Application Report

Common Inductive and Capacitive Sensing Applications

Mubina Toa

ABSTRACT

TI's inductive and capacitive portfolio consist of LDC and FDC devices. Inductive sensors detect the proximity of metal targets to an inductive coil sensor, whereas capacitive sensors detect the change in capacitance between a sensor and electrode.

This application report discusses four inductive and capacitive sensing applications, highlighting the benefits of using the technologies and resources available to combat the design challenges in each:

- FDC: Capacitive Level Sensing
- LDC: Inductive Touch Buttons
- LDC: Incremental Encoder & Event Counting
- LDC: Metal Proximity Sensor

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1 Inductive and Capacitive Theory of Operation

This section reviews the basic theory of operation of an inductive and capacitive sensing system.

1.1 Inductive Sensing Theory of Operation

LDC devices operate on a resonant sensing principle. The sensor connected to the LDC is essentially a fixed capacitor in parallel with an inductor, which is typically a coil printed on a PCB as shown in Figure 1-1.

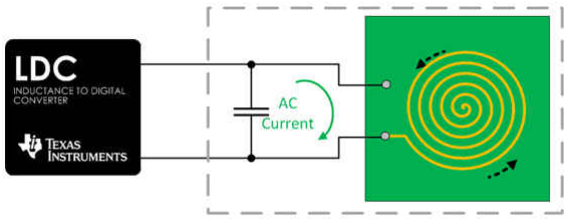

Figure 1-1. LDC Theory of Operation

The fixed capacitor and inductive coil form the external LC tank circuit required for LDC operation. Use Equation 1 to calculate the inherent resonant frequency of this LC tank.

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

As a conductive target approaches the inductive coil, eddy currents form on the surface of the conductive target. The magnetic field of these eddy currents resist the current of the inductive coil, which reduces the inductance of the system and increases the resonant sensing frequency. The LDC devices convert this resonant sensing frequency to a digital value for the user to see. The frequency shift upon a metal target is shown in Figure 1-2.

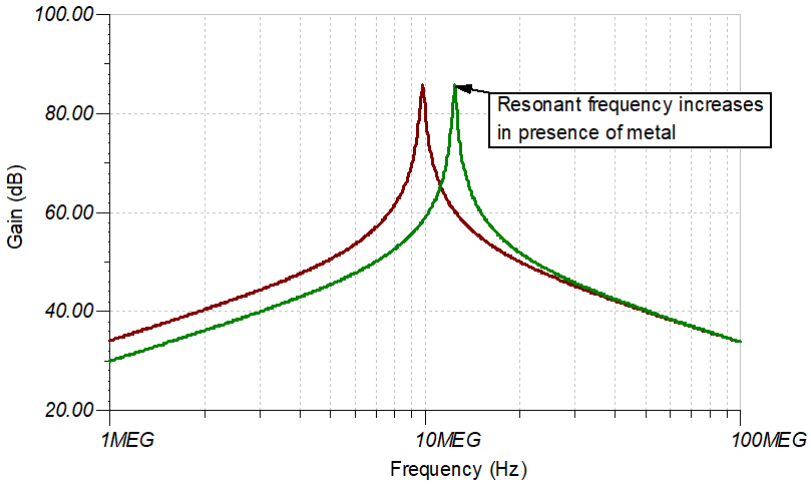

Figure 1-2. Resonant Frequency Shift in Presence of Metal

For a more detailed explanation of the LDC theory of operation, along with the differences between the LDC devices, see the *LDC Device Selection Guide*.

1.2 Capacitive Sensing Theory of Operation

TI's FDC1004 uses a traditional switched-cap approach to capacitive sensing. It includes an active shield driver that helps concentrate fields to a desired direction. This is useful in liquid sensing applications if the engineer only wants to monitor the direction of the liquid instead of the added effects of human hands or other parasitic capacitances in the area.

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The sensor electrode for a liquid level sensing system consists of both a sense and ground electrode. The device measures the fringe capacitance between the two electrodes, which can vary as the dielectric (or level of liquid) varies.

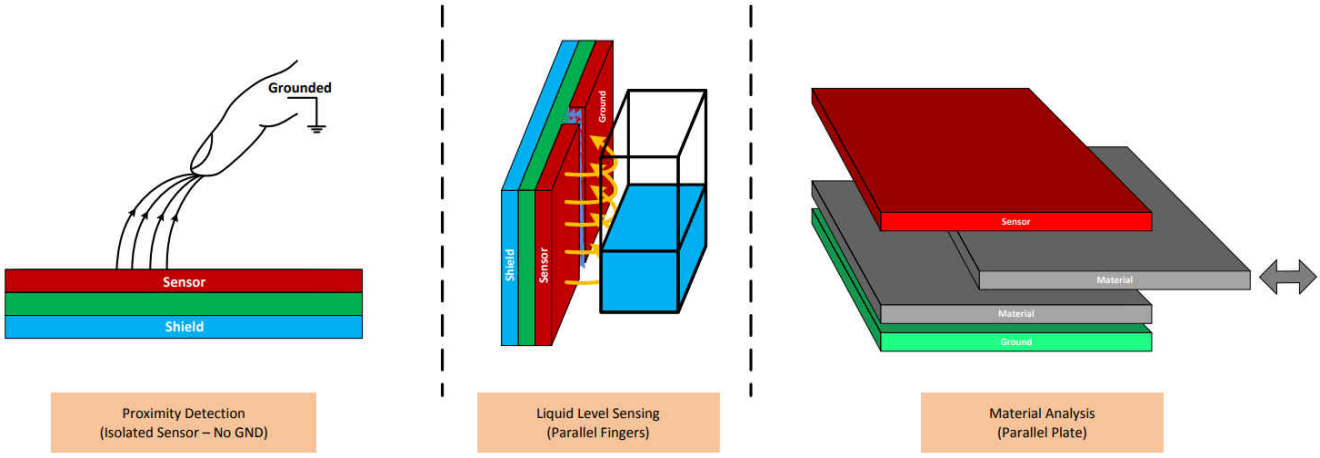

Figure 1-3. Capacitive Sensing Applications

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2 FDC: Capacitive Level Sensing

Capacitive level sensing allows for a contactless method of level sensing, enabling a more robust solution compared to mechanical level sensors that can be prone to rust. TI's capacitive level sensing solution incorporates an active shield driver that can reduce the external interference from foreign objects, such as a human hand. The engineer can use shield drivers using an out-of-phase technique to further stabilize the measurements and maximize the SNR.

Common applications include: wiper fluid and coolant level detection, coffee makers, refrigerators, small fuel tanks, and 3D printers.

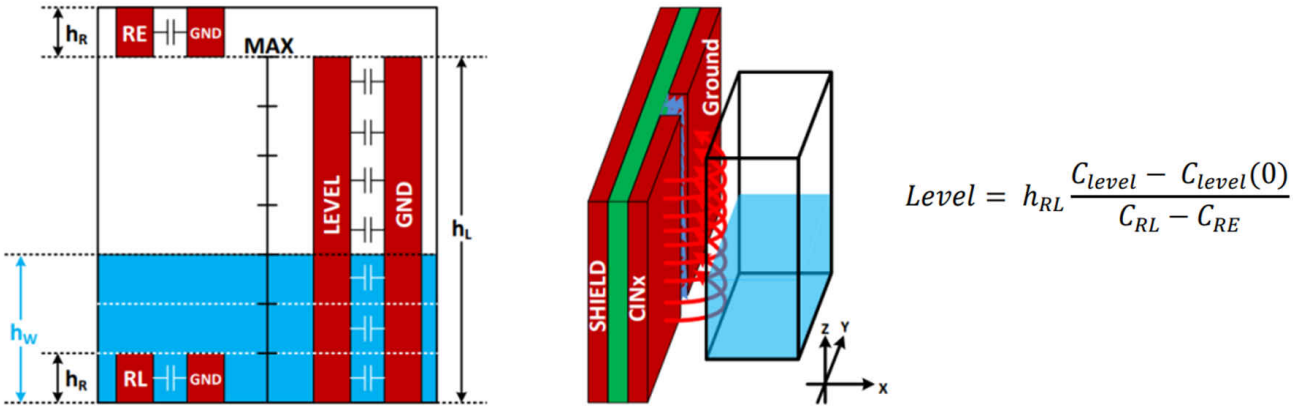

Figure 2-1. FDC Capacitive Level Sensing Application

2.1 Capacitive Technology Benefits in Liquid Level Sensing

Capacitive technology can offer unique benefits in liquid level sensing applications:

- Contactless solution as opposed to mechanical solutions which can be prone to rust
- Flexible system design where the sensor can be any metal or conductor, which is useful for low-cost system designs
- Accurate liquid height resolution (< 1 mm)
- Can use a flex PCB to target difficult container shapes and allow sensor placement on various surface shapes

2.2 Getting Started With Capacitive Liquid Level Sensing

For more information on liquid level sensing applications, see the following:

Reference design:

- TIDA-00317: Capacitive-Based Liquid Level Sensing Sensor

Technical Article:

- *What are you sensing? A novel approach for capacitive-based liquid-level sensing*

Video:

- *Liquid-Level Sensing Using the FDC1004EVM*

2.3 Device Selection

The FDC1004 is the device of choice for liquid level sensing due to its integrated active shield drivers.

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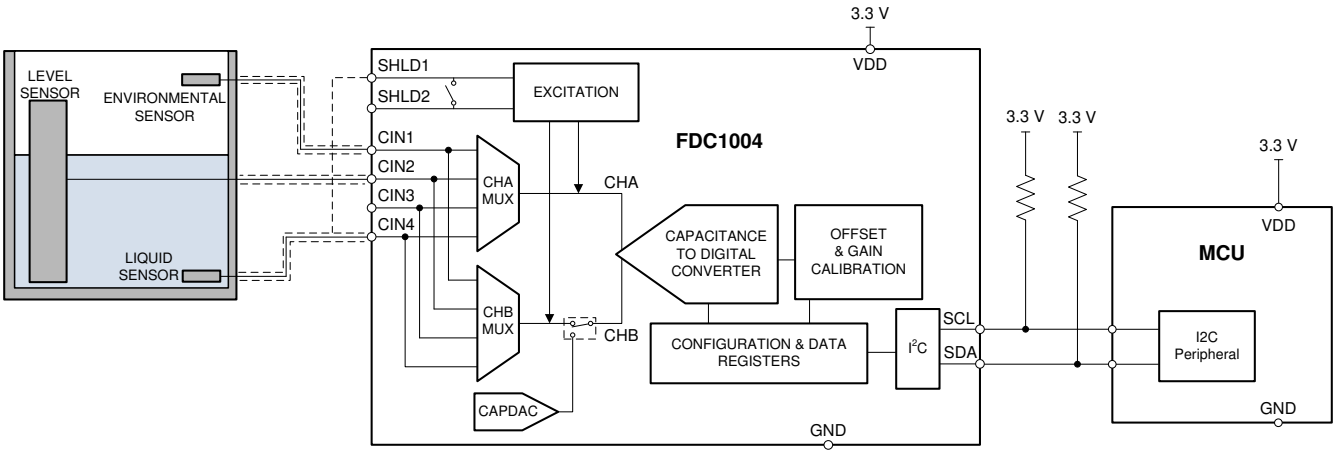

Figure 2-2. FDC1004 for Liquid Level Measurements

Key FDC1004 Parameters for Liquid Level Sensing:

- Active shield driver that can help focus sensing direction of a capacitive sensor and reduce interference from unintended targets.
- Four independent differential channels in one package enables a small footprint solution for differential and ratiometric measurements:
  - Level sensor
  - Reference sensor
  - Environmental Sensor to compensate for environmental changes (due to temperature, humidity, stress on container, and so forth)
- Parasitic capacitance compensation up to 100 pF for each channel allowing compensation for external interference from long signal paths
- High resolution that can enable less than 1-mm accuracy

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2.4 Design Challenges and Additional Collateral

Table 2-1 lists some solutions on how to fix specific design challenges with the FDC1004, and Table 2-2 lists additional resources for the FDC1004.

Table 2-1. Design Challenges

Design Challenge	Collateral
Sensitivity to interference from moving targets outside of the container	• Out-of-phase liquid level technique with active shielding: – Active shielding: focus sensing direction (*Capacitive Sensing: Ins and Outs of Active Shielding*), application report – Out of phase: counteract capacitance and stabilize measurements (*Capacitive Sensing: Out-of-Phase Liquid Level Technique*), application report – Reference design (TIDA-00317: *Capacitive-Based Liquid Level Sensing Sensor Reference Design*), see the *Out-of-Phase Liquid Level Technique* section
Compensating for environmental effects	• Incorporate an environmental sensor to compensate for drifts (temperature, humidity, material type, stress on material) (*FDC1004: Basics of Capacitive Sensing and Applications*) application report, see the *Differential and Ratiometric Measurements* section
No space for environmental reference sensor	• Immersive straw approach: submerge sensor system directly in liquid (*Liquid Level Sensing With the Immersive Straw Approach*), application report

Table 2-2. Additional Relevant Collateral

Collateral	Title
Application report	*FDC1004: Basics of Capacitive Sensing and Applications*
Application report	*How to Calibrate FDC1004 for Liquid Level Sensing Applications*

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3 LDC: Inductive Touch Buttons

Contactless inductive buttons allow for a longer shelf-life compared to traditional mechanical buttons due to less wear and tear on the button surfaces. Contactless inductive buttons also provide a reliable performance in debris-ridden environments. The sensor is a PCB coil, and the target is a flat metal surface. When a user presses on an inductive button, the metal deflects towards the PCB coil, which registers as a button press. The coil can detect various levels of force applied to the surface to allow multi-level functionality.

Common applications include: automotive infotainment buttons, buttons on industrial appliances and POS terminals, and buttons on smart watches and speakers.

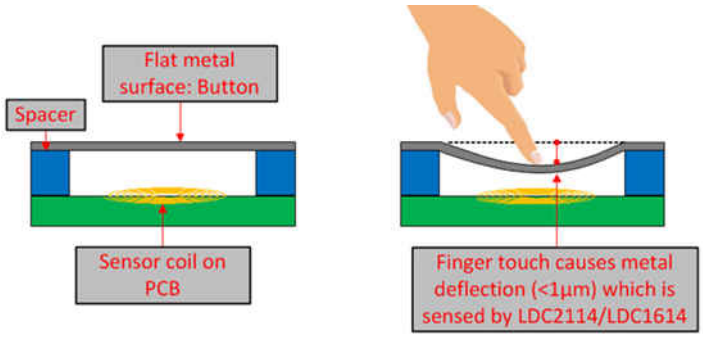

Figure 3-1. Inductive Touch Buttons

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3.1 Inductive Technology Benefits in Buttons

Inductive technology can offer unique benefits in touch button applications:

- **No cutouts or holes needed:** modern appearance, easier to waterproof
- **No moving parts:** no metallic contacts, gaskets
- **Allows force detection:** for multi-level button functions
- **Environmentally robust:** not affected by dirt, dust, oil, water, or magnets
- **Works with gloves**
- **Enable small form factors:** sensor is simply a PCB coil and button is a flat metal surface

3.2 Getting Started With Inductive Buttons

For more information on how to start applications with inductive buttons, see the following:

Reference Design:

- TIDA-01102: Inductive Touch Stainless Steel Keypad Reference Design for Waterproof/Noise Immune HMI Applications

Application Brief:

- *Inductive Touch Buttons for HMI*
- *Inductive Touch Buttons for Wearables*

Technical Article:

- *Re-Think the Button*

Video Series:

- *Building LDC Touch Buttons with the LDC2114* video training series
- *Buttons for the Modern World*

3.3 Device Selection

Figure 3-2 shows the device selection flow chart.

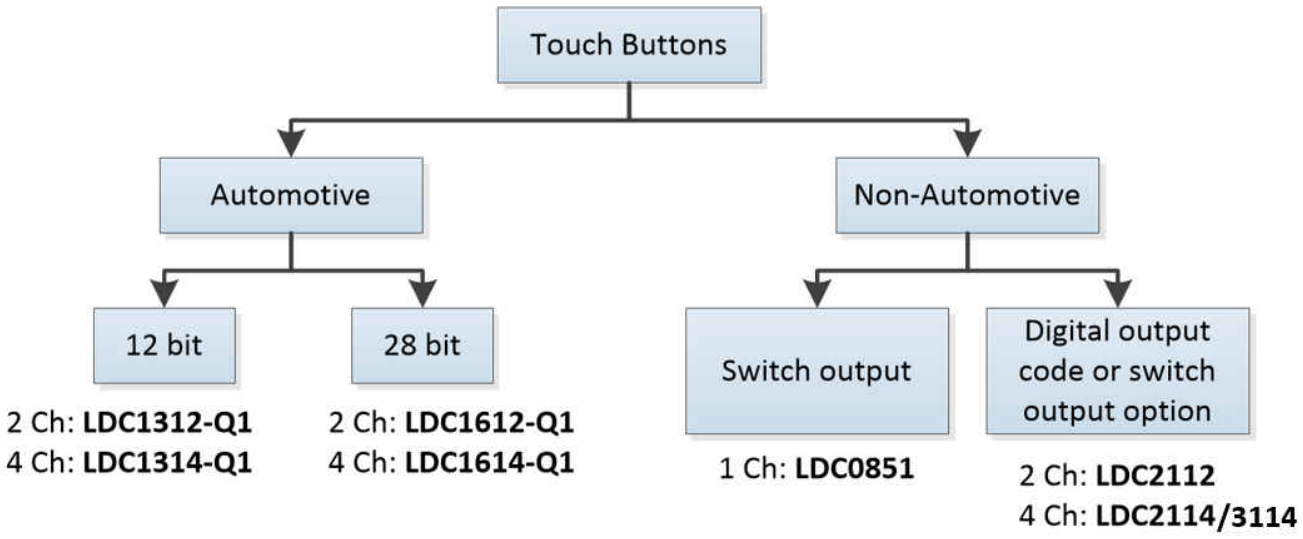

Figure 3-2. Inductive Touch Device Selection Flow Chart

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Table 3-1. Device Recommendations

Device	Features/Benefits
LDC1612 (Q1) LDC1614 (Q1) LDC1312 (Q1) LDC1314 (Q1)	• **High resolution** (LDC161x = 28 bit) allows for accurate detection of different conductive targets • **Sensing range beyond 2 coil diameters (LDC161x)** enables small coil design for smaller form factors • **Qualified for automotive applications**
LDC2112 LDC2114	• **Low power** (6 µA at 0.625 SPS) optimized for battery-powered applications • **Baseline tracking algorithm** compensates for temperature and other environmental drifts over time (this feature is always on)
LDC3114-Q1	• Pin and register compatible to LDC2114 • **Raw data mode** to access pre-processed measurement data • **Baseline tracking algorithm** to compensate for drift can be disabled or enabled • **Qualified for automotive applications**
LDC0851	• **Push/pull output** for simple applications (lowest cost)

3.4 Design Challenges and Additional Collateral

Table 3-2 lists some solutions on how to fix specific design challenges with LDC devices, and Table 3-3 lists additional collateral for LDC sensor design.

Table 3-2. Design Challenges

Design Challenges	Collateral
Interference from other metal in the area	• Ferrite shielding to concentrate and redirect magnetic flux (*Inductive sensing: How to shield from metal interference*), technical article
Temperature shifts	• Multi-coil design (*LDC100x Temperature Compensation*), application report, see the *Multi-Coil Design* section • Baseline tracking algorithm of LDC211x compensates for temperature drifts over time (*LDC211x Inductive Touch Solution for Low-Power HMI Button Applications Data Sheet*), see the *Tracking Baseline* section
Space constraints	• LDC161x: most accurate device and can sense beyond 2 coil diameters (*LDC161x Multi-Channel 28-Bit Inductance to Digital Converter With I2C Data Sheet*) • LDC211x: conductive plate should be close to sensor - 10% of sensor diameter (*Inductive Touch System Design Guide*)

Table 3-3. Relevant Collateral

Collateral	Title
Application report	*LDC Sensor Design*
Application report	*LDC Target Design*
Tool	LDC Calculator Tool
Application report	*Inductive Sensing Touch-On-Metal Buttons Design Guide*
Application report	*Inductive Touch System Design Guide for HMI Button Applications*
Application report	*LDC0851 Quick-Start Guide*

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4 LDC: Incremental Encoder and Event Counting

Incremental encoders can go on knobs to detect an increment or decrement of the knob's position (volume knob). Absolute encoders keep track of the exact position of the knob even when the device turns off (temperature knob on stove).

Common applications include: knobs on appliances (washers, dryers, refrigerators, stoves), fan speed counting, and gear tooth counting in industrial applications. Other applications include volume dials on personal electronics.

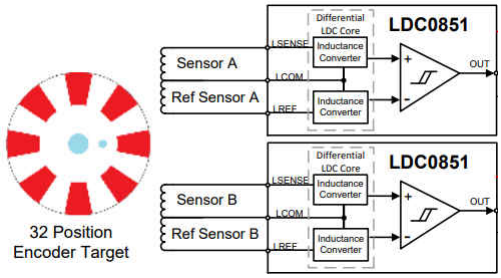

Figure 4-1. Incremental Encoder (TIDA-00828)

Event counters are used to detect the speed and calculate the coarse position of motors, fans, flow meters, or gears. Alternate solutions may be costly due to material costs and not robust in dirty environments.

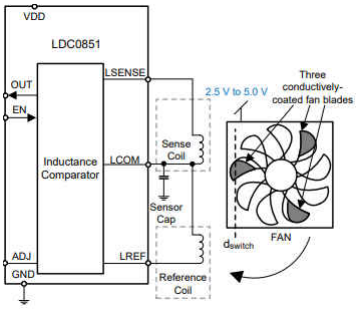

Figure 4-2. Event Counting (TIDA-00851-LDC0851)

4.1 Inductive Technology Benefits in Incremental Encoders

Inductive technology can offer unique benefits in incremental encoder applications:

- No calibration required
- Low cost as sensor is simply PCB coils and metal target
- Robust solution: immune against dirt and dust
- Not affected by magnets
- Can measure > 300 events per second
- Minimal MCU memory and instructions required

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4.2 Getting Started With an Inductive Incremental Encoder

For more information on how to use inductive incremental encoders in specific applications, see the following:

Reference Designs:

- TIDA-00828: Inductive Sensing 32-Position Encoder Knob using the LDC0851
- TIDA-00851-LDC0851: LDC0851 Event Counting

Technical Article:

- *Switch Applications Made Simple*

4.3 Device Recommendations

The LDC0851 is the preferred inductive device for simple incremental encoders due to the switch output of the device.

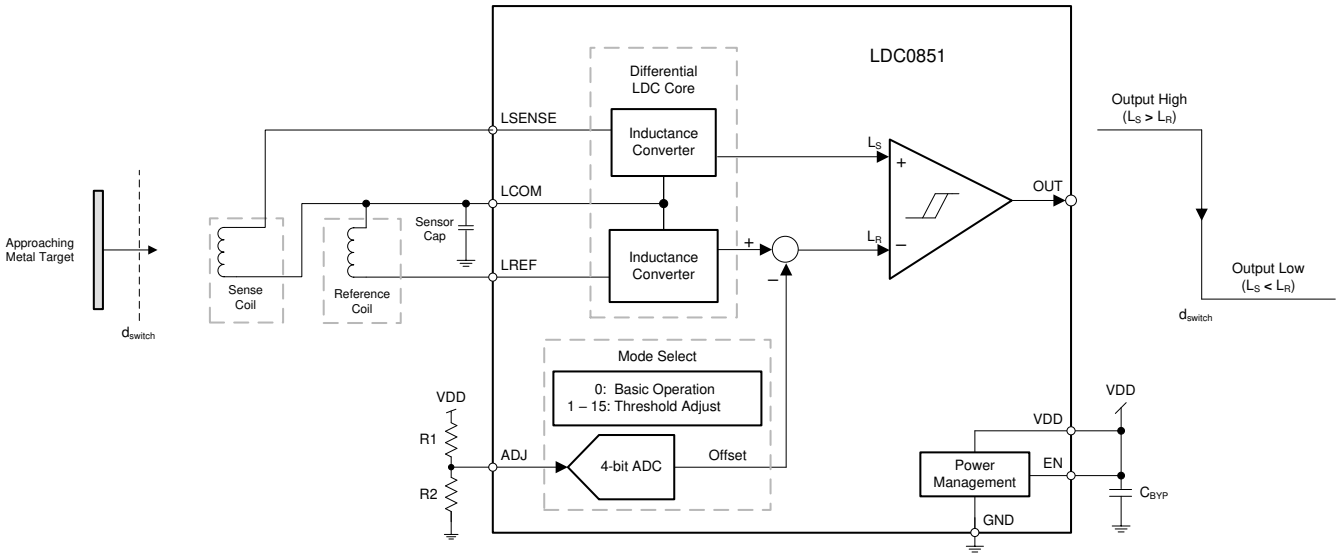

Figure 4-3. LDC0851 Functional Block Diagram

Key LDC0851 parameters for incremental encoders:

- Switch output allows for simplicity
- Differential implementation with reference and sense coils to prevent false triggering over environmental factors such as temperature variation or humidity effects
- Small size - 2.30-mm × 2.30-mm, 8-pin WSON package
- Internal hysteresis to prevent false switching due to noise or mechanical vibration at the switching threshold
- MCU-less operation allows for simple solution

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4.4 Design Challenges and Additional Collateral

Table 4-1 lists some solutions on how to fix specific design challenges with the LDC0851, and Table 4-2 lists additional collateral for LDC encoder design.

Table 4-1. Design Challenges

Design Challenges	Collateral
EMI Challenges	• Duty-cycle enable pin (*LDC0851 Differential Inductive Switch Data Sheet*), see the *Typical Application* section • Shielding to prevent EMI issues (*EMI Considerations for Inductive Sensing*), application report, see the *Shielding* section
Larger sensing range may require larger coils	• Switching distance of side-by-side coils is 40% of coil diameter (*LDC0851 Stacked Coil Design Considerations*), application report, see the *Shorter Switching Distance* section • Stacked coil approach places two coils on top of each other to minimize PCB area (*LDC0851 Stacked Coil Design Considerations*), application report

Table 4-2. Relevant Collateral

Collateral	Title
Application report	LD00851 Quick-Start Guide
Reference design	TIDA-00828: Inductive Sensing 32-Position Encoder Knob Reference Design Using the LDC0851
Reference design	TIDA-00851-LDC0851: LDC0851 Event Counting Reference Design
Application report	*LDC0851 – Troubleshooting : Identifying and Fixing Common Setup Issues*
Application report	*LDC Target Design*
Application report	*LDC Sensor Design*
Tool	LDC Calculator Tool

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5 LDC: Metal Proximity Sensor

Power tools and other industrial equipment must often detect metal in certain applications (like a pipe finder, for example). Inductive-based technologies are ideal for metal detection as an inductance-to-digital converter can sense the presence or proximity of a metal. Inductive sensors can also detect the level of compression of a spring and can measure the speed and position of a rotational system (like gear tooth counting, for example).

Common applications include: metal detection in power tools and pipe finders, along with spring compression detection.

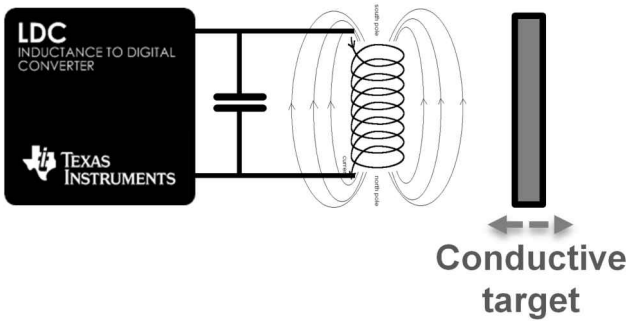

Figure 5-1. Wire Wound Sensor Coil

Figure 5-2. PCB Sensor Coil

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5.1 Inductive Technology Benefits in Metal Proximity Detection

Inductive technology can offer unique benefits in metal proximity detection:

- Immune against dirt and dust
- Not affected by magnets and no magnets are required
- Sensor is simply a PCB coil and the target is any metallic material, which enables smaller form factors and lower costs

5.2 Criteria to Consider when Choosing Inductive Sensing for Metal Proximity Applications

While inductive sensing offers unique benefits, it is important to understand the criteria which enable metal proximity detection. The following are some important items to consider when considering inductive for a metal proximity detection application.

5.2.1 Metal Target Movement in Relation to Inductive Coil

In general, movements in the z-axis (axial sensing) allow for higher sensitivity than those in the x and y-axis.

As far as the shape of the coil is concerned, a circular coil is recommended since it provides the highest Q factor for a given sized inductor. For applications that only allow for a smaller coil due to space constraints, a rectangular coil can be introduced, but will have tradeoffs such as sensing distance.

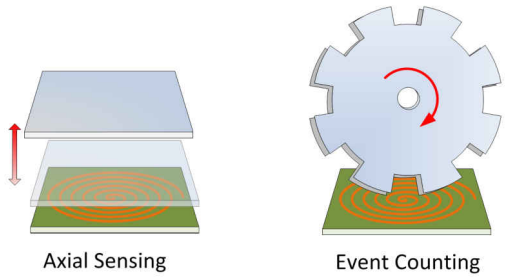

Figure 5-3. Inductive Sensing Target Movement Topologies

For more information on sensor and coil design for the various sensing topologies, visit the LDC Sensor Design application report.

5.2.2 Sensing Distance

Sensing distance is directly correlated to the size of the sensor coil. As a guideline, 1um-10cm is a viable sensing range for inductive technology. For most of the LDC devices, including the LDC131x family and the LDC3114, the maximum sensing range can be considered to be 50% of the coil diameter for higher precision applications. For low precision applications, such as a mere detection of metal presence, can be possible up to 100% of the coil diameter. The LDC161x family is the highest resolution LDC device and can add additional sensing range – this device family can sense targets up to 200% of the coil diameter. For simpler LDC metal proximity applications that only require a switch output, the LDC0851 can be considered; it can detect 40% of it's coil diameter by using the side-by-side coil approach and up to 30% when using a stacked coil approach for size-constrained applications. For more information and tradeoffs between the two different sensor approaches with the LDC0851, see the *LDC0851 Stacked Coil Design Considerations*.

For a rectangular or elliptical coil, consider the shortest dimension to be the critical dimension when estimating the sensing distance.

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Note that the sensitivity is the highest within 20% of the total sensing distance as seen in the below figure. This is because the relative inductance shift versus distance curve is logarithmic in nature and within the 20% cutoff, shorter shifts in distance equate to a stronger shift in relative inductance, allowing for µm level movements in the z-axis.

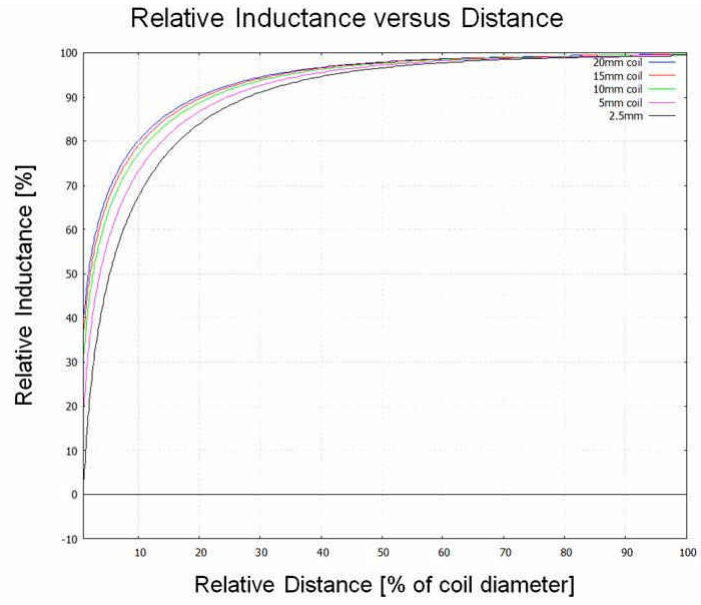

Figure 5-4. Relative Inductance vs Distance

5.2.3 Size and Shape of Metal Target

For the best axial sensing response, it is recommended that the size of the metal target to be sensed is at least the size of the coil beneath it. Best practice is to ensure the uniform metal target is flat, as any discontinuities (such as gaps, voids, indents) will result in noise.

It is also recommended to use the same target, as switching targets will result in a different frequency response detected by the LDC, making it difficult to determine the absolute distance. For example, a copper plate of size A may have a different response at a fixed distance compared to a copper plate of size B. Same goes for different conductive material types. This can be challenging since the device output might not be able to maintain a stable oscillation or have a degraded signal-to-noise ratio (SNR) in these applications.

For more information on LDC target design, see the *LDC Target Design*.

5.2.4 Speed (Sample Rate versus Resolution)

Resolution is inversely proportional to sample rate. The higher the desired resolution, the lower the sample rate must be configured. A list of samples rates and resolutions per device can be found on our LDC device selection guide. For more detailed criteria on how to optimize resolution, see *Optimizing L Measurement Resolution for the LDC161x and LDC1101* and *Optimizing L Measurement Resolution for the LDC1312 and LDC1314*.

5.2.5 Environmental Compensation

Inductive measurements may vary due to temperature. For high precision applications, it is recommended to use a channel in our multi-channel devices as a reference sensor. It is important for the reference sensor to be a duplicate of the sense coil in order to provide the most accurate matching. This additional sensor would enable a differential approach to inductive sensing, allowing for compensation due to drifts due to temperature and other environmental variants. The tradeoff is that this in this approach, is that there needs to be spacing to accommodate for an additional coil.

The LDC0851 is inherently a differential switch device – for simple switch applications, it is the recommended device

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The criteria mentioned are general guidelines to consider whether inductive sensing is suitable for a particular application. For a more specific study, download the LDC calculator tool to estimate the feasibility of a specific application. For other common questions, visit our inductive sensing FAQ page.

5.3 Getting Started With Inductive Metal Proximity Sensing

For more information on applications that use metal proximity detection, see the following:

Evaluation modules:

- LDC1614EVM: Evaluation module for the LDC1614
- LDCCOILEVM: Reference Coil Board EVM

Technical articles:

- *How Far can I Sense with Inductive?*

5.4 Device Recommendations

Figure 5-5 shows the device selection flow chart.

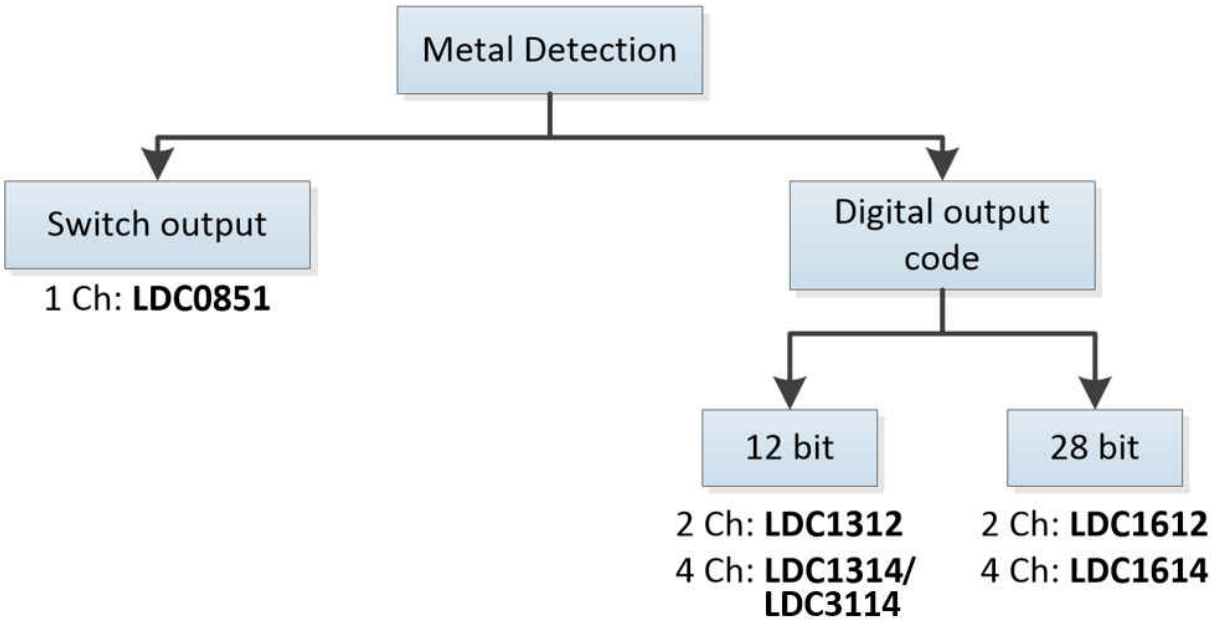

Figure 5-5. Device Selection Flow Chart for Metal Detection

Table 5-1. Device Recommendations

Device	Features/Benefits
LDC0851	• **Switch output** for simple applications (lowest cost) • **Minimal MCU memory and instructions required**
LDC1312 LDC1314 LDC1612 LDC1614 LDC3114-Q1	• **High resolution** (LDC161x = 28 bit) allows for accurate detection of different conductive targets • **Sensing range beyond 2 coil diameters (LDC161x)**, which enables small coil design for smaller form factors

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5.5 Design Challenges and Additional Collateral

Table 5-2 lists some solutions on how to fix specific design challenges with the LDC devices, and Table 5-3 lists additional collateral for LDC sensor design.

Table 5-2. Design Challenges

Design Challenge	Collateral
Optimize sensing distance	• Increase coil size (*LDC Sensor Design*), application report • Recommend an SNR > 10
Small spacing for coil (including environmental coil)	• External oscillator is more stable across temperature, low jitter (LDC1614 Evaluation Module) • Calibrate over temperature if there is no room for a reference coil (*LDC100x Temperature Compensation*), application report, see the *Inductance Variation* section
Interference from other metal in the area	• Ferrite shielding to concentrate and redirect magnetic flux (*How to Shield from Metal Interference*), technical article

Table 5-3. Relevant Collateral

Collateral	Title
Application Report	*LDC Sensor Design*
Application Report	*LDC Target Design*
Tool	LDC Calculator Tool

6 Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Revision A (March 2021) to Revision B (June 2021) **Page**

- Deleted linear and rotational sensing..... 17
- Added LDC3114.....17

Changes from Revision * (January 2020) to Revision A (March 2020) **Page**

- Updated Section 5.2.1..... 15
- Updated Section 5.2.2..... 15

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