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Application Report

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LDC1612/LDC1614 Linear Position Sensing

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ABSTRACT

This application note discusses two techniques for using LDC technology to measure the lateral position of a conductive target. A comparison of each approach, along with design guidelines, is provided. This application note focuses on the LDC1612 and LDC1614, but the same principles apply to other LDCs such as:

- LDC100x
- LDC1041
- LDC1312
- LDC1314

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[(1)] WEBENCH is a registered trademark of Texas Instruments.

1 Introduction

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), like the LDC1612 or LDC1614, senses 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 http://www.ti.com/lsds/ti/data-converters/inductance-to-digital-converter.page).

Inductive sensing is ideally suited for this type of application because it is a contactless and magnet-free technology that facilitates systems with very high measurement accuracy and high reliability at low system cost.

There are two approaches to implement a linear position sensing system with an inductance-to-digital converter. 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.

2 Approach 1: Measuring Lateral Movement with a Circular Coil and a Triangular Target

2.1 Concept

Moving a triangular target from the tip to the widest point over a circular PCB sensor coil at a fixed target distance d_z decreases coil inductance as the metal exposure over the coil increases. The increase or decrease in the amount of target metal exposed to the field in turn changes the eddy currents and the strength of the secondary field. Figure 1 shows a diagram of the target movement over the sensor coil.

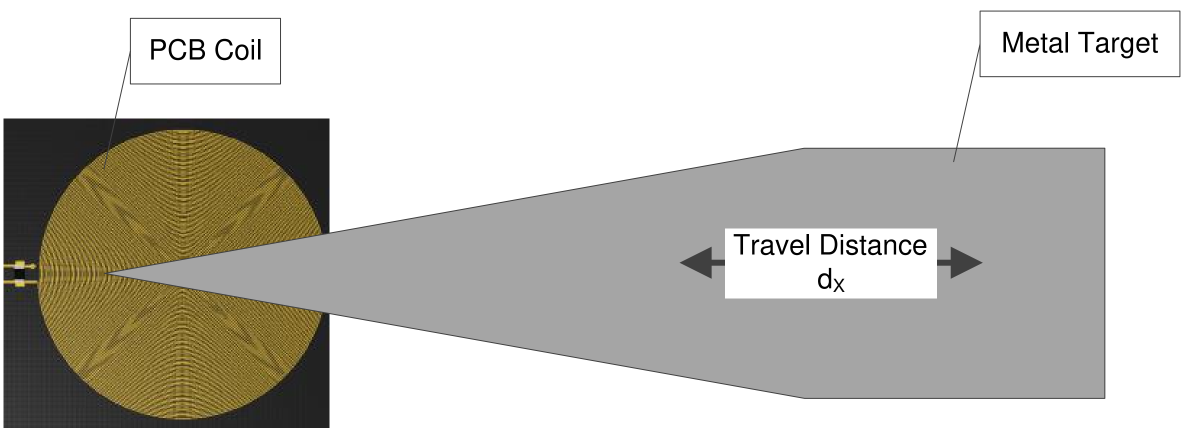

Figure 1. Lateral Movement of a Triangular Target at Position d_x (Top View)

2.2 Coil and Target Design

A circular PCB coil as shown in Figure 2 can be used as a sensor. To maximize travel range, the sensor coil diameter must match or exceed the widest end of the target that is to be measured. The example in this application note uses a 29-mm PCB coil with 70 turns per layer on a 2-layer PCB. The coil diameter of 29 mm exceeds the 25-mm width of the target.

Texas Instruments provides two tools to assist with design of suitable PCB coils:

- WEBENCH® Inductive Sensing Designer can be used to design a suitable coil for this application: http://www.ti.com/lsds/ti/analog/webench/inductive-sensing.page. An example that shows how to design a suitable coil in WEBENCH® is provided at this site: http://e2e.ti.com/blogs_/b/analogwire/archive/2014/09/17/inductive-sensing-five-minute-sensor-coil-design.
- Texas Instruments provides PCB layout scripts that generate coils for a variety of applications. Refer to the application note *LDC Sensor Design*, and also the coil generation scripts available in the tools section of the LDC product page.

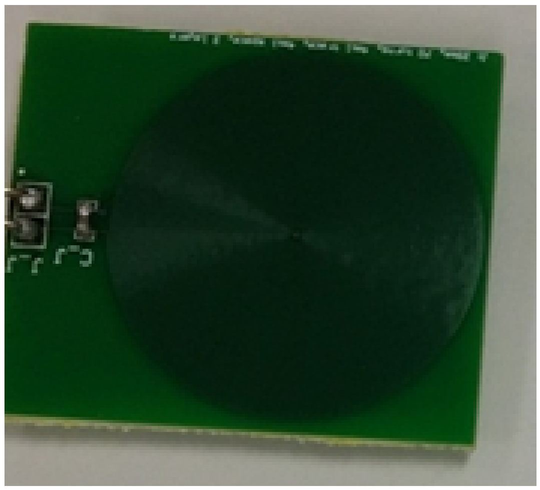

Figure 2. Circular PCB Sensor Coil

A suitable target is an isosceles triangle that is made from metal such as aluminum or copper. Other metal types, or plastic targets that have been painted with conductive paint are suitable alternatives but may result in different performance.

The measurements in this application note use a copper target with dimensions and mechanical positions as shown in Figure 3. The usable travel range of the target over the coil is limited to the range in which the data output is monotonic and provides sufficient output code change for system requirements. To provide output data monotonicity beyond the hypotenuse of the triangle, it is recommended to extend the target shape beyond the hypotenuse of the triangle by the coil diameter to increase the maximum usable travel distance. The diagram shows the target position in the starting position (d_x = 0 mm) and the final position (d_x = 100 mm).

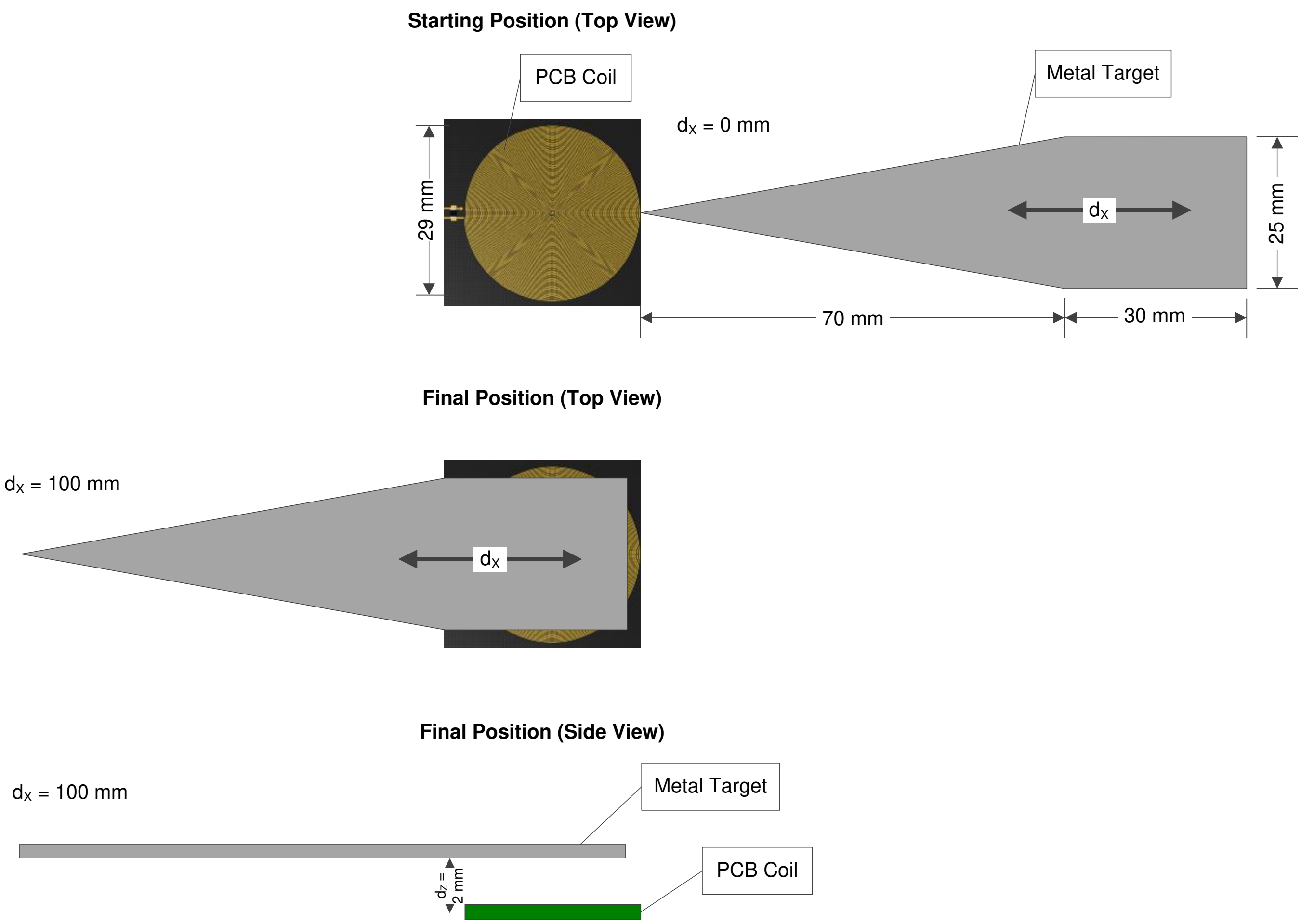

Figure 3. Target Dimensions and Position

2.3 Performance

Moving the target from d_x = 0 mm to d_x = 100 mm at a target distance of d_z = 2 mm in 0.5 mm steps results in the data output in Figure 4. Sliding the target from d_x = 0 mm to d_x = 100 mm decreases the sensor inductance from 216.3 μH to 122.2 μH. This results in a code change from 3,998,031 to 5,316,099 codes over this range and therefore can be used to determine the slider position.

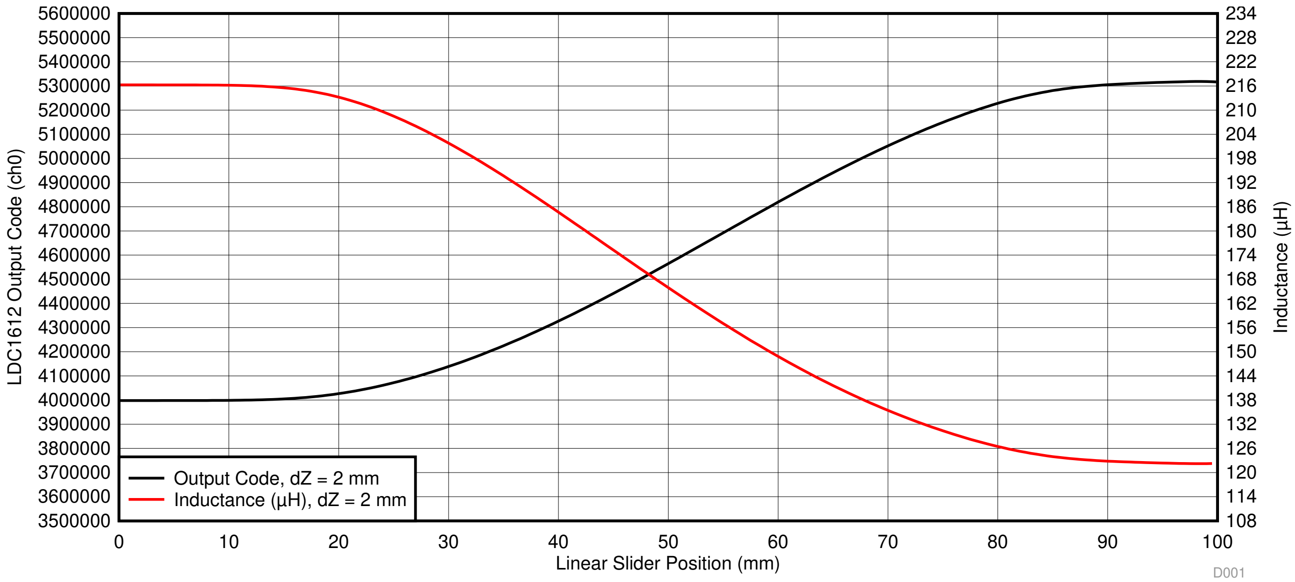

Figure 4. Linear Slider Position Versus Measured Inductance

The effective resolution changes with target position, and decreases at the extremes of the target.

1. For example, the data shows that moving from d_x = 50.0 mm to d_x = 50.5 mm results in an output code change of 12,630 codes (4,564,564 to 4,577,194). Therefore, the average code change over this range is 25.3 codes per μm.
2. By contrast, moving from d_x = 7.0 mm to d_x = 7.5 mm results in an output code change by 54 codes (3,998,249 to 3,998,303). Therefore, the average code increase over this range is 0.1 codes per μm.

To determine the lower end of system accuracy, it is necessary to include measurement noise addition to resolution. Measurement noise is affected by the reference count of the device (RCOUNT). An RCOUNT value of 0xFFFF was used to calculate this data, at which the standard deviation in output codes is 5.7 codes (refer to Table 2).

2.4 System Design Recommendations

2.4.1 Maximum Travel Range (d_x)

For high-accuracy systems, in which the code change at the extremes is insufficient, it is recommended to use a target whose length is longer than the required travel range such that accuracy requirements can be met. The target in the example above may be suitable for a precision application in which 82-mm travel range is required (13 mm ≤ d_x ≤ 95 mm), because the effective resolution is ≥ 1 code per μm of travel in this range.

By using an even narrower operating range, effective resolution can be improved further; for example, in the travel range of 23.5 mm ≤ d_x ≤ 82.5 mm, the effective resolution is ≥ 10 codes per μm of travel. Note that the distance resolution is constrained by the standard deviation of the output code (see Table 2).

2.4.2 Coil Design: Quality Factor

The coil design must aim to maximize the quality factor (Q) of the sensor. A high Q sensor results in higher noise immunity that leads to measurement accuracy and a lower dependence on temperature than a low Q sensor.

Q is determined by Equation 1, Sensor Coil Quality Factor:

$$Q = \frac{1}{R_S} \times \sqrt{\frac{L}{C}}$$

where

- R_S is the AC series resistance of the inductor, which increases with increasing frequency.
- L is the sensor inductance.
- C is the sensor capacitance. (1)

2.4.3 Target Distance (d_Z)

Since the magnetic field strength rapidly decays beyond one coil diameter distance, it is recommended to keep the target distance less than one coil diameter to ensure precise measurements.

However, best measurement accuracy can be achieved if d_z is kept even lower. A comparison of the measurement output in the example above 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, care must be taken that within the operating range, a drive current setting is available that satisfies R_P and maximum oscillation amplitude requirements.

Table 1. Resolution at Different Target Distances

d_z	Output Code at d_x = 13 mm	Codes Increase per µm Travel at d_x = 13 mm	Output Code at d_x = 50 mm	Codes Increase per µm Travel at d_x = 50 mm	Output Code at d_x = 95 mm	Codes Increase per µm Travel at d_x = 95 mm
1 mm	4,002,506	1.9 codes/µm	4,885,570	43.1 codes/µm	6,341,914	3.7 codes/µm
2 mm	4,001,197	1.4 codes/µm	4,564,564	25.3 codes/µm	5,315,157	1.0 codes/µm
3 mm	4,000,213	1.0 codes/µm	4,378,760	16.2 codes/µm	4,839,031	0.6 codes/µm

2.4.4 Reference Count

The conversion time of the LDC161x represents the number of reference clock cycles used to measure the sensor frequency. It is set by the CHx_RCOUNT register for the channel. The reference count value must be chosen to support the required resolution. A higher reference count value results in lower rms noise at the expense of a longer conversion time. Table 2 shows the standard deviation over 1000 samples. The table shows that increasing the RCOUNT value from 0x00FF to 0xFFFF improves SNR by 33.8 dB. Standard deviation and measurement resolution must both be included to calculate the lower limit on the system accuracy.

Note that as reference count is increased, the effective sample rate decreases.

Table 2. Standard Deviation at d_x = 50 mm, d_z = 2 mm

RCOUNT	Conversion time	Standard Deviation in Codes (1000 Samples)	Standard Deviation in µm (1000 Samples)
0xFFFF	26.2 ms at f_{REF}=40 MHz	5.7	0.36
0x0FFF	1.6 ms at f_{REF}=40 MHz	20.6	1.29
0x00FF	0.1 ms at f_{REF}=40 MHz	277.6	17.35

2.4.5 Output Linearization

The output is mostly linear over 60% of the travel range, and provided that the degree of linearization during this range is sufficient to meet system accuracy requirements, no additional linearization is necessary. However, a higher degree of linearization is often desired in order to minimize the required target length, and to improve system accuracy. There are several approaches to improving 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, and therefore the required processing power of the microcontroller.
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.
3. Instead of using an isosceles triangle, the target shape can be altered such that the output response is linear. To calculate the precise target shape to result in a linear output, either complex electromagnetic modeling or complex iterative experimental modeling is required.

2.4.6 Z-axis Compensation

Figure 4 shows that the LDC depends on both d_x and d_z. If no measures are taken to compensate for mechanical tolerances of the target distance, then any error introduced by the mechanical tolerance introduces an error in d_z. Table 3 shows the effect that a ± 10% tolerance of the target distance has on the measurement. For example, the error that is introduced by a +0.2-mm target distance change causes a -1.8-mm error in d_x. While a system with a lower d_z offers superior resolution than a system with higher d_z, it is also more dependent on z-axis tolerance. For example, an uncompensated system that has a 0.2-mm tolerance in d_z creates a larger d_x error if d_z = 1 mm than if d_z = 3 mm.

Table 3. Z-axis Dependence

	d_z = 1.8 mm	d_z = 2.0 mm	d_z = 2.2 mm
Output code (d_x = 50 mm)	4,613,716	4,564,564	4,519,173
Error [codes]	49,152	0	-45,391
Error [% of frequency]	1.08%	0%	0.99%
Equivalent d_x position change	1,940 µm	0	-1,792 µm

Therefore, it is necessary to ensure that an error that is introduced by the mechanical tolerance of the target height does not exceed resolution requirements.

In systems in which linear position must be determined more accurately than tolerances in target height normally allow, a dual-coil coils can be used to compensate for the z-axis tolerance. Such a system utilizes two coils; one coil whose objective it is to determine d_x, and a second coil which is used to determine d_z. By using a two-dimensional look-up table or curve fitting, a higher degree of accuracy can be achieved to determine d_x over a range of d_Z as it would be possible with a single-coil solution.

3 Approach 2: Measuring Lateral Movement with a Stretched Coil and a Rectangular Target

3.1 Concept

As an alternative to shaping the target to produce a varying output when moving a target over a coil, it is possible to instead shape the AC magnetic field that the coil produces. Figure 5 shows an example of such a system, in which a rectangular target slides over a coil at a fixed target distance to produce an LDC output that can be used to determine the target position d_x.

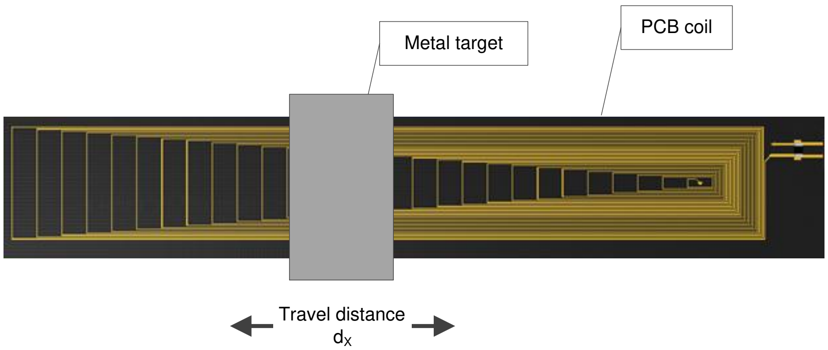

Figure 5. Lateral Movement of a Rectangular Target at Position d_x (Top View)

The advantage of choosing a stretched coil with rectangular target over a circular coil with triangular target is that the target can be much smaller and also 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.

3.2 Coil and Target Design

To use a rectangular target for linear position sensing, the coil has to be shaped to produce a non-homogeneous AC magnetic field. This 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 coil. The coil measures 100 * 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 the innermost turn, and decays towards the right side. Therefore, the peak strength of the AC magnetic field lies left of the geometric center of the coil.

Texas Instruments provides PCB layout scripts that generate stretched coils for linear position sensing applications. These sensor design generation scripts can be downloaded from www.ti.com/ldc. Application report SNOA930 contains further information on LDC sensor design.

The target is a rectangular copper or aluminum target. Other metal types, or plastic targets that have been painted with conductive paint, are suitable alternatives, but may result in different performance. Figure 6 through Figure 8 show the target position in the starting position (d_x = 0 mm) and the final position (d_x = 100 mm).

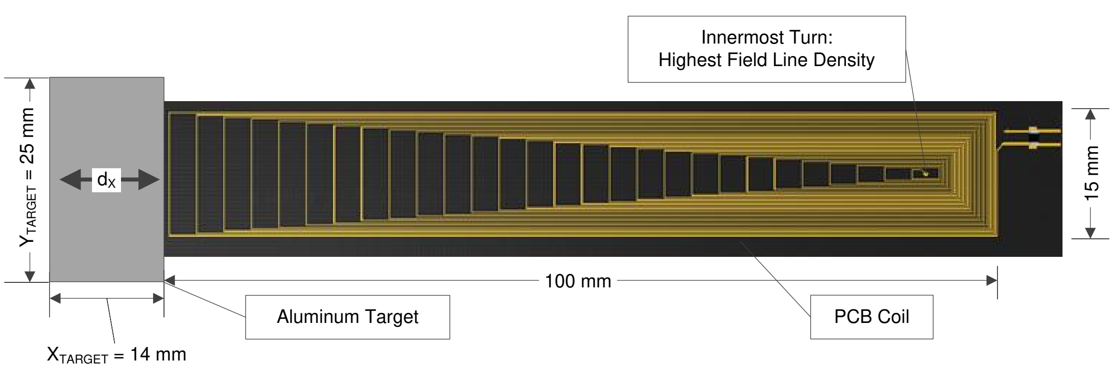

Figure 6. Starting Position: d_x = 0 mm (Top View)

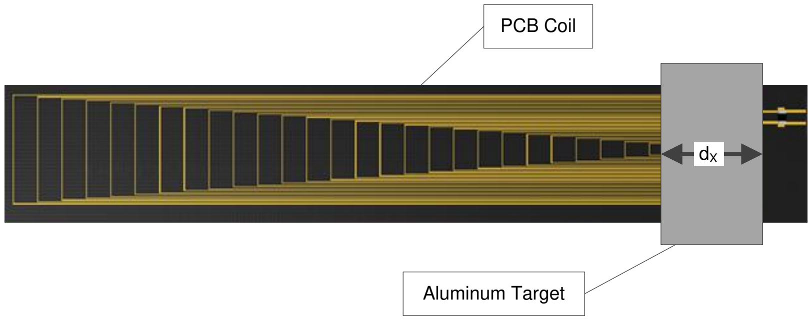

Figure 7. Final Position: d_x = 100 mm (Top View)

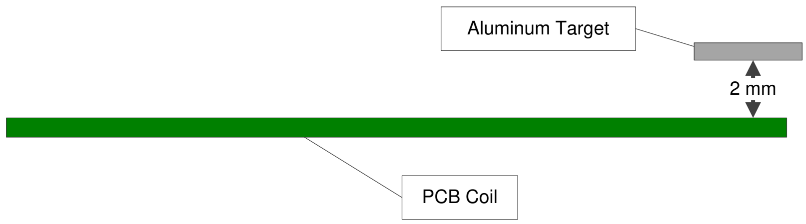

Figure 8. Final Position: d_x = 100 mm (Side View)

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.

3.3 Performance

Moving a target from d_x = 0 mm to d_x = 100 mm at a target distance of d_z = 2 mm in 0.5 mm steps results in the data output seen in Figure 9 below. The target is a 14×25 mm aluminum target.

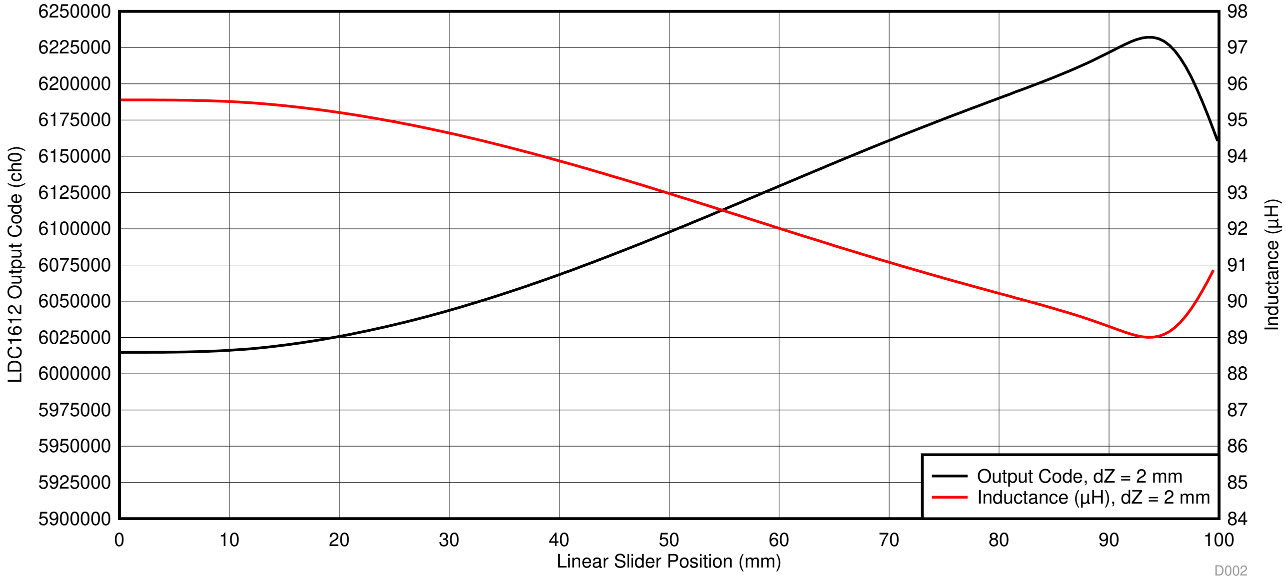

Figure 9. Linear Slider Position Versus Measured Inductance

The graph 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. Between 0.0 mm and 15.0 mm, the target enters the magnetic field of the coil. This region can be used to determine target position, but the resolution is less than in the center region. For example, moving from d_x = 5.0 mm to d_x = 5.5 mm results in an output code change from 6,014,920 to 6,014,969, a 49 code change. Therefore, the average code increase over this range is 0.1 codes per µm.
2. The center region spans from 15.0 mm to 92.0 mm over which the sensor inductance decreases from 95.4 µH to 89.1 µH. This region can be used to most accurately determine target position. For example, the data shows that moving from d_x = 50.0 mm to d_x = 50.5 mm results in an output code change by 1,565 codes. Therefore, the average code increase over this range is 3.1 codes per µm.
3. Between d_x = 92.0 mm and d_x = 100.0 mm, the trend reverses, which is due to the drop in magnetic field strength past the center coil loop. Since the LDC output codes cannot be uniquely mapped into this region, use of this region poses significant system challenges for the small increase in target travel range it provides.

To determine the lower end of system accuracy, it is necessary to include measurement noise addition to resolution. Measurement noise is affected by the reference count of the device (RCOUNT). An RCOUNT value of 0xFFFF was used to calculate this data, at which the standard deviation is 2.38 codes (refer to Table 5).

3.4 System Design Recommendations

3.4.1 Maximum Travel Range (d_x)

The performance calculations in Section 3.3 show that not every region is suitable for measurement. The region past the center coil loop (between d_x = 92.0 mm and d_x = 100.0 mm) is not monotonic and is therefore unusable for this application. This limits the usable travel range to 92 mm.

Depending on system accuracy requirements, precision applications may also need to discard the region between 0.0 mm and 15.0 mm. This leads to a usable travel range of 77 mm (77% of coil length). As a result, the coil design length needs to extend beyond the required travel range.

3.4.2 Coil Design

The coil design must aim to maximize the quality factor (Q) of the sensor (refer to Equation 1). A high-Q sensor results in higher noise immunity, which leads to measurement accuracy and a lower dependence on temperature than a low-Q sensor.

3.4.3 Target Distance (d_z)

Since the magnetic field strength rapidly decays beyond one coil diameter distance, it is recommended to keep the target distance less than 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, best measurement accuracy can be achieved if d_z is kept even lower. A comparison of the measurement output in the example above 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, care must be taken that within the operating range, a drive current setting is available that satisfies RP and maximum oscillation amplitude requirements.

Table 4. Resolution at Different Target Distances

d_z	Output Code at d_x = 15 mm	Codes Increase per µm Travel at d_x = 15 mm	Output Code at d_x = 50 mm	Codes Increase per µm Travel at d_x = 50 mm	Output Code at d_x = 92 mm	Codes Increase per µm Travel at d_x = 92 mm
1 mm	6,022,444	1.5 codes/µm	6,142,007	4.7 codes/µm	6,354,896	7.2 codes/µm
2 mm	6,019,754	1.0 codes/µm	6,097,690	3.1 codes/µm	6,229,048	2.9 codes/µm
3 mm	6,018,212	0.7 codes/µm	6,071,355	2.1 codes/µm	6,155,486	0.9 codes/µm

3.4.4 Reference Count

The conversion time of the LDC161x represents the number of reference clock cycles used to measure the sensor frequency. It is set by the CHx_RCOUNT register for the channel. The reference count value must be chosen to support the required resolution. A higher reference count value results in lower rms noise at the expense of a longer conversion time. Table 5 shows the standard deviation over 1000 samples. The table shows that increasing the RCOUNT value from 0x00FF to 0xFFFF improves SNR by 43.8 dB. Standard deviation and measurement resolution must both be included to calculate the lower limit on the system accuracy.

Note that as reference count is increased, the effective sample rate decreases.

Table 5. Standard Deviation at d_x = 50 mm, d_z = 2 mm

RCOUNT	Conversion time	Standard Deviation in Codes (1000 Samples)	Standard Deviation in µm (1000 Samples)
0xFFFF	26.2 ms at f_{REF} = 40 MHz	2.38	0.85
0x0FFF	1.6 ms at f_{REF} = 40 MHz	15.85	5.66
0x00FF	0.1 ms at f_{REF} = 40 MHz	370.40	132.28

3.4.5 Output Linearization

The output is mostly linear over 77% of the travel range, and provided that the degree of linearization during this range is sufficient to meet system accuracy requirements, no additional linearization is necessary. However, a higher degree of linearization is often desired in order to minimize the required coil length, and to improve system accuracy. There are several approaches to improving 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, and therefore the required processing power of the microcontroller.
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.

3.5 Z-axis Compensation

Figure 4 shows that the LDC depends on both d_x and d_z. If no measures are taken to compensate for mechanical tolerances of the target distance, then any error introduced by the mechanical tolerance introduces an error in d_z. Table 5 shows the effect that a ± 10% tolerance of the target distance has on the measurement. For example, the error that is introduced by a +0.2-mm target distance change causes a -2.0-mm error in d_x. While a system with a lower d_z offers superior resolution than a system with higher d_z, it is also more dependent on z-axis tolerance. For example, an uncompensated system that has a 0.2-mm tolerance in d_z creates a larger d_x error if d_z = 1 mm than if d_z = 3 mm.

Table 6. Z-axis Dependence

	d_z = 1.8 mm	d_z = 2.0 mm	d_z = 2.2 mm
Output code (d_x = 50 mm)	4,613,716	4,564,564	4,519,173
Error [codes]	7,020	0	-6,336
Error [% of frequency]	0.12%	0%	0.10%
Equivalent d_x position change	2.243 µm	0	-2,024 µm

Therefore, it is necessary to ensure that an error that is introduced by the mechanical tolerance of the target height does not exceed resolution requirements.

In systems in which linear position must be determined more accurately than tolerances in target height would normally allow, a dual-coil coils can be used to compensate for the z-axis tolerance. Such a system utilizes two coils; one coil whose objective it is to determine d_x, and a second coil which is used to determine d_z. By using a two-dimensional look-up table or curve fitting, a higher degree of accuracy can be achieved to determine d_x over a range of d_Z as it would be possible with a single-coil solution.

4 Summary

Inductive sensing is an ideal sensing method for linear position sensing due to the contactless nature and high reliability of the method.

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. Space requirements for coil and target are the primary deciding factors on which approach to use for a system:

- Using a circular coil and a triangular target offers excellent resolution in systems in which a target length that is longer than the required travel range is acceptable. Texas Instruments provides the WEBENCH® Inductive Sensing Designer and coil scripts that greatly simplify coil design for this approach.
- Using a stretched coil and rectangular target is suitable for systems in which system space constraints dictate use of a small target. Texas Instruments provides coil scripts that greatly simplify coil design for this approach.

Revision History

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

Changes from Original (April 2015) to A Revision	Page
• Updated sentence structure throughout	1
• Fixed broken cross-reference to Table 5.	12
• Changed LDC1000 to LDC100x throughout	13

IMPORTANT NOTICE AND DISCLAIMER

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