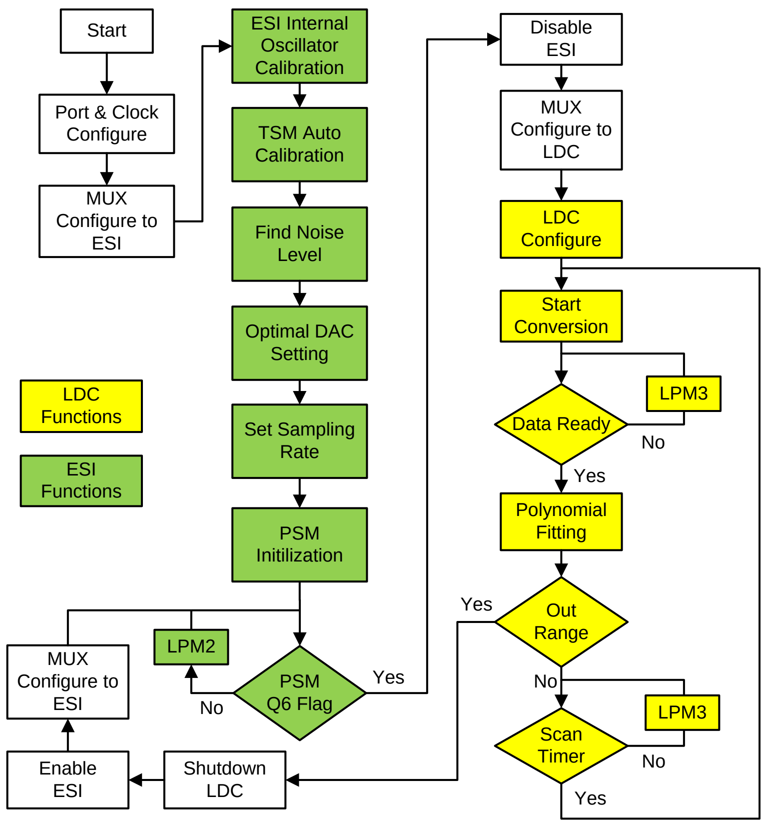


Figure 13. Flowchart of the Firmware

5.1 Port and Clock Setting for Low-Power Operation

To lower the system power consumption all ports must be set to minimize low leakage. Unused pins must be set to output zero. Port 2.4 is used as the input to take the interrupt bit from LDC1612 when the data is ready to read. Port 3.4 and port 3.5 are used for UART as RXD and TXD, and they are set to low in power consumption measurement mode. Port 4.0 and port 4.1 are used for I2C interface with the LDC1612 device.

In this reference design, the SMCLK and MCLK are sourced by DCO with 8MHz frequency and ACLK is sourced by external crystal with 32768Hz frequency. At the initialization, the MUX is configured to connect the coil to ESI module.

5.2 ESI Sampling Process

The software is optimized to reduce power consumption of the system. The process begins with initialization which includes ports setting for low current leakage, LCD, ESI internal oscillator calibration, ESI registers, sampling rate, timing state machine (TSM) with auto-TSM calibration, optimal DAC level, and processing state machine (PSM) table setting. After initialization, the design works well in low-power mode with the ESI as the only module that are actively running. In this reference design, the MSP430 goes to low-power mode 2 instead of 3 because of the USCI41 errata. However, the difference of power consumption between LPM2 and LPM3 is only 0.5 uA at 3 V supply voltage.

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, refer to Section 5.2.5.The system is in LPM2 mode when there is no metal present. To further lower the power consumption, the user may disable the LCD and add a key button to wake up the LCD when reading is required.

5.2.1 ESI Internal Oscillator Calibration

There are three clock sources associated with the ESI: ACLK, SMCLK, and the internal oscillator of ESI. The internal oscillator and the SMCLK are the sources of high-frequency clocks that are used in the TSM timing control. For low- power and standalone 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 may be found in esi.c from the MSP Driver Library.

5.2.2 Auto-TSM Calibration

The Timing State Machine (TSM) is to control the timing of each state and the registers used are ESITSMx. Referring to the *MSP430FR58xx, MSP430FR59xx, MSP430FR68xx, and MSP430FR69xx Family User's Guide* (SLAU367G), the 5 most significant bits of the register are used to determine the period of time for the corresponding state to last for. Afterwards, the TSM jumps to the next state. Repeating 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. The ESI module may also be configured to immediately start after ESISTOP flag is asserted.

Figure 14 shows the setting of the 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
```

Figure 14. TSM Registers Code

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

Second, ESITSM1 is to makes an excitation pulse for the channel 1 with timing last for 10 clock 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 its signal amplitude gets smaller. A delay with a high frequency clock from ESI oscillator is turned on to fine tune the delay time and last 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_INDUCTIVELINEAR_autoCalibrateTSM* is constructed to tune the time delay of the LC signal. As for the calibration routine algorithm to find a lower peak of the oscillation signal level and timing to capture a signal. This function is to add on one high frequency clock cycle delay every time. The captured signal is then measured by a function *TIDM_INDUCTIVELINEAR_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 comparator so that the upper and lower reference level of the DAC needs to 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 us and for comparator is 3 us.

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

This TSM-Auto calibration routine is designed to demonstrate the ESI compatibility with different LC sensors, but does not guarantee to locate the portion of signals with maximum difference. To achieve the maximum sensing distance, the user may manually modify the TSM register to change the delay to locate the portion of signals with maximum difference according to their specific LC sensors. To learn more about the TSM registers, refer to the device datasheet (SLAU367G).

5.2.3 Find Noise Level and Optimal DAC Setting

The DAC in the ESI 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, there are two DAC registers 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 is how large should it be for the separation of these two levels. If the separation is small, oscillation may frequently occur. If it 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 signal is then a significant data for the optimal setting of analog hysteresis. The noise level is measured when there is no metal presented. The function *TIDM_INDUCTIVELINEAR_findNoiseLevel()* is responsible for this measurement, in which *TIDM_INDUCTIVELINEAR_findDAC_Fast_Range()* is the algorithm to search for the signal level. This function is to measure 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 value of the sensor signal. The function *TIDM_INDUCTIVELINEAR_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 needs to be swapped. For this reason, the upper voltage level is been set to *Max_DAC_Ch0* + *DISTANCE_FACTOR*. The lower voltage level is set to *Max_DAC_Ch0* + *NoiseLevel* + *DISTANCE_FACTOR*. Figure 15 shows the optimal DAC setting.

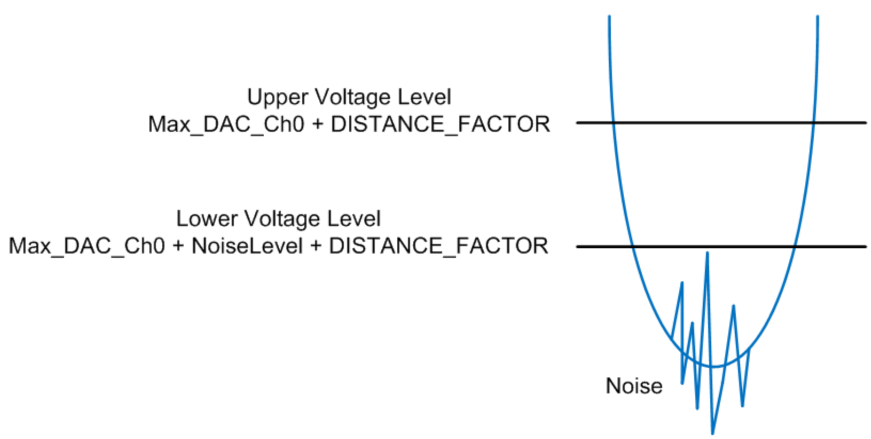


Figure 15. Optimal DAC Setting

The DISTANCE¬_FACTOR allows user to adjust metal detection range. Setting a DISTANCE_FACTOR of 0 will return the maximum range detection capable by the calibration algorithm.

5.2.4 Sampling Rate Setting

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

Table 2. TSM ACLK DIVIDER OPTIONS

ACLK DIVIDER	ESIDIV3Bx	ESIDIV3 Ax		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				

5.2.5 PSM Operation

The PSM is a programmable state machine used to determine presence of metallic objects with its state table stored within the Extended Scan Interface memory (ESI RAM). The processing state machine controls interrupt generation based on the inputs from the timing state machine 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 setup the PSM because the ESI allows selecting either two signals or three signals for the PSM processing.

Only use channel 0 so all the input change from channel 1 will be 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 with red highlight in Table 3. Q6 is set when the system detect the change from metal to nonmetal or nonmetal to metal, indicating with blue highlight in Table 3. Q2, Q4 and Q5 are not used in the application code. The Q6 is another interrupt flag of PSM table. In the application code, when Q6 is set, it triggers an interrupt code to switch the multiplexer to LDC1612 and disable the ESI module and start the LDC sampling process.

Table 3 shows the PSM table.

Table 3. PSM TABLE

PRESENT STATE	CH1/CH0 INPUT	DESCRIPTION	Q1	NEXT STATE (Q3/Q0)	Q7 (ERROR)	Q6 (CHANGE)	BYTE CODE
00	00	No change	0	00	0	0	0×00
00	01	Change	1	01	0	1	0×43
00	10	Error	0	00	1	0	0×80
00	11	Error	0	00	1	0	0×80
01	00	Change	1	00	0	1	0×42
01	01	No change	0	01	0	0	0×01
01	10	Error	0	00	1	0	0×80
01	11	Error	0	01	1	0	0×81

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

5.3 LDC Sampling Process

After the ESI module detects the metal present, the system switches to the LDC sampling process.

5.3.1 LDC Configuration

The first step of the LDC sampling process is to configure all the necessary registers according to the designer's requirement. For more information about each registers and configurations please refer to http://www.ti.com/lit/ds/symlink/ldc1614.pdf. In this reference design, input is set to deglitch filter bandwidth for 10 MHz and reference count conversion interval time for 25000 and the conversion settling time for 1024. The user may find other specific register configurations for this reference design in provided firmware code.

5.3.2 Getting Data

To optimize the power consumption, MSP430 will go to LPM3 mode while LDC1612 is doing the conversion. After LDC1612 completed the conversion it will send an interrupt to wake up MSP430 to read the raw count using I2C. The resolution for the LDC raw count contains more bits than necessary, and in order to get more accurate result with polynomial regression method, shift the 12-bit to the right of the 28-bit raw count data. For IQmath fixed point operation we need to center the data at the origin of the x-axis so we add -1100 offset to the raw count to make it in the range of -50 to 50.

5.3.3 Polynomial Fitting

Figure 21 shows the relationship of raw count and position data. Notice that in the optimal operation region, the relationship is close to linear. The following two approaches may be used to improve the linearity of the measurement:

Approach 1:

The output code may be translated to travel distance by calculating the best-fit curve through the output response. For this approach, system accuracy requirements dictate the minimum polynomial degree, thereby also dictating the required processing power of the microcontroller. In this reference design, use the 3rd order polynomial curve. The user may incorporate the coefficients of the polynomial into the microcontroller.

In this reference design, the test setup shown in Figure 15 shows to collect the raw data and the position information. Use MATLAB® to calculate the 3rd order polynomial coefficients. The user may edit the coefficients in the code for both fixed point operation and floating point operation. The function *calculateDistanceFloat()* and *calculateDistanceIQMath()* perform the polynomial regression method to calculate the position in mm with the LDC raw count data. The user may choose to either use floating point or fixed point operation. Floating point operation gives more accurate result but higher power consumption and fixed point operation, and vice-versa.

Approach 2:

The raw data may also be translated to travel distance by employing a look-up table. This approach requires little processing power, but requires memory for the look-up table. After polynomial fitting, the LCD displays the current metal target position. If the value is below the threshold of metal present, then the system shuts down the LDC and switches to the ESI sampling process.

5.3.4 Scan Timer

In this reference design, a timer is used on the MSP430 to control the scan rate of the LDC1612. The user may set the scan period in the header file, and after the timer count for one period wakes up the LDC1612 from the sleep mode.

5.4 Header File Modification

In the *TIDM_INDUCTIVELINEAR.h* header file, users may modify the code to change:

1. The number of iterations for finding noise level time
2. The ESI detection distance
3. The scan rate of the LDC1612
4. The polynominal fitting operation modes
5. Enable and disable the power consumption measurement mode

NOISE_LEVEL_DETECTION_TIME is a variable that allows the user to 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, the user may reduce the number of iterations to reduce the calibration time. If you notice false metal detection triggers, increase the **NOISE_LEVEL_DETECTION_TIME** value.

SEPARATION_FACTOR is a variable that allows the user to adjust the metal detection range. Set this value to 0 to get the maximum detection range provided by this application code.

LDC_SCAN_PERIOD is a variable that allows the user to adjust the LDC1612 scan period in milliseconds.

ENABLE_CURRENT_CONSUMPTION_MEASUREMENT allows the user to enable the power consumption measurement mode by uncommenting this define in header file.

ENABLE_FLOATING allows the user to enable the floating point operation for the polynomial fitting. By using floating point operation, the user receives a more accurate position, but higher power consumption. To enable the floating point, uncomment this define and comment the **ENABLE_IQMATH** define in header file.

ENABLE_IQMATH allows the user to enable the IQMath fix point operation for the polynomial fitting. By using IQMath fix point operation, the user will get a less accurate position, but lower power consumption. To enable this you must uncomment this define, and comment the **ENABLE_FLOATING** define in the header file.

6 Test Setup

This section demonstrates the test setups for collecting the LDC1612 raw data and power consumption test.

6.1 Collecting the LDC1612 Raw Data

The inductance measurement is obtained at each position with the test setup, shown in Figure 16. The raw data includes the information of the target position and the raw count of LDC1612. The reference BoosterPack coil is located at the top of the linear table that is attached to a screw controlled by Y motor, so it may move with the Y axis. On the other hand, the metal target is attached to a screw that is controlled by two Z motors and the X motor so it may move with the X axis and the Z axis.

The raw count of the LDC1612 device and the position information was measured for every 1-mm x- axis increment of the metal target, and was logged in a PC for further processing. The gap between the metal target and the coil may be controlled the by Z motor, and is maintained at 1 mm, 2 mm, and 3 mm. The metal target used in this reference design is a 25- × 25- × 50- mm steel target.

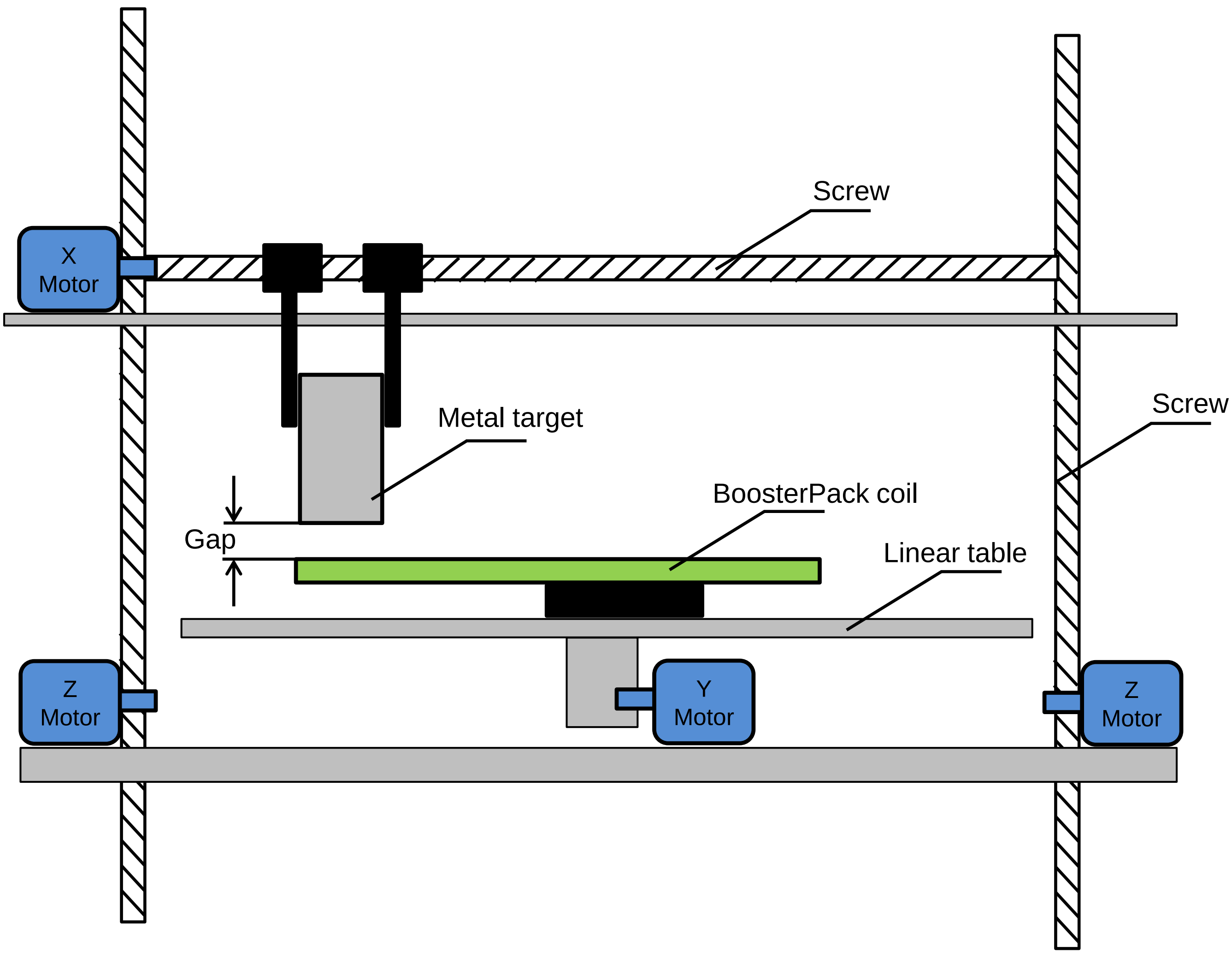


Figure 16. Raw Data Collection Setup

6.2 System Errors

There are several important factors that may cause the error between the actual metal target position and the calculated position.

1. To obtain the polynomial coefficients, the user must collect the raw data for the full range of the coil.

The setup used to collect raw data need to move the metal target with the consistent increment and the consistent air gap. If the setup does not meet the requirements, the calculated polynomial coefficients will not be accurate.

2. Use the 3rd order polynomial curve to best fit the data and errors between the raw data and the polynomial curve appear. Figure 17 shows the 3rd order polynomial fitting errors for 1 mm air gap.

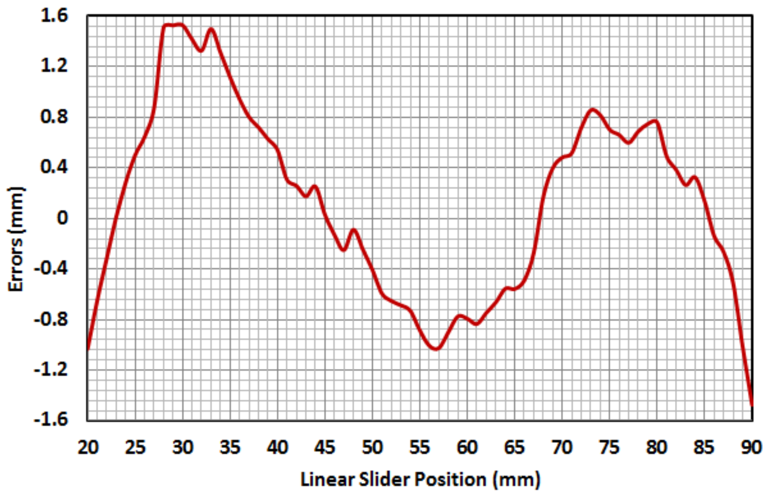


Figure 17. Polynomial Fitting Errors

6.3 Power Consumption Test

For the power consumption test, the KEYSIGHT™ N6705B DC Power Analyzer is used for the power supply, and the input voltage is 3.3 V.

1. Program the LaunchPad.
2. Connect the BoosterPack to the LaunchPad.
3. Because an external power supply is being used, remove all connections from the eZ-Fet, as shown in

Figure 18 shows the external power supply jumper configuration.

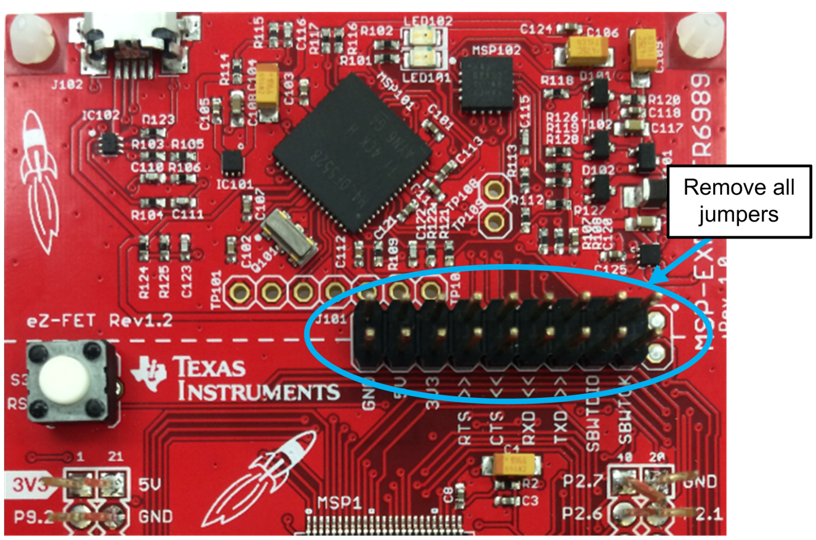


Figure 18. External Power Supply Jumper Configuration

1. connect the DC Power Analyzer to the header J6 on the LaunchPad, as shown in Figure 19.
2. Wait for 30 seconds so that the system goes into ESI mode.

3. Place the metal on top of the coil for another 30 seconds for the system to go into LDC mode.
4. Use the software for the KEYSIGHT N6705B to get the average current for both the ESI and LDC modes.
5. Repeat this process for different sampling frequencies.

Figure 19 shows the DC power analyzer power consumption test configuration.

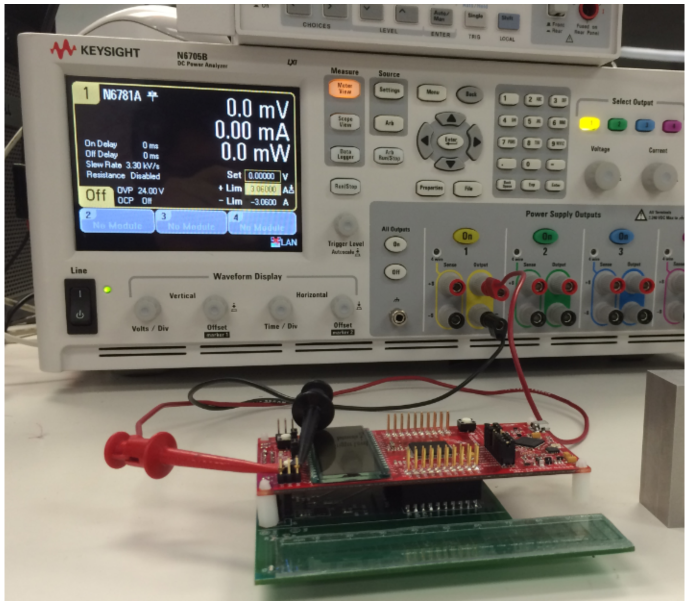


Figure 19. DC Power Analyzer Power Consumption Test Configuration

7 Test Data

The test data in the following sections were measured with the system at room temperature, unless otherwise noted.

7.1 Linear Position Test Data

The distance data we provide here is only the typical value for the test setup showed in Figure 15. There are many factors that can affect the raw data like temperature and metal material.

Moving a target from dX = 0 mm to dX = 100 mm (Figure 21) at an air gap of dz = 1mm, 2mm, and 3mm in 1-mm increments results in the data output, as shown in Figure 21 and Figure 22. Figure 23 shows the calculated inductance value data. The target is a 25- × 25- × 50- mm steel target.

Notice that on the booster pack the 0 mm marker is at the end of the more dense traces side of the coil. However, the test result is collected, the 0 mm marker is at the less dense traces side of the coil, as shown in Figure 20.

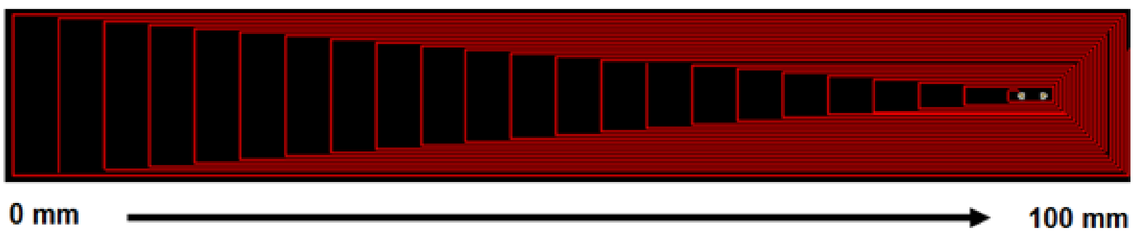


Figure 20. Target Metal Moving Direction

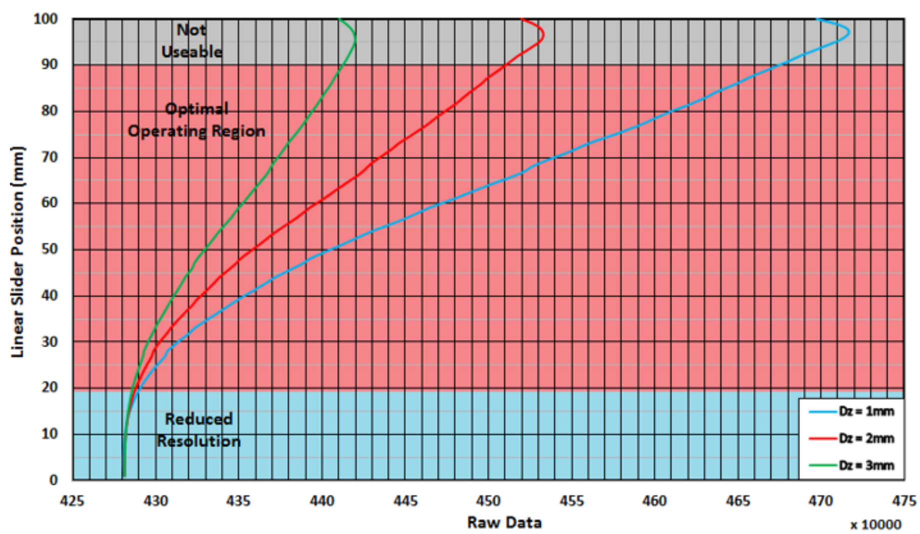


Figure 21. Linear Position Versus LDC1612 Raw Data

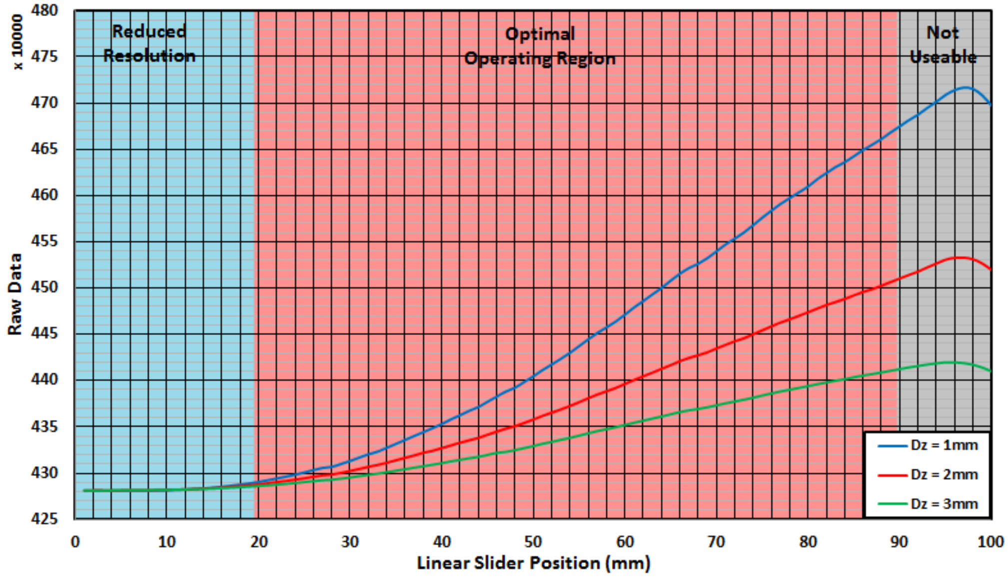


Figure 22. LDC1612 Raw Data Versus Linear Position

After collecting the raw data, calculate the inductance value using Equation 1 and Equation 2.

$$f_{sensorx} = CHx\_FIN\_DIVIDER \times f_{REFx} \left(\frac{DATAx}{2^{28}} + \frac{CHx\_OFFSET}{2^{16}} \right) \quad (1)$$

Where:

- DATAx = Conversion result from the DATA_CHx register
- CHx_OFFSET = Offset value set in the OFFSET_CHx register

$$L = \frac{1}{C \times (2\pi f_{sensor})^2} \quad (2)$$

Where:

- C is the parallel capacitance of the resonator

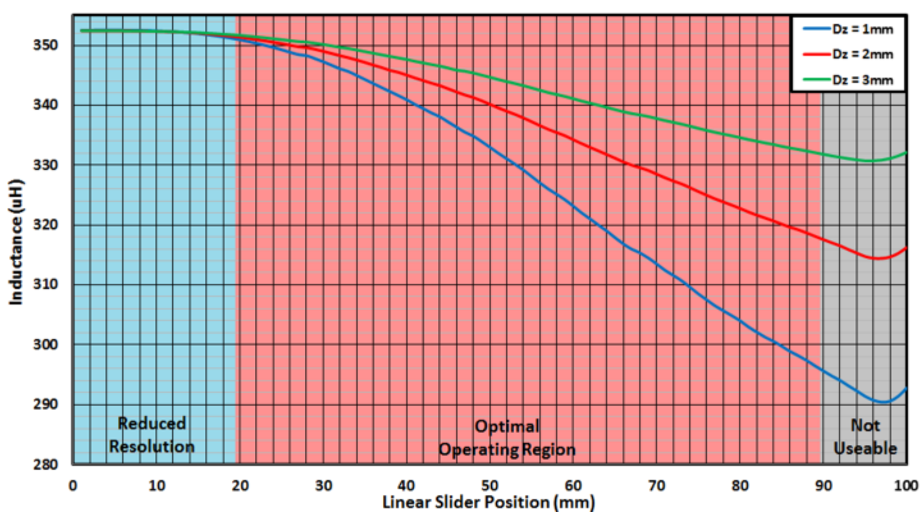


Figure 23. Sensor Inductance Versus Linear Position

The graph in Figure 21 Figure 22 and Figure 23 that result from sliding the target from dX = 0 mm to dX = 100 mm can be broken up into three distinct regions.

Reduced Resolution:

Between 0.0 mm and 20.0 mm, the target enters the magnetic field of the coil. This region can be used to determine the target position, but its resolution is less than in the center region (optimal operating region). For example, moving from dX = 5.0 mm to dX = 6.0 mm at Dz = 1 mm results in an inductance change from 352.555µH to 352.541 µH, which is a 0.014-µH inductance change. Therefore, the average inductance decrease over this range is 0.119-µH per mm.

Optimal Operating Region:

The center region spans from 20.0 mm to 90.0 mm over which the sensor inductance decreases from 350.935 µH to 295.618 µH. This region can be used to most accurately determine the target position. For example, the data shows that moving from dX = 50.0 mm to dX = 51 mm at Dz = 1 mm results in an inductance change from 332.983µH to 331.986µH, which is a 0.997-µH inductance change. Therefore, the average inductance decrease over this range is 0.791-µH per mm.

Not Usable:

Between dX = 90 mm to dX = 100 mm, the downward trend reverses, which is due to the drop in magnetic field strength past the center coil loop. The use of this region poses significant system challenges for the small increase in target travel range that it provides because the LDC output codes cannot be uniquely mapped into this region. In conclusion, the region past the center coil loop (between dX = 90.0 mm and dX = 100.0 mm) is not monotonic and is therefore unusable for this application. This unusable region limits the usable travel range to 90 mm. Depending on system accuracy requirements, precision applications may also require to discard the region between 0.0 mm and 20.0 mm. This discarding leads to a usable travel range of 70 mm (70% of the total coil length). As a result, the coil design length must extend beyond the required travel range.

7.2 Power Consumption Test Data

This section shows the system current consumption of the MSP430FR6989 and the linear BoosterPack in ESI mode and LDC mode, not including all current flowing into the LCD, power, and other modules on the board. The data is taken by measuring the current flowing into the MSP430FR6989 Launchpad and the Linear BoosterPack varying with different sampling rate of the ESI and LDC1612. Table 4, Table 5, Figure 24, and Figure 25 show the detailed test result. The data shows that the power consumption for both ESI and LDC1612 increase as the sampling rate increases.

Table 4. ESI Mode Current Consumption Test

SAMPLING RATE (Hz)	AVERAGE CURRENT (uA)
9	11.09
72	12.01
121	12.58
218	13.69
466	16.80
655	19.10
1400	29.50

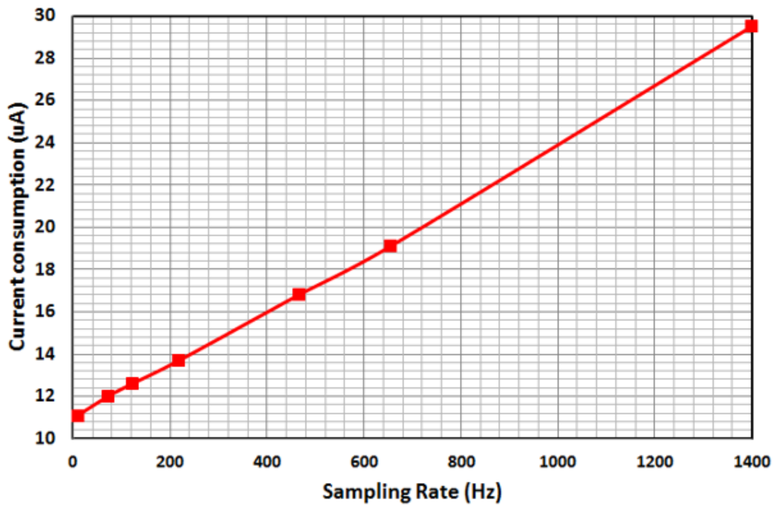


Figure 24. System Power Consumption for ESI Mode

Table 5. LDC Mode Current Consumption Test

SAMPLING RATE (Hz)	AVERAGE CURRENT (uA)
1	77.45
5	227.22
10	413.09
20	785.06
50	1908
100	3490

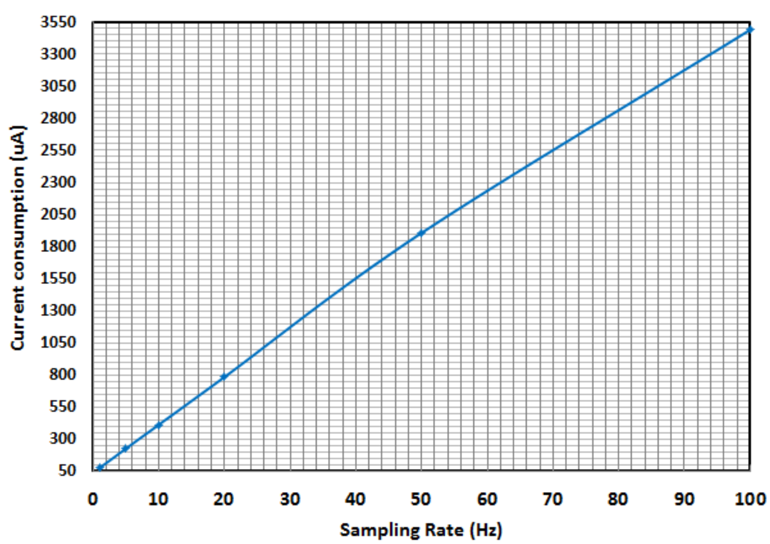


Figure 25. System Power Consumption for LDC Mode

8 Design Files

8.1 BoosterPack Schematics

To download the schematics for each board, see the design files at http://www.ti.com/tool/TIDM-INDUCTIVELINEAR. Figure 26 shows the LC sensor board schematic.

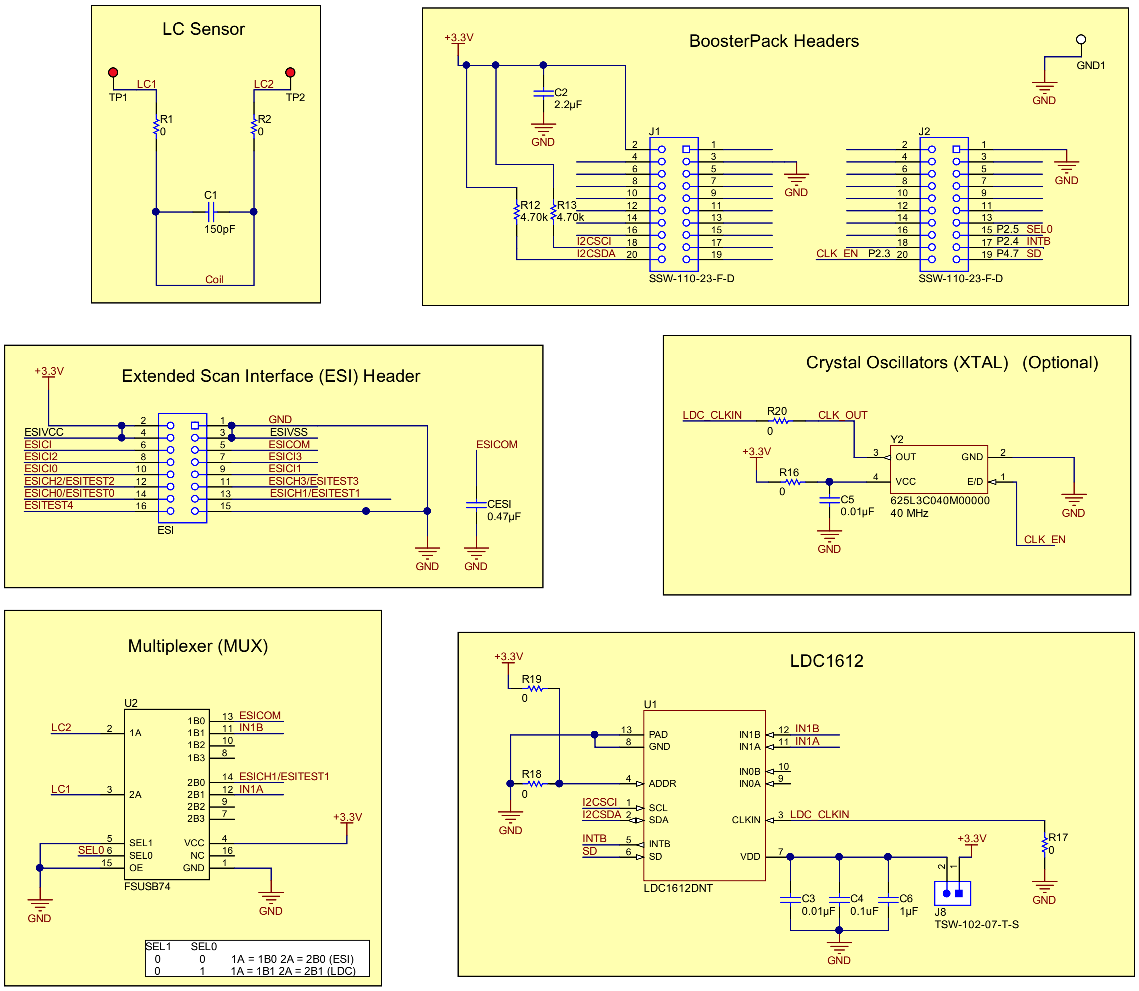


Figure 26. LC Sensor Board Schematic

8.2 Bill of Materials

To download the Bill of Materials (BOM) for each board, see the design files at http://www.ti.com/tool/TIDM-INDUCTIVELINEAR. Table 6 lists the BOM for the LC sensor board.

Table 6. Bill of Materials: LC Sensor Board

DESIGNATOR	QUANTITY	VALUE	DESCRIPTION	PACKAGE REFERENCE	PART NUMBER	MANUFACTURER
PCB1	1		Printed Circuit Board		ISE4002	Any
U1	1		LDC1612, Inductance to Digital Converter	DNT0012B	LDC1612DNT	TI
U2	1		4:1 High-Speed USB Multiplexer and Switch	16-Lead UMLP	FSUSB74	Fairchild Semiconductor™
Y2	1	40 MHz	3.3 V, 40 MHZ HCMOS Clock Oscillator	2.5×1×2.5 mm	625L3C040M00000	CTS Electronic®
ESI	1		Connector Receptacle, 100 mil, 8×2, Gold, TH	8×2 Receptacle	SSQ-108-02-G-D	Samtec™
J1, J2	2		Connector, Receptacle, 100mil, 10x2, Gold plated, TH	10×2 Receptacle	SSW-110-23-F-D	Samtec
J8			Header, 2.54 mm, 2x1, Tin, TH	2.54 mm, 2×1	TSW-102-07-T-S	Samtec
R1, R2	2	0 Ω	RES, 0, 5%, 0.125 W	0805	ERJ-6GEY0R00V	Panasonic™
R16, R17, R18, R19, R20	5	0 Ω	RES, 0 Ω, 5%, 0.1 W	0603	CRCW06030000Z0EA	Vishay-Dale™
R12, R13	2	4.7 kΩ	RES, 4.70k Ω, 1%, 0.1 W	0603	RC0603FR-074K7L	Yageo America™
C1	1	150 pF	CAP, CERM, 150 pF, 100 V, ±5%, C0G/NP0	0603	GRM1885C2A151JA01D	MuRata
C2	1	2.2 µF	CAP, CERM, 2.2 uF, 10 V, ±10%, X5R	0603	C0603C225K8PACTU	KEMET®
C3	1	0.01 µF	CAP, CERM, 0.01 µF, 16 V, ±10%, X7R	0402	C1005X7R1C103K	TDK®
C4	1	0.1 µF	CAP CER 0.1 µF 16 V 5% X7R	0402	GRM155R71C104JA88D	MuRata
C5	1	0.01 µF	CAP, CERM, 0.01 uF, 25 V, ±5%, C0G/NP0	0603	C1608C0G1E103J	TDK
C6	1	1 µF	CAP, CERM, 1 uF, 10 V, ±10%, X5R	0402	GRM155R61A105KE15D	MuRata
CESI	1	0.47 µF	CAP, CERM, 0.47 µF, 10 V, ±10%, X5R	0402	GRM188R61A474KA61D	MurRata
GND1	1		Test Point, Compact		5016	Keystone

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 do not contribute much to the inductance but add resistance.
- The sensor capacitor must 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. Typically, 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-INDUCTIVELINEAR.

8.4 Altium Project

To download the Altium project files for each board, see the design files at http://www.ti.com/tool/TIDM-INDUCTIVELINEAR.

9 References

1. *MSP-EXP430FR6989 LaunchPad Development Kit User's Guide* (SLAU627A)
2. *LDC1612, LDC1614 Multi-Channel 28-Bit Inductance to Digital Converter (LDC) User's Guide* (SNOSCY9)
3. *MSP430 Microcontroller Single Chip Inductive Proximity Sensing Reference Design* (TIDUAK9)
4. *Inductive Linear Position Sensing Booster Pack* (TIDUA26A)

10 About the Author

YIDING LUO is a Systems Application Engineer at Texas Instruments, where he is responsible for developing reference design solutions for the industrial segment and supporting customers in the industrial segment. Yiding brings to this role his experience in inductive sensing and MSP430 microcontrollers. Yiding received his Bachelor of Science in Electrical Engineering (BSEE) from the University of Texas at Dallas in 2015.

IVAN CALZADA is an Applications Engineer in the MSP Embedded Software group at Texas Instruments, where he primarily works on software development for MSP MCU family. Ivan received his Bachelor of Science in Electrical Engineering (BSEE) and his Master of Science in Electrical Engineering (MSEE) from the University of Texas at El Paso in 2009 and 2011, respectively.

LUIS REYNOSO is an Applications Engineer at Texas Instruments. He has taken multiple customer-facing roles in the embedded industry, and during this time he has published several Applications Notes and papers for microcontrollers. He joined the MSP430 Applications team in 2010.

IMPORTANT NOTICE FOR TI REFERENCE DESIGNS

Texas Instruments Incorporated ('TI") reference designs are solely intended to assist designers ("Designer(s)") who are developing systems that incorporate TI products. TI has not conducted any testing other than that specifically described in the published documentation for a particular reference design.

TI's provision of reference designs and any other technical, applications or design advice, quality characterization, reliability data or other information or services does not expand or otherwise alter TI's applicable published warranties or warranty disclaimers for TI products, and no additional obligations or liabilities arise from TI providing such reference designs or other items.

TI reserves the right to make corrections, enhancements, improvements and other changes to its reference designs and other items.

Designer understands and agrees that Designer remains responsible for using its independent analysis, evaluation and judgment in designing Designer's systems and products, and has full and exclusive responsibility to assure the safety of its products and compliance of its products (and of all TI products used in or for such Designer's products) with all applicable regulations, laws and other applicable requirements. Designer represents that, with respect to its applications, it has all the necessary expertise to create and implement safeguards that (1) anticipate dangerous consequences of failures, (2) monitor failures and their consequences, and (3) lessen the likelihood of failures that might cause harm and take appropriate actions. Designer agrees that prior to using or distributing any systems that include TI products, Designer will thoroughly test such systems and the functionality of such TI products as used in such systems. Designer may not use any TI products in life-critical medical equipment unless authorized officers of the parties have executed a special contract specifically governing such use. Life-critical medical equipment is medical equipment where failure of such equipment would cause serious bodily injury or death (e.g., life support, pacemakers, defibrillators, heart pumps, neurostimulators, and implantables). Such equipment includes, without limitation, all medical devices identified by the U.S. Food and Drug Administration as Class III devices and equivalent classifications outside the U.S.

Designers are authorized to use, copy and modify any individual TI reference design only in connection with the development of end products that include the TI product(s) identified in that reference design. HOWEVER, NO OTHER LICENSE, EXPRESS OR IMPLIED, BY ESTOPPEL OR OTHERWISE TO ANY OTHER TI INTELLECTUAL PROPERTY RIGHT, AND NO LICENSE TO ANY TECHNOLOGY OR INTELLECTUAL PROPERTY RIGHT OF TI OR ANY THIRD PARTY IS GRANTED HEREIN, including but not limited to any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services, or a warranty or endorsement thereof. Use of the reference design or other items described above may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

TI REFERENCE DESIGNS AND OTHER ITEMS DESCRIBED ABOVE ARE PROVIDED "AS IS" AND WITH ALL FAULTS. TI DISCLAIMS ALL OTHER WARRANTIES OR REPRESENTATIONS, EXPRESS OR IMPLIED, REGARDING THE REFERENCE DESIGNS OR USE OF THE REFERENCE DESIGNS, INCLUDING BUT NOT LIMITED TO ACCURACY OR COMPLETENESS, TITLE, ANY EPIDEMIC FAILURE WARRANTY AND ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, AND NON-INFRINGEMENT OF ANY THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

TI SHALL NOT BE LIABLE FOR AND SHALL NOT DEFEND OR INDEMNIFY DESIGNERS AGAINST ANY CLAIM, INCLUDING BUT NOT LIMITED TO ANY INFRINGEMENT CLAIM THAT RELATES TO OR IS BASED ON ANY COMBINATION OF PRODUCTS AS DESCRIBED IN A TI REFERENCE DESIGN OR OTHERWISE. IN NO EVENT SHALL TI BE LIABLE FOR ANY ACTUAL, DIRECT, SPECIAL, COLLATERAL, INDIRECT, PUNITIVE, INCIDENTAL, CONSEQUENTIAL OR EXEMPLARY DAMAGES IN CONNECTION WITH OR ARISING OUT OF THE REFERENCE DESIGNS OR USE OF THE REFERENCE DESIGNS, AND REGARDLESS OF WHETHER TI HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES.

TI's standard terms of sale for semiconductor products (http://www.ti.com/sc/docs/stdterms.htm) apply to the sale of packaged integrated circuit products. Additional terms may apply to the use or sale of other types of TI products and services.

Designer will fully indemnify TI and its representatives against any damages, costs, losses, and/or liabilities arising out of Designer's non-compliance with the terms and provisions of this Notice.