TI Designs
Inductive Linear Position Sensing Booster Pack

Design Overview

This design guide provides a foundation for building linear position sensing systems with TI's inductance-to-digital converters. TI Designs provide the foundation that you need including methodology, testing, and design files to quickly evaluate and customize the system. TI Designs help *you* accelerate your time to market.

Design Resources

[TIDA-00460]	Tool Folder Containing Design Files
[LDC1101]	Product Folder
[MSP430F5528]	Product Folder
[LP5951]	Product Folder
[TPD2E001]	Product Folder
[TPD1E10B06]	Product Folder

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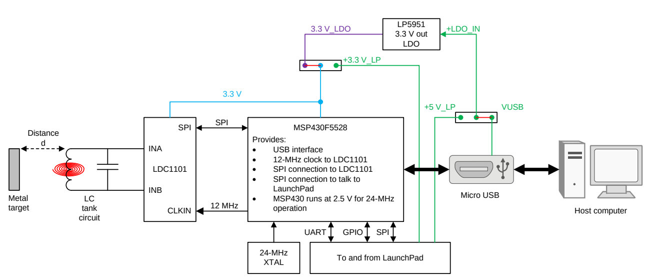
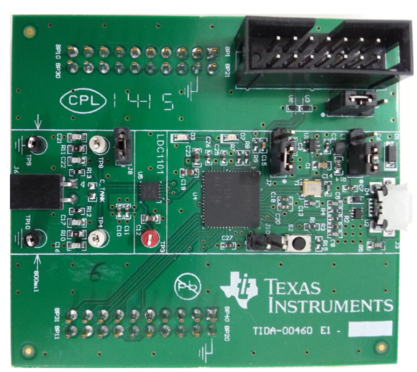
Design Features

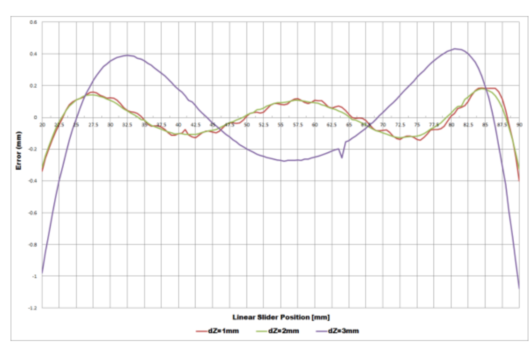
- Inductive Sensing Technology
- Non-Contact Detection and Measurement
- Increased Flexibility and Performance Without Requiring Analog Trimming Techniques
- Remote Sensor Placement
- Insensitive to Environmental Contaminations
- More Reliable Operation Sensor Self-Diagnostic
- High Resolution and Accurate
- Replaces Legacy Analog Only Solutions
- Low Power, Low Cost, and Low Footprint Solution

Featured Applications

- Factory Automation and Process Control
- Sensors and Field Transmitters
- Building Automation
- Portable Instruments







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1 Key System Specifications

Table 1. Key Specifications

PARAMETER	SPECIFICATION
Sensor type	Stretched rectangular PCB inductor coils, 15 mm × 100 mm, 28 turns per layer
Target materials	Aluminum (14 mm × 25 mm)
Measurement geometry	Linear
Full range	100 mm
Usable range	70 mm (70% of full range)
Measurement type	Absolute (no need for recalibration or reset after power loss)
Sensor operating frequency	< 1 MHz
Maximum measured error	At d_Z = 1 mm: −0.401 mm At d_Z = 2 mm: −0.325 mm At d_Z = 3 mm: −1.077 mm
System calibration	Best-fit 4th order polynomial using regression analysis
Power supply	Can be powered from either USB power or LaunchPad

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2 System Description

In all automated factory floor applications, sensors are necessary to provide the programmable logic controller (PLC) with information. The sensors supply the necessary signals for positions and limits, or serve as pulse pick-ups for counting tasks or for monitoring rotational speed. Even the best controllers cannot control the process without reliable sensors. When accurately measuring the distance less that is less than a few inches is necessary and the application calls for metal sensing, then the inductive sensor provides the required sensing solution. The inductive sensing technology solution seems to be a natural choice due its contactless, magnet-free sensing, contamination-resistant, and maintenance free operation. Additionally, inductive sensing technology is suitable for use in harsh environments because vibration, dust, dirt, oil, and moisture do not hinder the performance. Inductive sensors detect all ferrous metals without contact, which means no wear and tear.

The technology of inductive sensing has been around for decades. Additionally, the inductive sensor is currently the best-selling sensing technology worldwide, indicating a well-proven solution over a period of decades in long-term industrial use. 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 distance 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 from TI for linear position sensing without the use of any expensive rare-earth magnets. Linear position sensing determines the position of a target that moves laterally across an inductive sensor that is generating a magnetic field. An inductance-to-digital converter (LDC), such as an LDC1000 or LDC1101 device, senses the inductance changes of an inductor that comes into proximity with a conductive target, such as a piece of metal. The LDC measures this inductance shift to provide information about the position of a conductive target over a sensor coil. The inductance shift is caused by eddy currents generated in the target due to the magnetic field of the sensor. These eddy currents generate a secondary magnetic field that opposes the sensor field, causing a shift in the observed inductance (see Section 4 for a more detailed explanation).

There are two approaches to implement a linear position sensing system with an inductance-to-digital converter (LDC). Both approaches utilize a PCB coil as a sensor.

1. A circular coil can be used to detect the position of a triangular conductive target.
2. A stretched coil design that produces a non-homogeneous AC magnetic field can be used to determine the position of a rectangular conductive target.

The intention of this reference design is to mainly focus on the second approach and provide a head-start advantage to system designers for integrating TI's family of inductance-to-digital converters into new applications that require high-resolution linear position sensing. The following lists the overall system-level challenges for this design:

- Proper sensor coil design to achieve desired measurement resolution
- Proper conversion
- Calibration of inductance-to-digital converter output into usable data
- Testing

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2.1 Inductance-to-Digital Converter Selection

The LDC1101 is an inductance-to-digital converter that can simultaneously measure the impedance and resonant frequency of an LC resonator. The high resolution measurement capability enables this device to directly measure changes in physical systems, allowing the resonator to sense the proximity and movement of conductive materials.

The LDC1101 device measures the impedance and resonant frequency by regulating the oscillation amplitude in a closed-loop configuration at a constant level, while monitoring the energy dissipated by the resonator. By monitoring the amount of power injected into the resonator, the LDC1101 device can determine the parallel resistance of the resonator, R_P, which the LDC1101 returns as a digital value. In addition, the LDC1101 device also measures the oscillation frequency of the LC circuit, which is then used to determine the inductance of the LC circuit.

The LDC1101 inductance-to-digital converter is a high-resolution and low-cost device that enables contactless, short-range sensing even in harsh environments. Using a printed circuit board (PCB) coil as a sensor, the LDC1101 device provides a way for system designers to achieve high performance and reliability at a lower system cost than other competing solutions. The LDC1101 was chosen because the device has the ability to measure inductance at a 16- or 24-bit resolution. The device has a simple four-wire serial peripheral interface (SPI). The power supply for the device can range from 1.8 V − 5% to 3.3 V + 5%. Figure 1 shows a block diagram of the LDC1101.

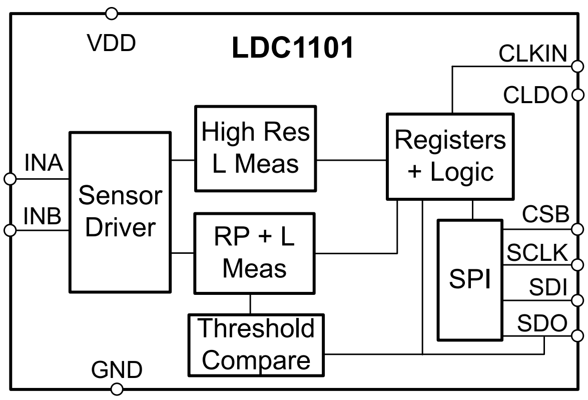

Figure 1. LDC1101 Block Diagram

2.2 Microcontroller Selection

TI's MSP430™ family of ultra-low-power microcontrollers consists of several devices featuring different sets of peripherals targeted for various applications. The architecture, combined with extensive low power modes, is optimized to achieve extended battery life in portable measurement applications. The device features a powerful 16-bit reduced instruction set computing (RISC) CPU, 16-bit registers, and constant generators that contribute to maximum code efficiency. The digitally-controlled oscillator (DCO) allows wake-up from low-power modes to active mode in 3.5 µs (typical). The MSP430F5528 microcontroller was chosen as the central processor for the subsystem based on memory, processor power, integrated USB and PHY supporting USB2.0, and the peripheral module requirements necessary to support the LDC1101 device. This application requires a USB connection to communicate with the LabVIEW-based graphical user interface (GUI) running on a laptop or PC. The MSP430F5528 device contains two USCI_A communication modules, as well as two USCI_B communication modules. The two USCI modules are a requirement to communicate with an LDC1101 device and LaunchPad by way of an SPI.

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2.3 Power Management

The LP5951 low-dropout (LDO) regulator devices were chosen as the power management devices for the subsystem for several reasons. The first reason is that this particular subsystem is designed to work from a nominal input voltage of 3.3 V or 5 V (from a LaunchPad or 5-V USB). The LP5951 device has a current limit of 150 mA and an adjustable output voltage range from 1.3 V to 3.7 V at a low quiescent current of 29 µA (typical), which is significantly higher than the anticipated, maximum total operating load of the subsystem. Only one LP5951 device is used in this subsystem, to regulate a 3.3-V output for the MSP430F5528 and LDC1101 devices.

2.4 ESD Protection for Programming Interface

The TPD1E10B06 single-channel, electro-static discharge (ESD) protection device was chosen to protect the Spy-Bi-Wire (SBW) programming interface. The device offers an over ±30-kV IEC air-gap, over ±30-kV contact ESD protection, and has an ESD clamp circuit with a back-to-back diode for bipolar or bidirectional signal support. The 10-pF line capacitance is suitable for a wide range of applications supporting data rates up to 400 millions of bits per second (Mbps). The 0402 package is an industry standard and convenient for component placement in space-saving applications. The TPD1E10B06 device is characterized for operation over an ambient air temperature of –40°C to 125°C. Figure 2 shows the TPD1E10B06 block diagram.

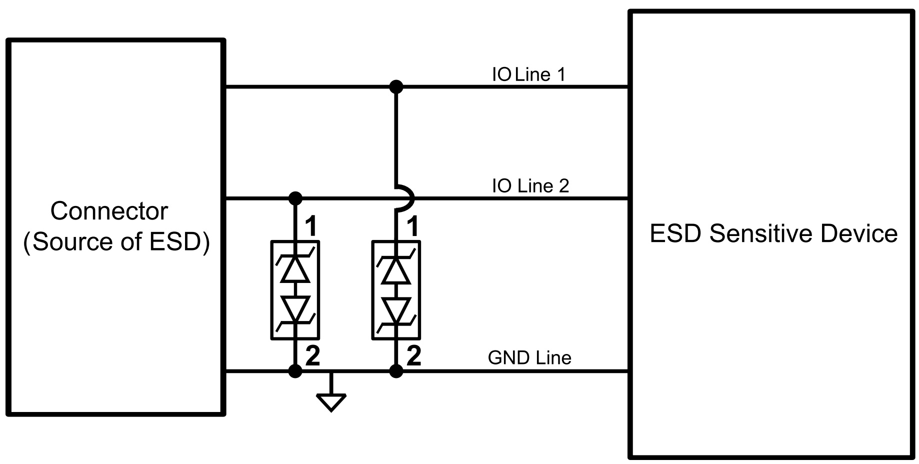

Figure 2. TPD1E10B06 Block Diagram

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2.5 ESD Protection for USB

The TPD2E001 is a unidirectional ESD protection device with low capacitance. The device construction consists of a central ESD clamp that features two hiding diodes per line to reduce the capacitive loading. This central ESD clamp is also connected to V_{CC} to provide protection for the V_{CC} line. Each IO line is rated to dissipate ESD strikes above the maximum level specified in the IEC 61000-4-2 level 4 international standards. The TPD2E001 device's low-loading capacitance makes it ideal for protecting high-speed signal terminals like a USB.

The TPD2E001 is a passive integrated circuit that activates whenever voltages above V_{BR} or below the lower diode's $V_{FORWARD}$ (–0.6 V) are present during a transient event. During ESD events, voltages as high as ±15 kV can be directed to ground and V_{CC} through the internal diode network. As soon as the voltages on the protected lines fall below the trigger voltage of the TPD2E001 (usually within tenths of nanoseconds) the device reverts back to a high impedance state.

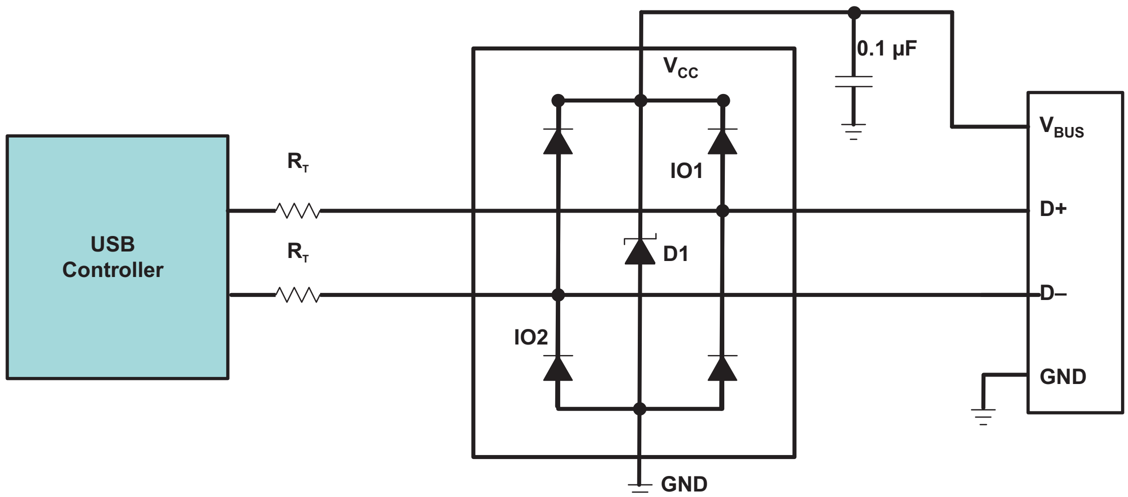

Figure 3. TPD2E001 Block Diagram

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3 Block Diagram

The system consists of the LDC1101 inductance-to-digital converter, the MSP430 microcontroller and the supporting electronics. The MCU acts as a bridge between the LDC1101's SPI and the GUI's USB COM port. The MCU also provides non-volatile storage for the LDC1101's initial register values as well as the calibration data. The GUI software receives the sensor data like L, F_{SENSOR}, and R_P measured by the LDC1101 device and displays them graphically. The user can set the same data to be logged into a file for further processing to determine the position of target. The algorithm that determines the position of the target can also be easily ported into an MCU for stand-alone applications. A two-pin connector allows connection to different coils. The system design is in a standard 40-pin BoosterPack plugin module that fits on top of a LaunchPad evaluation kit. The following Figure 4 shows the TIDA-00460 block diagram.

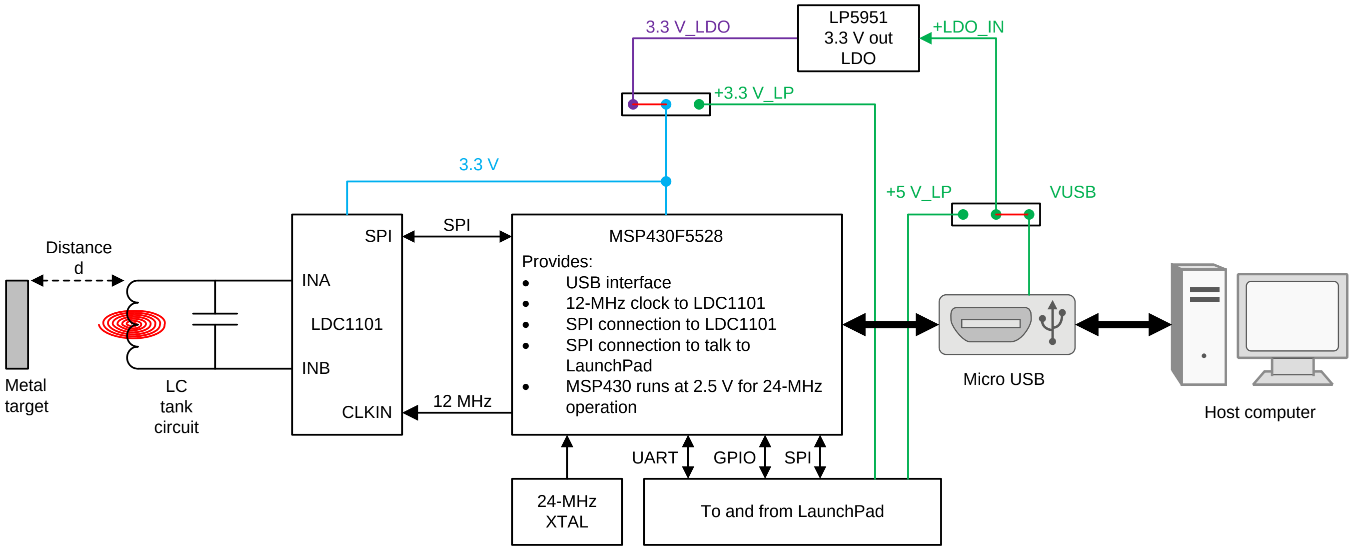

Figure 4. TIDA-00460 Block Diagram

3.1 *Highlighted Products*

The linear position sensing using inductive sensing reference design features the following devices:

- **LDC1101** – 1.8-V high resolution inductance-to-digital converter
- **MSP430F5528** – Ultra-low power MSP430 with 128KB flash
- **LP5951** – Micro-power, 150-mA low-dropout CMOS voltage regulator
- **TPD1E10B06** – Single-channel ESD protection diode in 0402 package
- **TPD2E001** – Low-capacitance two-channel ESD-protection for high-speed data interfaces

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

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3.1.1 LDC1101 Features

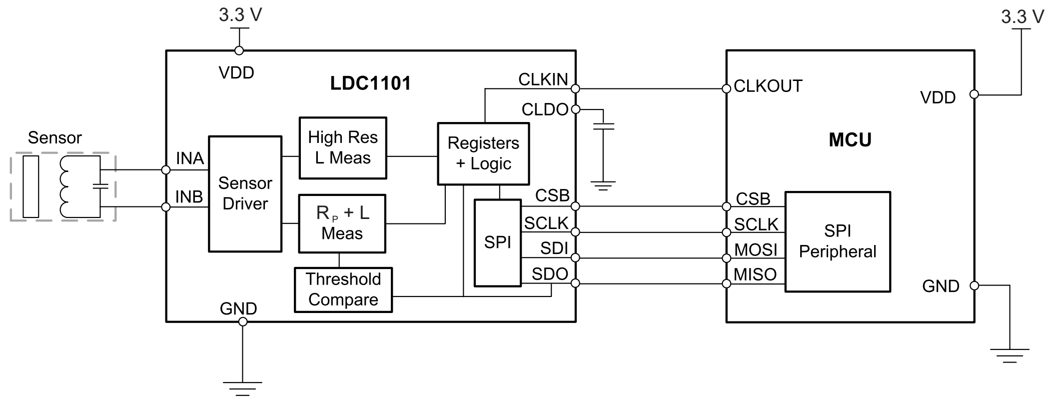

Figure 5. LDC1101 Functional Diagram

- R_P resolution: 16-bit
- L resolution: 16/24-bit
- 150-kSPS conversion rate
- Wide operating voltage range: 1.8 V to 3.3 V
- Supply current:
  - 5-µA shutdown mode
  - 150-µA sleep mode
  - 2 mA (no sensor connected)
- Sub-micron resolution
- Adjustable sensing range (through coil design)
- Remote sensor placement – isolates the LDC from harsh environments
- Robust against environment interference such as dirt and dust
- Sensor frequency range: 500 kHz to 10 MHz
- Magnet-free Operation

For more details, please refer to the LDC1101 datasheet (SNOSD01).

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3.1.2 MSP430F5528 Features

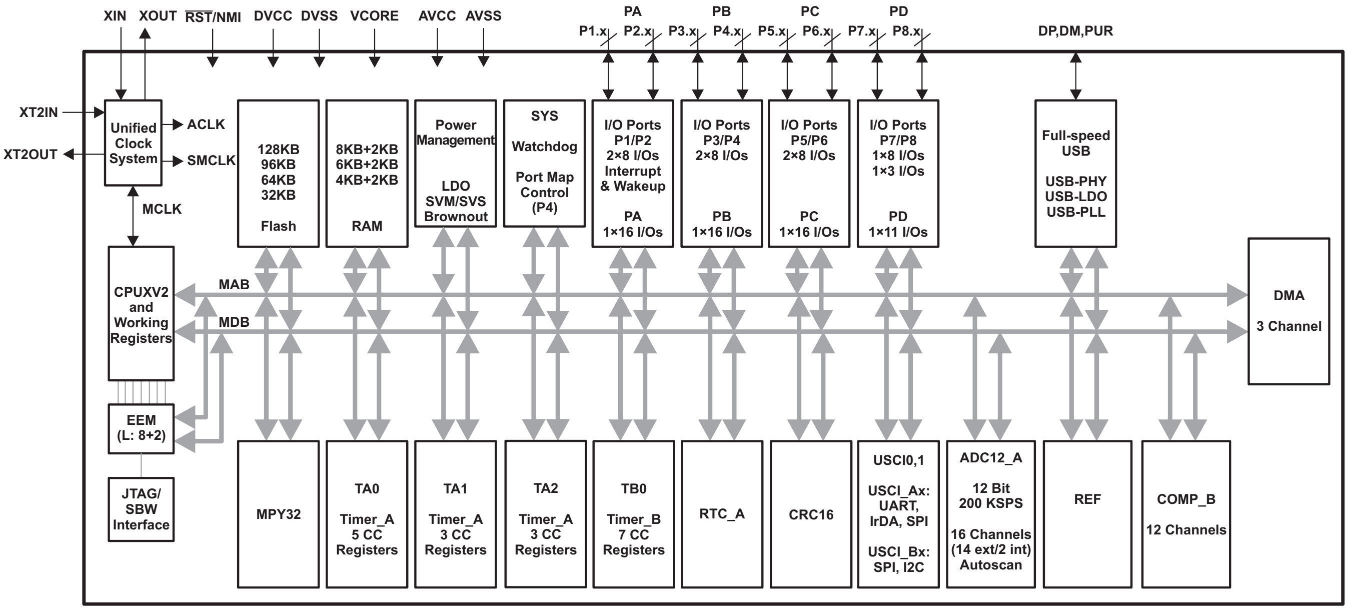

Figure 6. MSP430F5528 Functional Diagram

- Low supply-voltage range: 3.6 V down to 1.8 V
- Ultra-low power consumption
  - Active mode (AM):
    - All system clocks active
    - 290 µA/MHz at 8 MHz, 3.0 V, Flash program execution (typical)
    - 150 µA/MHz at 8 MHz, 3.0 V, RAM program execution (typical)
  - Standby mode (LPM3):
    - Real-time clock with crystal, watchdog, and supply supervisor operational, full RAM retention, fast wake-up:
      - 1.9 µA at 2.2 V, 2.1 µA at 3.0 V (typical)
      - Low-power oscillator (VLO), general-purpose counter, watchdog, and supply supervisor operational, full RAM retention, fast wake-up: 1.4 µA at 3.0 V (typical)
  - Off mode (LPM4)
    - Full RAM retention, supply supervisor operational, fast wake-up: 1.1 µA at 3.0 V (typical)
  - Shutdown mode (LPM4.5): 0.18 µA at 3.0 V (typical)
- Wake-up from standby mode in 3.5 µs (typical)
- 16-bit RISC architecture, extended memory, up to 25-MHz system clock
- Flexible power management system:
  - Fully integrated LDO with programmable regulated core supply voltage
  - Supply voltage supervision, monitoring, and brownout
- Unified clock system
  - Frequency-locked loop (FLL) control loop for frequency stabilization
  - Low-power, low-frequency internal clock source (VLO)
  - Low-frequency trimmed internal reference source (REFO)
  - 32-kHz watch crystals (XT1)
  - High-frequency crystals (XY1)
  - High-frequency crystals up to 32 MHz (XT2)

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- 16-bit timer TA0, Timer_A with five capture/compare registers
- 16-bit timer TA1, Timer_A with three capture/compare registers
- 16-bit timer TA2, Timer_A with three capture/compare registers
- 16-bit timer TB0, Timer_B with seven capture/compare shadow registers
- Two universal serial communication interfaces
  - USCI_A0 and USCI_A1 each support:
    - Enhanced UART supports auto-baud rate detection
    - IrDA encoder and decoder
    - Synchronous SPI
  - USCI_B0 and USCI_B1 each support:
    - I^{2}C™
    - Synchronous SPI
- Full-speed USB
  - Integrated USB-PLL
  - Integrated 3.3- and 1.8-V USB power system
  - Integrated USB-PLL
  - Eight input, eight output endpoints
- 12-bit analog-to-digital converter (ADC), for MSP430F552x device family only) with internal reference, sample-and-hold, and auto-scan feature
- Comparator
- Hardware multiplier supporting 32-bit operations
- Serial on-board programming, no external programming voltage required
- Three-channel internal direct memory access (DMA)
- Basic Timer with real-time clock feature
- For complete module descriptions, see the *MSP430x5xx and MSP430x6xx Family* User's Guide (SLAU208).

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3.1.3 LP5951 Features

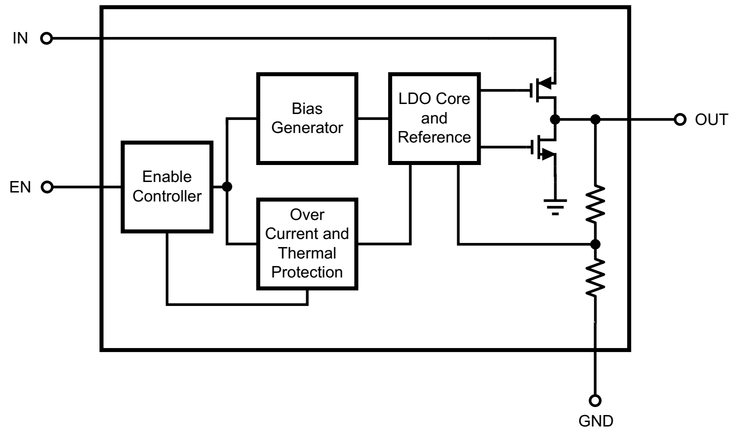

Figure 7. LP5951 Block Diagram

- Input voltage range: 1.8 V to 5.5 V
- Output voltage range: 1.3 V to 3.7 V
- Excellent line transient response: ±2 mV (typical)
- Excellent power supply rejection ratio (PSRR): –60 dB at 1 kHz typical
- Low quiescent current of 29 µA typical
- Small SC70-5 and SOT-23-5 packages
- Fast turn-on time of 30 µs (typical)
- Typical < 1-nA quiescent current in shutdown
- Ensured 150-mA output current
- Logic controlled enable 0.4 V/0.9 V
- Good load transient response of 50 mVpp (typical)
- Thermal overload and short-circuit protection
- −40°C to 125°C junction temperature range

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3.1.4 TPD1E10B06 Features

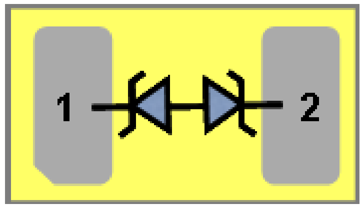

Figure 8. TPD1E10B06 Block Diagram

- Provides system-level ESD protection for low-voltage IO interface
- IEC 61000-4-2 level 4
- ±30-kV (air-gap discharge)
- ±30-kV (Contact discharge)
- IEC 61000-4-5 (surge): 6 A (8/20 µs)
- IO capacitance 12 pF (typical)
- RDYN 0.4 Ω (typical)
- DC breakdown voltage ±6 V (minimum)
- Ultra-low leakage current 100 nA (maximum)
- 10-V clamping voltage (maximum at I_{PP} = 1 A)
- Industrial temperature range: –40°C to 125°C
- Space-saving 0402 footprint (1.0 mm × 0.6 mm × 0.5 mm)

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3.1.5 TPD2E001 Features

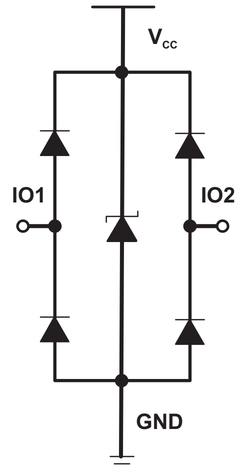

Figure 9. TPD2E001 Block Diagram

- IEC 61000-4-2 ESD protection (level 4)
  - ±8-kV contact discharge
  - ±15-kV air-gap discharge
- IO capacitance: 1.5 pF (typical)
- Low leakage current: 1 nA (maximum)
- Low supply current: 1 nA
- 0.9- to 5.5-V supply-voltage range
- Space-saving DRL, DRY, and QFN package options

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4 System Design Theory

The basic principle of inductive linear position sensing is related to the phenomenon of eddy currents. Walter Pepperl and Ludwig Fuchs first employed inductive sensing in 1958 in Mannheim, Germany. They wanted to find a technology to replace mechanical contacts that would wear out in hostile environments or were simply dangerous in explosive atmospheres due to arching. The basic principle of inductive sensing remains the same as Pepper and Fuchs' original design.

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 (see Figure 10). This transferred energy induces tiny circulating electrical currents known today 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.

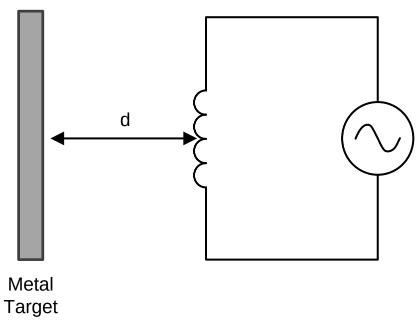

Figure 10. Inductor With Metal Target

This mechanism is best compared to a transformer, where the coil is the primary core and the eddy current is the secondary core. The inductive coupling between both cores depends on distance, shape, and the conductor's characteristics. Hence, the resistance and inductance of the secondary core (eddy current), shows up as a distant, dependent resistive and inductive component on the primary side (coil). The following figures show a simplified circuit model. In Figure 11, the inductance L_S is the coil's inductance and R_S is the coil's parasitic series resistance. The inductance L(d), which is a function of distance d, is the coupled inductance of the metal target. Likewise, R(d) is the parasitic resistance of the eddy currents.

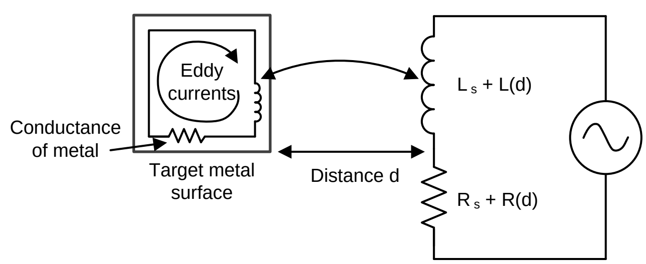

Figure 11. Metal Target Modeled as L and R With Circulating Eddy Currents

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Generating an alternating magnetic field with just an inductor consumes a large amount of power. The user can reduce this power consumption by adding a parallel capacitor, turning the circuit into a resonator. By turning the circuit into a resonator, the power consumption is reduced to the eddy and inductor losses R_S + R(d) only. However, the LDC1101 device does not measure the series resistance directly; instead it measures the equivalent parallel resonance impedance R_P. This representation is equivalent to the one that Figure 12 shows, where the parallel resonance impedance R_P(d) is given by Equation 1:

$$R_P(d) = \left(\frac{1}{R_S + R(d)}\right)\left[\frac{L_S + L(d)}{C}\right] \quad (1)$$

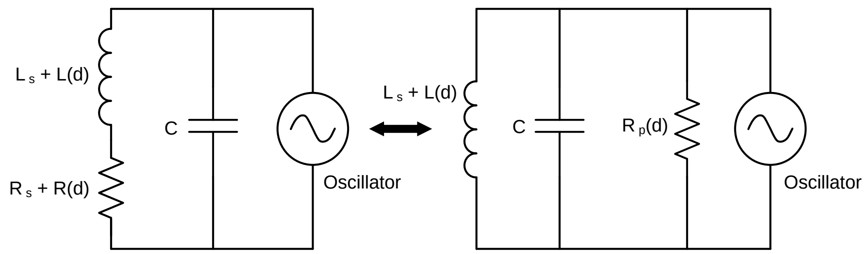

Figure 12. Series and Parallel LC Tank Circuits Connected With Oscillator

The LDC1101 device accomplishes this task by regulating the oscillation amplitude in a closed-loop configuration to a constant level (see Figure 13), while monitoring the energy dissipated by the resonator. By monitoring the amount of power injected into the resonator, the LDC1101 device can determine the value of R_P. When measuring R_P with the LDC1101 device, the intention is to measure only the eddy current losses on the target.

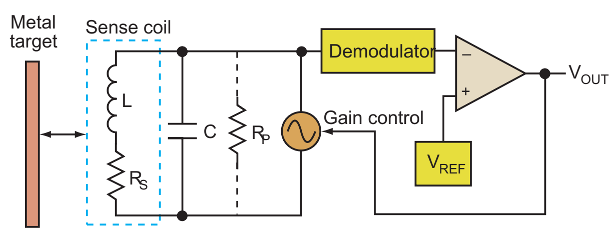

Figure 13. Oscillation Amplitude Regulation

The LDC1101 device provides two independent measurement blocks to measure the impedance and resonant frequency of an attached sensor. The R_P + L block can simultaneously measure the impedance and resonant frequency of an LC resonator with up to 16 bits of resolution. The high resolution L (LHR) block only measures the sensor resonant frequency, with up to 24 bits of resolution. To determine the position of the target above the sensor coil, a designer can use any of the two measurement modes of the LDC1101 device. The SPI then transmits the results as a digital value to a connected MCU.

The digital value of R_P is called “Proximity Data”. In situations where the distance between the coil and the target changes, the value of the R_P changes, too. Consequently, the LDC1101 determines the change of distance in the dependence on the change of R_P. To determine the inductance of the LC resonator, the LDC1101 device measures the frequency of the sensor with a frequency counter, too. The SPI also transmits this value to the MCU.

This reference design solely uses the resonant frequency information from the LDC1101 device by way of using the inductance-only measurement mode, because the basis of inductive sensing consists of measuring the variation of inductance, L, and resonance impedance, R_P of the sensor coil. Both of these parameters can be sensitive to temperature based on the coil design, material, and operating conditions. Temperature-induced effects in R_P are mainly due to temperature coefficients of the coil and target materials. Temperature-induced effects in L are a result of the temperature coefficient expansion of the coil structure. These effects are generally much smaller in magnitude; therefore, measurements based on L are less sensitive to temperature variations.

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4.1 Sensor Target Configuration

To design an inductive sensing application, the first step is to convert the desired measurement into the amount of exposed metal from a target in the electromagnetic field generated by the coil. Commonly used methods include axial proximity and lateral proximity, as in the following Figure 14 shows. As the metal target moves closer to the sensor coil, or the metal target shape covers more of the coil, a greater portion of the electromagnetic field is intercepted. The eddy current increases as more electromagnetic field flux is intercepted, thereby decreasing the effective inductance of the coil generating the field and increasing the LC tank oscillation frequency. This series of events leads to a greater digital output value from the LDC1101 device.

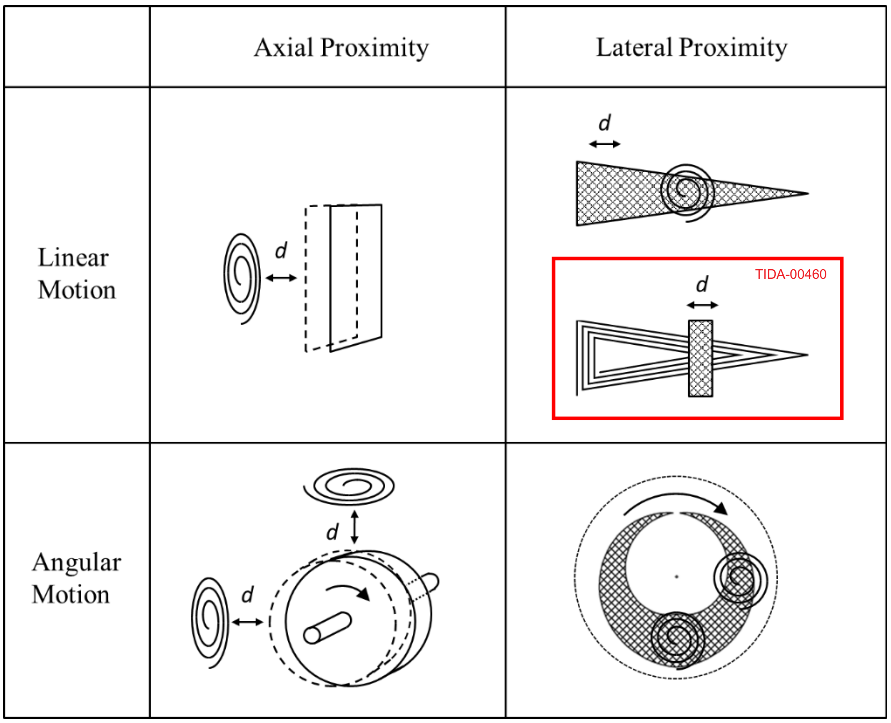

Figure 14. Commonly Used Sensor-Target Configurations

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4.2 Coil and Target Design

As an alternative to shaping the target to produce a varying output when moving a target over a coil, the designer can instead shape the AC magnetic field that the coil produces. The basic 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. Also, 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 15 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 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 can 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.

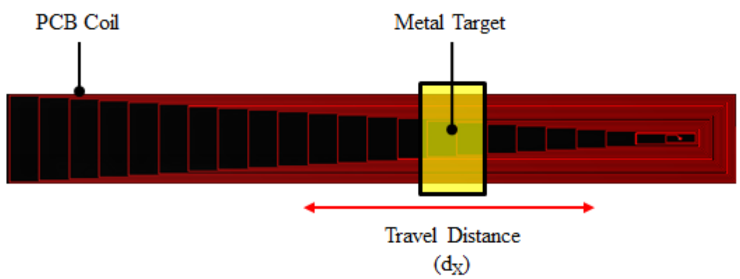

Figure 15. Lateral Movement of Rectangular Target at Position d_X (Top View)

To verify these assumptions, use the FEMM 4.2 (Finite Element Method Magnetics 4.2) magnetic simulation software. Defining the PCB coils in FEMM 4.2 is not a possibility; so, to obtain a basic idea of the induced magnetic field, design a cylindrical coil design instead. This time, the coil is axis symmetric to the x-axis. The coil is divided into eleven sections that are connected in serial, thus carrying the same current. The lengths of the segments add up to 100 mm. The current can be set to any value, because only the basic characteristic of the evolving magnetic field is of importance. To simulate the design of the PCB coils, every segment has a different number of turns, compared to its neighboring segments. The simulation result in Figure 16 shows that the magnetic flux density is minimum at d_X = 0 mm. Then, the magnetic flux density increases to its maximum at d_X = 100 mm, validating the aforementioned assumptions.

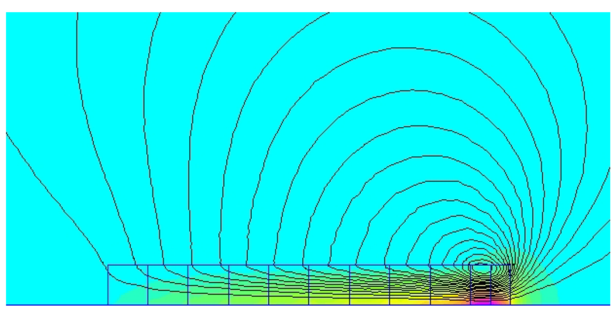

Figure 16. Simulated Magnetic Field of Asymmetric Coil

The coil measures 100 mm × 15 mm, has 28 turns per layer on two layers, and a 3.3-mm loop stepping. 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. Texas Instruments provides PCB layout scripts that generate stretched coils for linear position sensing applications. The application report SNOA930 contains further information on LDC sensor design.

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Figure 17, Figure 18, and Figure 19 show different target positions with respect to the sensor coil in different views.

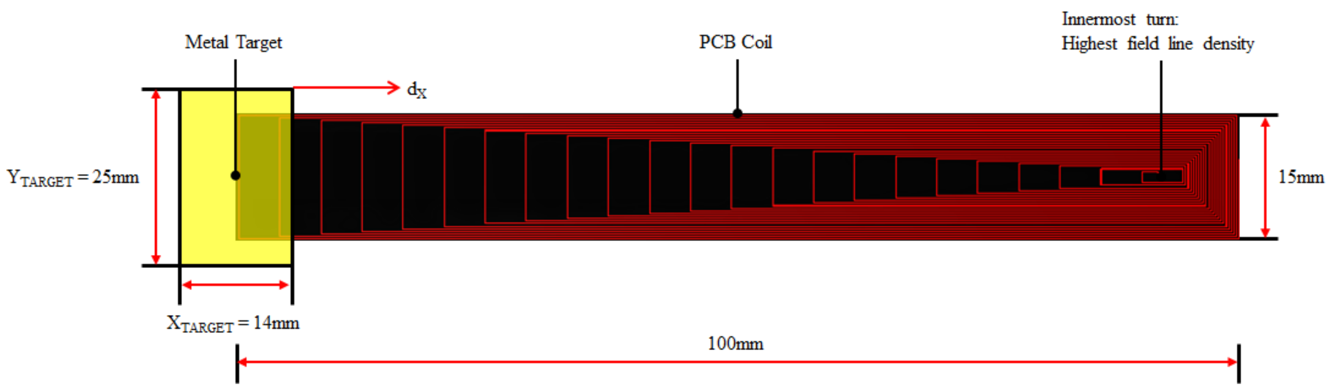

Figure 17. Starting Position: d_X = 0 mm (Top View)

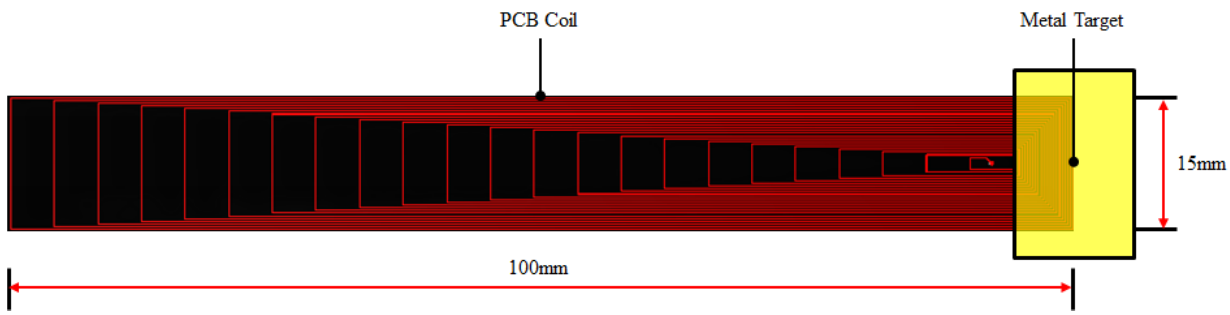

Figure 18. Final Position: d_X = 100 mm (Top View)

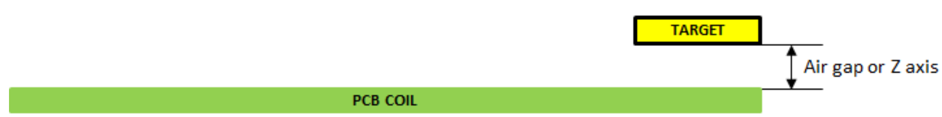

Figure 19. Final Position: d_X = 100 mm (Side View)

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

The wide range of oscillation frequency and the driving current of the LDC1101 device provide 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 LDC1101 devices is 500 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 R_P (the parallel loss resistance) are not violated.
- **R_P of the LC tank** – The LC tank is “lossy” due to the inductor’s loss and the energy dissipated by the target metal. This loss can be modeled by a parallel equivalent resistance R_P. The more the energy loss in the LC tank, the smaller is the value of R_P. The range of R_P values that the LDC1101 device can be ranges from 1 kΩ to 128 kΩ. Different sensing applications may use different ranges of the resonance impedance R_P to measure. The LDC1101 measurement range of R_P is controlled by setting the RP_SET register: RP_MIN and RP_MAX bits. For a given application, R_P must never be outside the range set by these register values to avoid clipping the measured value. For optimal sensor resolution, the range of RP_MIN to RP_MAX must not be unnecessarily large.

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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 NPO/C0G ceramic capacitors or film capacitors with a tolerance of 1% to 5%. The tank capacitor is a 300-pF, NP0/C0G ceramic surface-mount device (SMD) part. These values make the tank oscillate at a resonant frequency that is slightly less than 1 MHz, which is 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 would then require a fewer number of turns (frequency is proportional to 1 / N2). Also, fewer turns help to reduce the temperature drift of the frequency due to the target's resistance change.

4.3 Target Metal: Composition and Thickness

Certain metal types perform better than other types in terms of creating a greater change in sensor output. These metals have high electrical conductivity and low magnetic permeability, for example, common aluminum (alloys) and copper (alloys). The 300 series of non-ferrite stainless steel materials also work well, in that they cannot be picked up by a magnet.

Because alternating currents (such as eddy currents) tend to concentrate on the metal surface facing the sensor coil (known as the "skin effect"), a thin layer of metal usually works well enough. The following Table 2 shows the recommended minimum thickness for several commonly used metals.

Table 2. Recommended Minimum Target Metal Thickness

TARGET METAL	SENSOR FREQUENCY (MHz)		
	1	3	10
Copper	63	37	20
Silver	64	37	20
Gold	77	45	24
Aluminum	82	47	26
Aluminum Alloy	99	57	31
Brass (yellow)	127	73	40
Solder	214	123	68
Non-ferritic stainless steel (3xx series)	421	243	133

4.4 Boundary Conditions

For proper use of the LDC1101 device, setting its registers depending on the connected LC tank is necessary. Primarily, the following two conditions must be fulfilled for the capacitor C of the LC tank that must be connected in parallel to the coil.

$$500\ \text{kHz} \le F_{SENSOR} \le 10\ \text{MHz}$$

$$1\ \text{k}\Omega \le R_P \le 128\ \text{k}\Omega \quad (2)$$

These two boundary conditions must be satisfied for minimum and maximum target distances.

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4.5 Criterion for Maximizing Resolution

The number of code words difference between two extreme positions (d_X = 0 mm and d_X = 100 mm) is determined by using Equation 3:

$$\Delta CODE = \frac{RESP\_TIME \times \left(\frac{F_{CLKIN}}{F_{SENSOR\_at\_0mm}} - \frac{F_{CLKIN}}{F_{SENSOR\_at\_100mm}} \right)}{3}$$

where

- F_{CLKIN} is the external time-base clock input into the LDC1101
- F_{SENSOR} at 0mm is the resonant frequency of sensor when the target is at position X = 0 mm
- F_{SENSOR} at 100mm is the resonant frequency of sensor when the target is at position X = 100 mm
- RESP_TIME is the programmed value of the LDC1101 register field RESP_TIME (3)

To achieve the optimum resolution:

- Maximize the difference of readings between the “maximum” and “minimum” position of the target over the sensor. For lateral sensing, the target moves from the least amount of material covering the coil to the most amount of material covering the coil.
- Use the maximum supported reference frequency (= 12 MHz).
- Use the slowest possible sampling rate (largest response time = 6144).
- Improve the resolution further by averaging over multiple samples externally.

4.6 Measuring Inductance

The LDC1101 device measures the sensor’s frequency of oscillation by the use of a frequency counter, as Figure 20 shows. The frequency counter timing is set by an external clock (12 MHz typical) from the microcontroller and is provided on the CLKIN pin. The sensor resonance frequency is derived from the frequency counter registers value (see registers 0x23 - 0x24 in R_P + L mode and registers 0x38 through 0x3A in LHR mode) as follows in Equation 4 and Equation 5.

In R_P + L mode:

$$\text{Sensor Frequency, } F_{SENSOR} = \frac{F_{CLKIN} \times RESP\_TIME}{3 \times L\_DATA}$$

where

- F_{CLKIN} is the frequency input to the CLKIN pin
- L_DATA is the contents of registers 0x23 and 0x24
- RESP_TIME is the programmed response time in register 0x04 (4)

In LHR mode:

$$F_{SENSOR} = F_{CLKIN} \times 2^{SENSOR\_DIV} \times \left(LHR\_DATA + LHR\_OFFSET \times 2^{8} \right) \times 2^{-24}$$

where

- F_{CLKIN} is the frequency input to the CLKIN pin
- LHR_DATA is the contents of registers 0x38, 0x39, and 0x3A
- LHR_OFFSET is the programmed contents of registers 0x32 and 0x33, note that this value is scaled by 256
- SENSOR_DIV is the contents of LHR_CONFIG.SENSOR_DIV (register 0x34-bit [1:0]) (5)

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The following Equation 6 can be used to calculate the inductance:

$$L = \frac{1}{C \times \left(2\pi F_{SENSOR}\right)^2} \tag{6}$$

where

- C is the parallel capacitance of the resonator

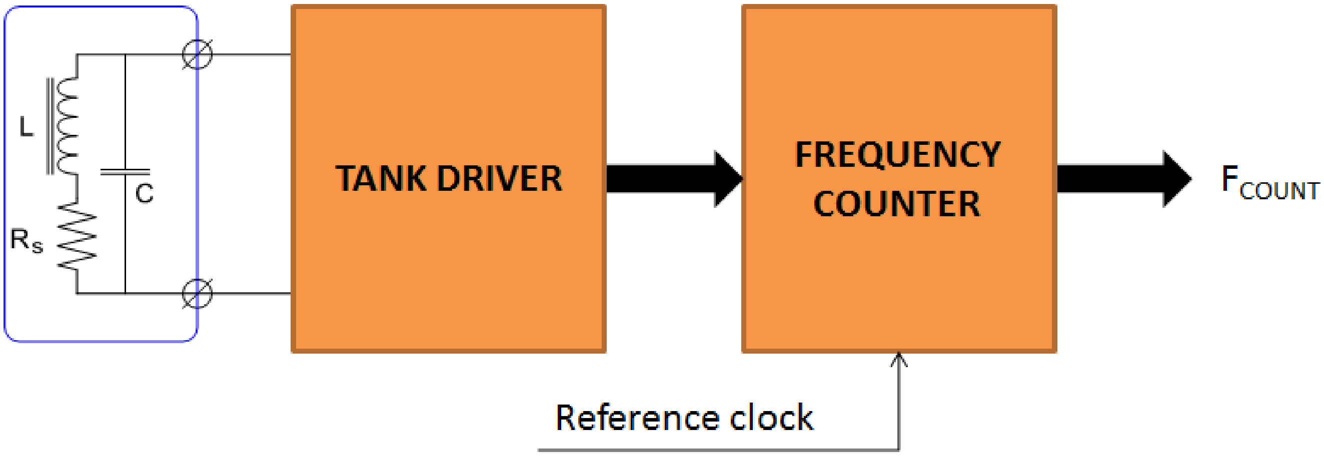

Figure 20. Sensor Frequency Measurement

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5 Test Setup

The inductance measurement is obtained at each position with the test setup that the following Figure 21 shows. A motorized linear table is used to set the accurate position. The PCB sensor coil is located at the top of the linear table so that its position can be controlled by the servo motor. A jig stand that affixes to the top of the sensor coil holds the metal target in place. The air gap between the sensor coil and the metal target is maintained at 1 mm, 2 mm, and 3 mm. The inductance values are measured for every 0.5-mm increment of the sensor coil using the TIDA-00460 board and are logged in a PC using a GUI for further processing. The sensor coil moves up to the maximum displacement of 100 mm.

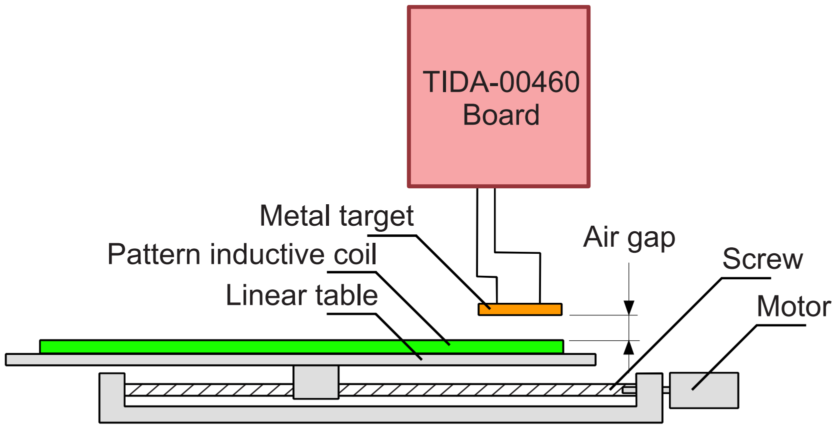

Figure 21. Motorized Linear Table Test Setup

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6 Test Data

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

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

Moving a target from d_x = 0 mm to d_x = 100 mm at an air gap of d_z = 1mm, 2mm, and 3mm in 0.5-mm increments results in the data output that the following Figure 22 shows. The target is a 14- × 25-mm aluminum target.

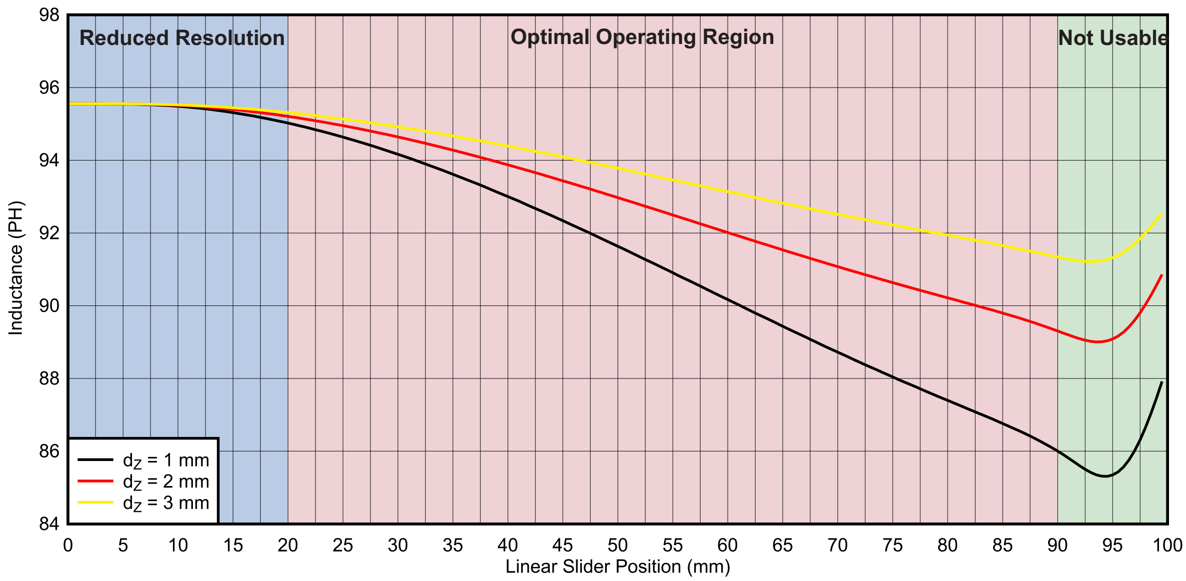

Figure 22. Sensor Inductance Versus Distance

The graph in Figure 22 that results from sliding the target from d_x = 0 mm to d_x = 100 mm can be broken up into three distinct regions.

1. **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 d_x = 5.0 mm to d_x = 5.5 mm at d_z = 1 mm results in an inductance change from 95.547 µH to 95.544 µH, which is a 0.003-µH inductance change. Therefore, the average inductance decrease over this range is 0.006-µH per mm.
2. **Optimal operating region**: The center region spans from 20.0 mm to 90.0 mm over which the sensor inductance decreases from 95.023 µH to 86.003 µH. This region can be used to most accurately determine the target position. For example, the data shows that moving from d_x = 50.0 mm to d_x = 50.5 mm at d_z = 1 mm results in an inductance change from 91.636 µH to 91.565 µH, which is a 0.071-µH inductance change. Therefore, the average inductance decrease over this range is 0.142-µH per mm.
3. **Not usable**: Between d_x = 90 mm to d_x = 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 d_x = 90.0 mm and d_x = 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.

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The output is mostly linear over 70% of the travel range. Provided that the degree of linearization during this range is sufficient to meet the system accuracy requirements, no additional linearization is necessary. However, users often desire a higher degree of linearization to minimize the required coil length and improve system accuracy. The following two approaches can be used to improve the linearity of the measurement:

1. The output code can 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. The user may incorporate the coefficients of the polynomial into the microcontroller. When the sensor coil is moved using the linear table, the microcontroller receives the data from the LDC1101 device and runs the data through the polynomial equation using the programmed coefficients, which then generates the distance in mm.
2. The output code can 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.

To convert the output of the LDC1101 device into useful, real-world data, a system calibration is necessary. The output of the LDC1101 device at each data point was recorded and the regression method was used to generate a 4th order polynomial curve to best fit the data from d_X = 20.0 mm to d_X = 90.0 mm (see Figure 23).

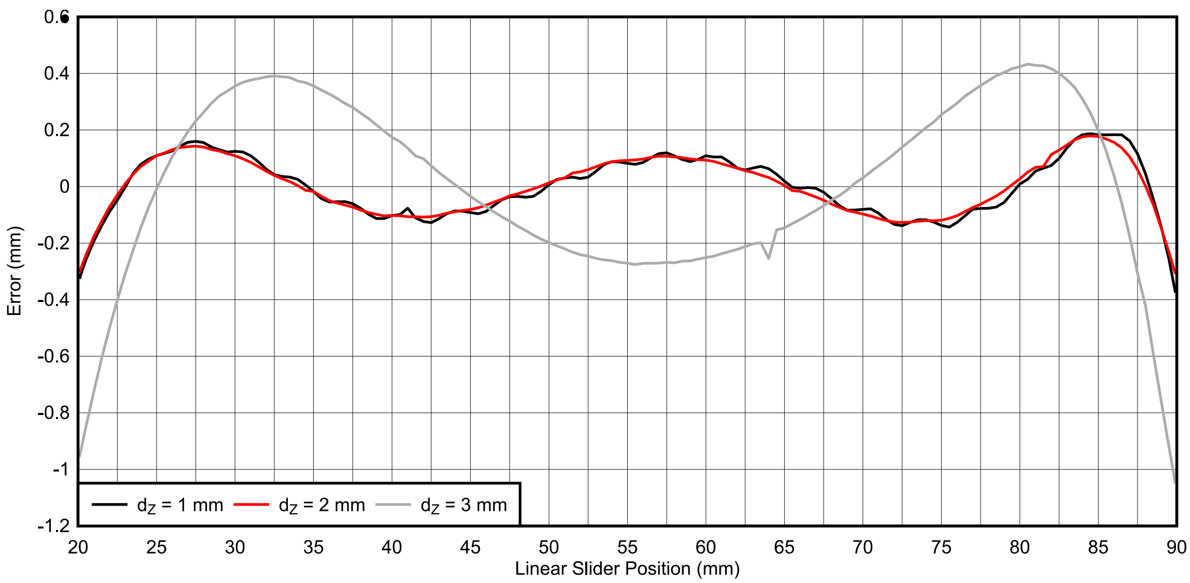

Figure 23. Measured System Errors

Because the magnetic field strength rapidly decays beyond one coil diameter distance, TI recommends keeping the target distance (air gap or d_Z) to less than that of the coil diameter to ensure precise measurements. For non-circular coils (such as the one used in this example), the smaller coil dimension must be considered to be the coil diameter. However, the best measurement accuracy is achievable if d_Z is kept even lower. As the following Table 3 shows, a comparison of the measurement output at three different target distances shows that the maximum resolution can be achieved at the lowest d_Z height. When determining the minimum target distance that can be used in a system, ensure that there is an available drive current setting within the operating range that satisfies R_P and the maximum oscillation amplitude requirements.

Table 3. Comparison of Measurement Output

AIR GAP OR d_Z	SENSITIVITY FROM d_X = 0 mm TO d_X = 20 mm	SENSITIVITY FROM d_X = 20 mm TO d_X = 90 mm
1 mm	−0.0266 µH/mm	–0.1289 µH/mm
2 mm	−0.0174 µH/mm	−0.0843 µH/mm
3 mm	−0.0121 µH/mm	−0.0568 µH/mm

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7 Summary

Inductive sensing is an ideal sensing method for linear position sensing due to its contactless nature and high reliability. A linear position can be measured either by using a circular coil and a triangular target, or by using a stretched coil and a rectangular target. The space requirements for a coil and target are the primary deciding factors as to which approach to use for a system. Using a stretched coil and rectangular target is suitable for systems in which system space constraints dictate the use of a small target.

Texas Instruments provides coil scripts that greatly simplify coil design for this approach.

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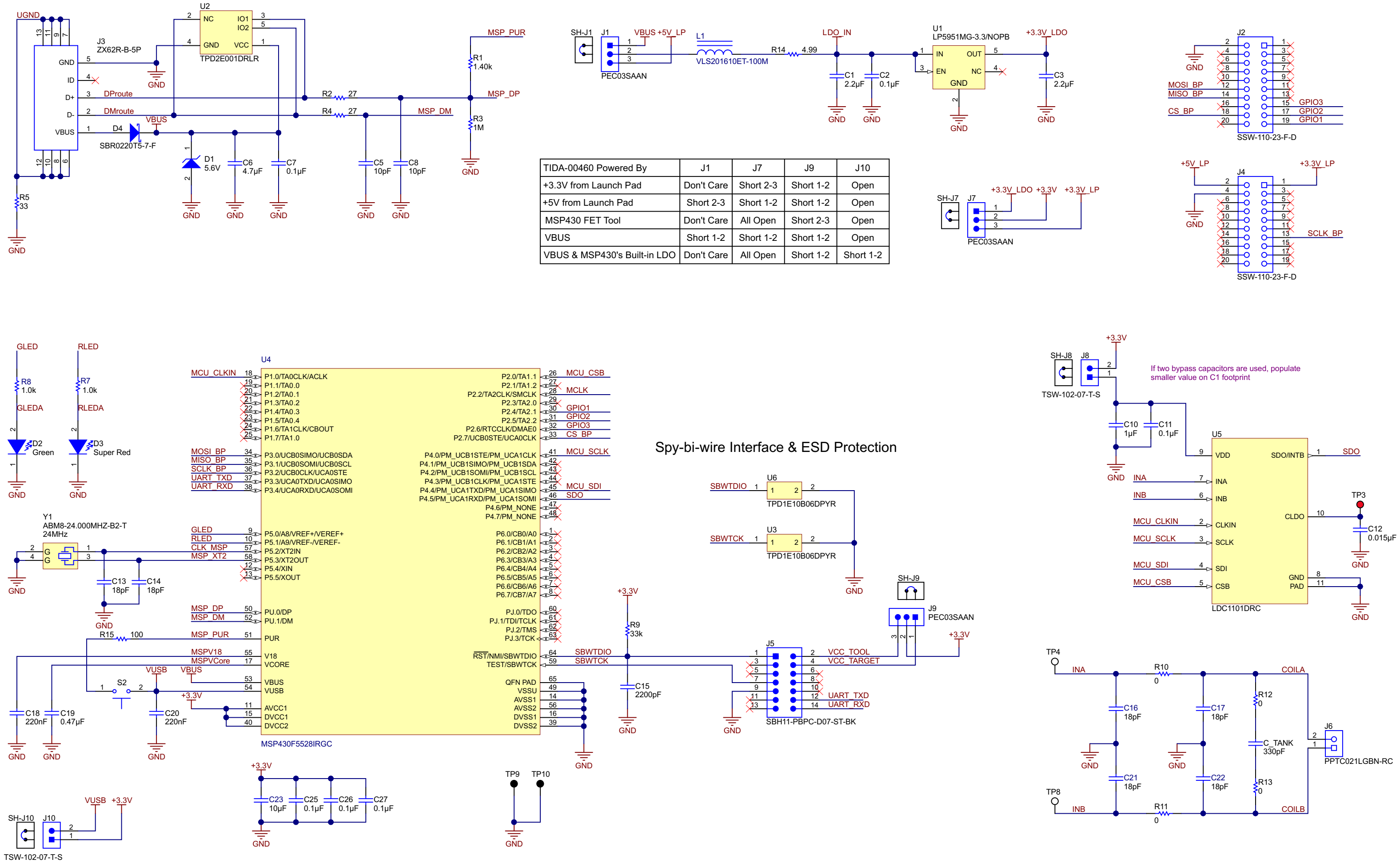
8 Design Files

8.1 Schematics

To download the schematics for each board, see the design files at TIDA-00460.



TIDA-00460 Powered By	J1	J7	J9	J10
+3.3V from Launch Pad	Don't Care	Short 2-3	Short 1-2	Open
+5V from Launch Pad	Short 2-3	Short 1-2	Short 1-2	Open
MSP430 FET Tool	Don't Care	All Open	Short 2-3	Open
VBUS	Short 1-2	Short 1-2	Short 1-2	Open
VBUS & MSP430's Built-in LDO	Don't Care	All Open	Short 1-2	Short 1-2

Figure 24. TIDA-00460 Schematic

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8.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-00460.

8.3 Layout Prints

To download the layout prints for each board, see the design files at TIDA-00460.

8.4 Altium Project

To download the Altium project files, see the design files at TIDA-00460.

8.5 Gerber Files

To download the Gerber files, see the design files at TIDA-00460.

8.6 Assembly Drawings

To download the assembly drawings for each board, see the design files at TIDA-00460.

9 References

1. Texas Instruments, *LDC1101 1.8 V High-Resolution, High-Speed Inductance-to-Digital Converter*, LDC1101 Datasheet (SNOSD01)
2. Texas Instruments, *LDC1101EVM User Guide*, LDC1101EVM User's Guide (SNOU137)
3. Texas Instruments, *LDC1612/LDC1614 Linear Position Sensing*, LDC1612/LDC1614 Application Report (SNOA931)
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5. Texas Instruments, *TI E2E Community*, TI E2E™ Online Community Forum (http://e2e.ti.com/)

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