TI Designs

LDC1312 Incremental Encoder Knob

Design Overview

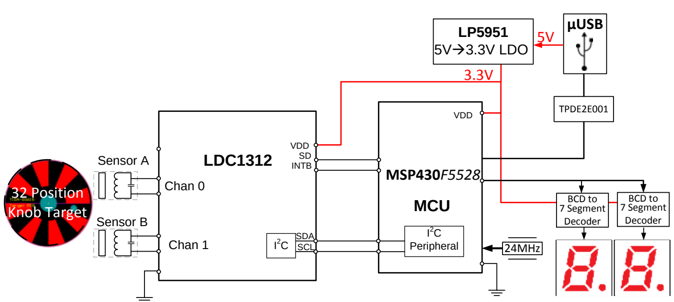
An inductive sensing based incremental position knob design can provide a robust and low-cost interface for control inputs. It can reliably operate in environments which have dirt, moisture, or oil which would pose issues for alternate sensing technologies. This solution requires no magnets.

Using only 2 LDC sensing channels, an LDC1312 can support 1 knob, while the 4 channel LDC1314 can support 2 knobs.

Design Resources

[TIDA-00615]	Design Folder
[LDC1312]	Product Folder
[MSP430F5528]	Product Folder
[LP5951]	Product Folder
[TPDE2E001]	Product Folder
[CD74HC4511]	Product Folder
[TIDA-00508]	Tools Folder

Block Diagram



Design Features

- Contactless, high reliability incremental position knob using LDC technology
- No calibration required
- 2.7 V to 3.6 V operation
- Power consumption of <3.5 mA (excluding MCU & LED indicators)
- Sensor and knob can be placed remotely with respect to LDC1312/4 device
- 32 steps/rotation
  - design can scale to support multiples of 4 positions
- Measurement of >1000 RPM
- Minimal MCU memory and instructions:
  - 40 bytes of RAM
  - 800 bytes of ROM/Flash
  - 0.1 MIPS for 5 ms response rate

Featured Applications

- Infotainment interfaces for automotive
- Rolling jog wheels
- Appliance interfaces, including cooktops and cleaning appliances
- Home audio and consumer electronics
- System control

1 Key System Specifications

Table 1: System Specifications

Parameter	Specification
Physical Dimensions	40.8 x 89 x 27 mm
Knob Dimensions	26 mm Ø x 25.3 mm
Sensor Geometry	2 x 6mm multi-segment series inductors
Sensor Inductance (no target interaction)	5.6 µH
Sensor Capacitance	330 pF
Sensor Frequency (no target interaction)	3.7 MHz
Rotational Resolution	32 steps/rotation (11.25° /step)
Target to Sensor distance	<0.2mm
Total current consumption (including MCU and 7 Segment displays	49mA
LDC Current consumption	<3.5mA
LDC Sample Rate	4.9 kSPS
Operating Temperature	-40°C to +85°C

2 System Description

Historically, rotary control knobs have been implemented using predominantly mechanical contact-based systems. These systems are prone to reliability issues and consequently may result in expensive replacement over their lifetimes due to wear of moving parts. Alternate solutions using optical sensing are not immune to dirt and dust, which also pose lifetime reliability issues in many automotive and industrial applications.

Inductive sensing is a contactless sensing technology that offers a more durable control dial implementation. Furthermore, this technology is extremely resistant to harsh environments and can even be implemented as a water-resistant solution. TIDA-00615 features the LDC1312 and offers a low cost and robust solution targeted for implementing knobs, dials, and encoders in industrial, consumer, and automotive applications.

To learn more about inductive sensing, go to www.ti.com/ldc.

For TIDA-00615, power is supplied by the 5V USB connection and regulated to 3.3V for the MSP430 MCU and LDC1312. The LDC1312 measures inductance changes due to changes in the position of the knob. The MCU retrieves the measurements from the LDC1312, processes the data, updates the knob position as appropriate, and displays the current knob position using the 7 segment LED displays.

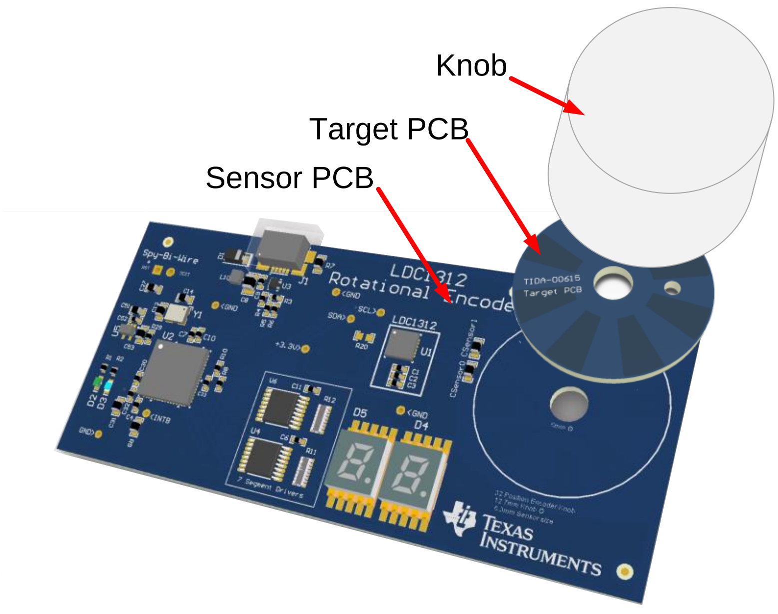


Figure 1: System Assembly

As shown in Figure 1, TIDA-00615 is composed of a sensor PCB, which contains all of the electrical components, a target PCB, which contains no components, and the mechanical components which form the rotating knob assembly. The target PCB is attached to the knob, which rotates at a fixed distance above the sensor PCB.

2.1 LDC1312

The LDC1312 measures the inductive shift due to knob movement and converts the inductive shift to digital values corresponding to the sensor inductance.

2.2 MSP430F5528

The MSP430F5528 retrieves the LDC1312 conversion results, calculates the knob position based on the sensor measurements, and updates the 7 segment displays as appropriate.

2.3 LP5951

The LP5951 is a Low-Dropout Regulator (LDO) that converts the 5V provided from the USB interface to 3.3V used as the main supply for TIDA-00615. It provides sufficient output current using a small SC70 footprint.

2.4 CD74HC4511

This 7-segment display driver takes the 4bit wide, binary-coded decimal output from the MSP430F5528 and drives the 7-segment display drivers with the appropriate digit.

2.5 TPDE2E001

This ESD protection array protects the digital inputs of the MSP430F5528 that are attached to the USB interface.

3 Block Diagram

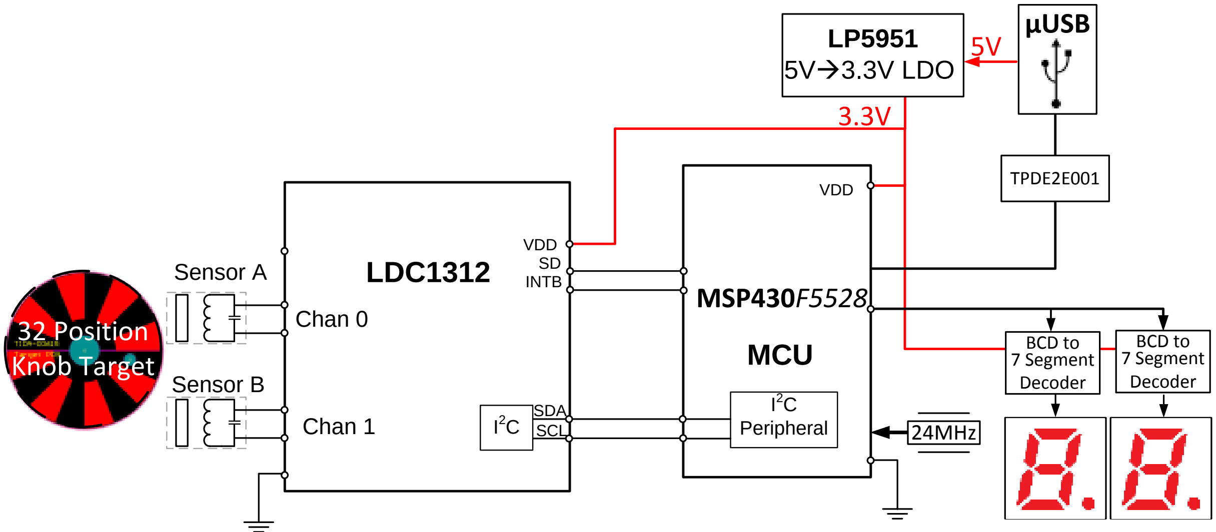


Figure 2: TIDA-00615 System Block Diagram

3.1 Highlighted Products

3.1.1 LDC1312

The LDC1312 is a medium-resolution 12/16 bit multiplexed 2-channel LDC with an I2C connection and an internal reference oscillator. It can operate from 2.7V to 3.6V and supports sample rates up to 13.3kSPS.

4 Getting Started

The operation of TIDA-00615 is simple – connect a micro-USB cable into J1 of TIDA-00615, and connect the other end of the cable to a PC or a powered USB hub, as shown in Figure 3.

The 7-segment displays on the board indicate the current position of the knob; a rotation of the knob in a clockwise direction will increment the count, while a counter-clockwise rotation will decrement the counted position. As TIDA-00615 has 32 positions, each increment or decrement corresponds to an angular shift of 11.25°.

The count will wrap-around when hitting the maximum or minimum – for example, rotating the knob one position clockwise when the counter shows 31 will change the counted position to 00.

This behavior is a function of the firmware and other behaviors can be supported (such as halting the count or continuing further).

TIDA-00615 includes a mechanical design to provide a tactile indexing for each knob position and allows for continuous rotation; alternative mechanical designs which have a physical stop can be supported.

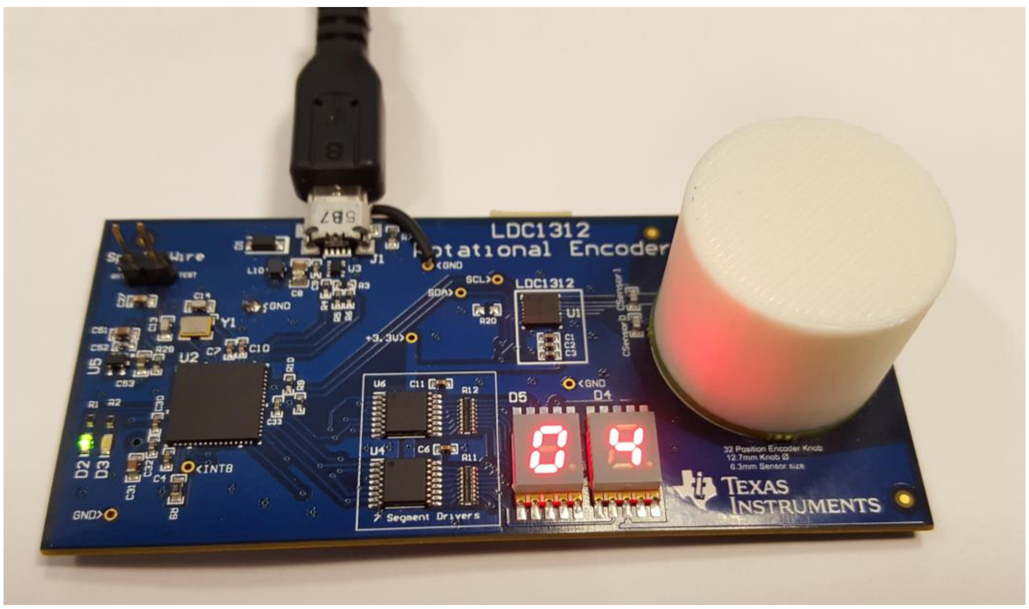


Figure 3: TIDA-00615 powered up by USB Connection after 4 steps

5 TIDA-00615 Comparison to TIDA-00508

TIDA-00508 (http://www.ti.com/tool/TIDA-00508) is another TI rotational measurement reference design using LDC technology. It brings many of the same benefits of the TIDA-00615 – the contactless, hostile environment immunity, and low cost implementation, but provides an absolute angular measurement capability. It requires 4 LDC channels per measurement, while TIDA-00615 requires 2 channels.

Table 2: Comparison of TIDA-00615 and TIDA-00508

	TIDA-00615	TIDA-00508
Description	LDC1312	1 Dial using LDC1314
Number of LDC channels	2	4
LDC device compatibility	LDC1312 (or ½ of LDC1314)	LDC1314
Measurement output	Incremental change in position and direction	Absolute position
Resolution	11.25°	0.1°
Calibration	None	Required 1° accuracy; otherwise not needed for 3° accuracy
Maximum Rotation Speed	>1000 RPM, is a function of number of positions	200 RPM
Sampling Requirements	Continuous – changes will not be detected without active LDC sampling	As needed – 1 sample required

6 System Design Theory

6.1 Inductive to Digital Converter Theory of Operation

An AC current flowing through an inductor will generate an AC magnetic field. If a conductive material, such as a metal object, is brought into the vicinity of the inductor, the magnetic field will induce a circulating current (eddy current) on the surface of the conductor.

The eddy current is a function of the distance, size, and composition of the conductor. The eddy current generates its own magnetic field, which opposes the original field generated by the sensor inductor. By opposing the original field, the original field is weakened; this produces a reduction in inductance compared to the inductor’s free space inductance.

This effect is equivalent to a set of coupled inductors, where the sensor inductor is the primary winding and the eddy current in the target object represents the secondary inductor. The coupling between the inductors is a function of the sensor inductor, and the conductive material resistivity, distance, size, and shape. The resistance and inductance of the secondary winding caused by the eddy current can be modeled as a distance dependent resistive and inductive component on the primary side (coil). Figure 3 shows a simplified circuit model of the sensor and the target as coupled coils.

An EM field appropriate for sensing can be generated using an L-C resonator. One topology for an L-C tank is a parallel R-L-C construction, as shown in Figure 4. To simplify the inductor amplitude calculations, the parallel electrical model is generally used, as shown in Figure 5. For inductive sensing applications, the resistive element is represents parasitic circuit losses and is not a discrete component.

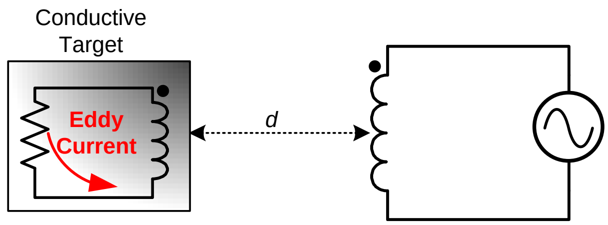


Figure 4: Conductor in AC Magnetic Field

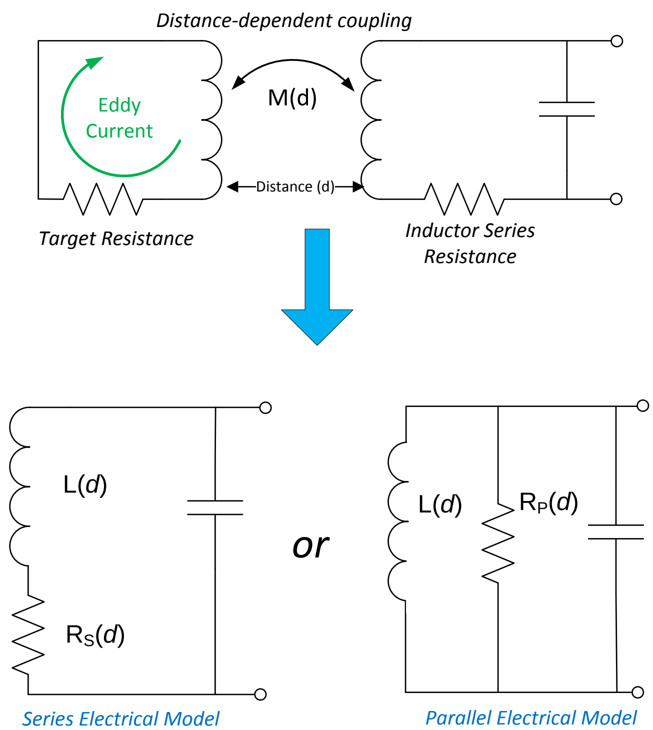


Figure 5: Electrical Model of Parallel Inductive Sensor

In brief, an oscillator is constructed by combining a frequency selective circuit with a gain block in a closed loop. The criteria for oscillation are: (1) loop gain > 1, and (2) closed loop phase shift of 2π radians.

In the context of an oscillator, the R-L-C resonator provides the frequency selectivity and contributes to the phase shift. At resonance, the impedance of the reactive components (L and C) cancels; leaving only the lossy (resistive) element in the circuit.

At resonance, the circuit voltage amplitude is maximized and the circuit appears as a pure resistance. Representing the resistance as a parallel resistance R_P as shown in Figure 5, we can use:

$$R_P = Q\sqrt{\frac{L}{C}} \quad (1)$$

Where:

- Q is the quality factor of the circuit, which is the ratio of the reactive components to the resistive component
- L is the parallel inductance in H
- C is the parallel capacitance in F

The R_P can be used to determine the sensor drive current. A lower R_P requires a larger sensor current to maintain constant oscillation amplitude. It is clear that increasing the Q or L of the circuit or decreasing the C will increase the R_P.

6.2 Movement of a Conductive Target

Consider a flat conductive target moved axially with respect to an L-C resonant circuit, as shown in Figure 6. In this example, the resonant LC circuit consists of a 14mm diameter PCB inductor with a parallel capacitor.

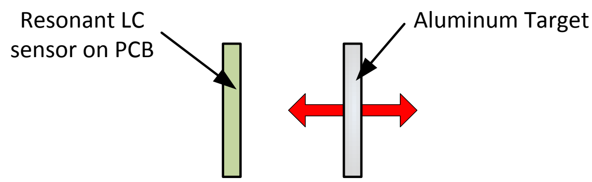


Figure 6: Aluminum Target moved axially with respect to LC resonant circuit

The target is an aluminum disk that is positioned so that the surface of the inductor and the surface of the aluminum target are always parallel. The target is moved closer to or farther from the inductor while maintaining the parallel alignment to the sensor.

Figure 7 shows the change in inductance and sensor frequency due to the target movement. The change in response is larger when the target is closer to the sensor. For example, when the target-to-sensor distance changes from 5.0 mm to 4.0 mm, the sensor frequency increases by 47 kHz. When the target to sensor distance is changed from 2.0 mm to 1.0 mm, the sensor frequency increases by 365 kHz. This larger shift in frequency can be measured with more discrete intermediary points, which corresponds to a higher resolution physical measurement.

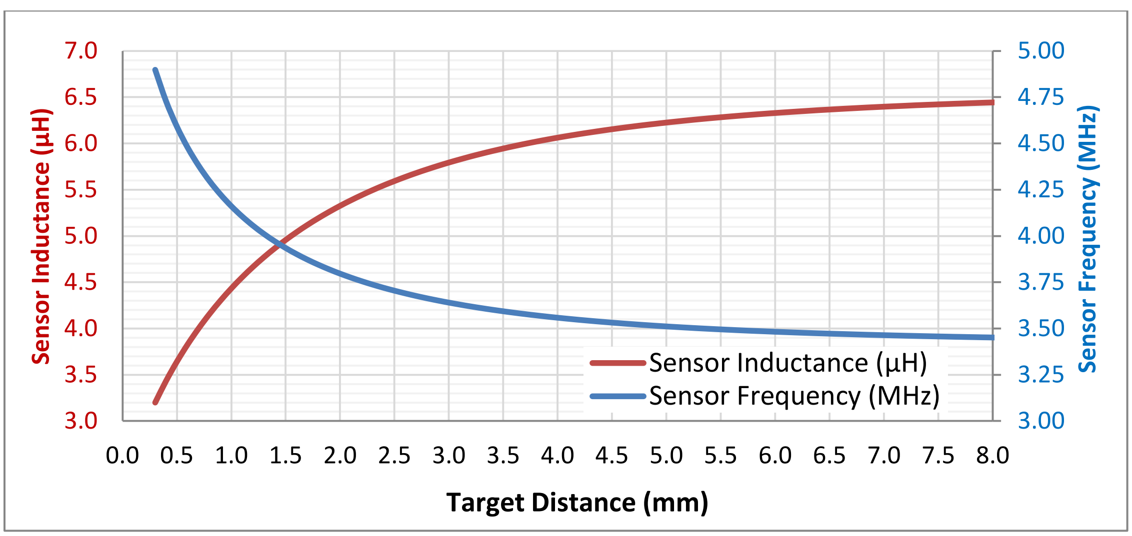


Figure 7: Example Sensor Response vs. Target Distance

The inductance change scales with the sensor outer diameter – doubling the sensor outer diameter will double the effective sensing range. When plotting an inductive sensing response, it is common to use a normalized distance, in which the target distance is divided by the sensor diameter, as shown in Figure 8.

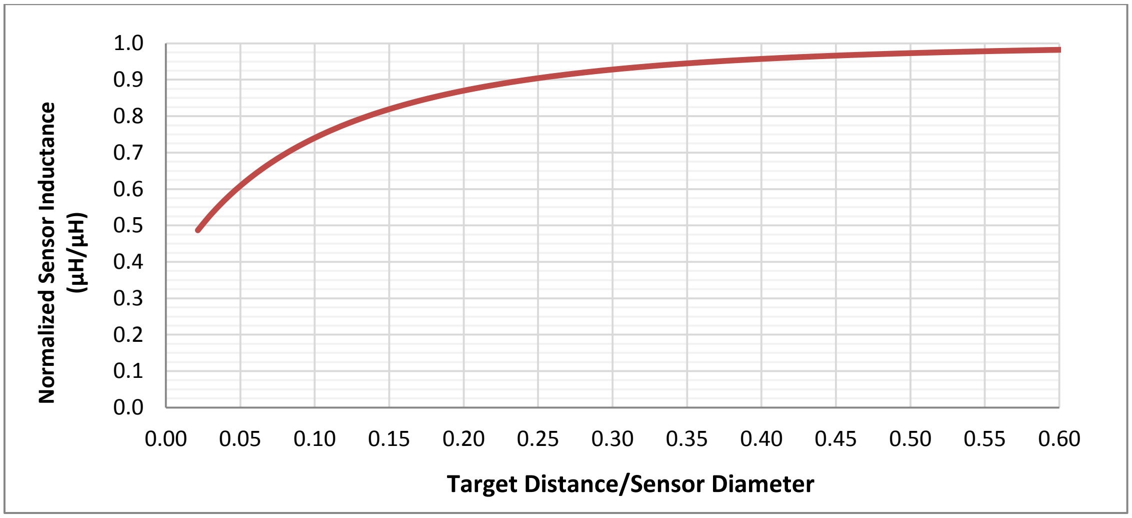


Figure 8: Normalized Sensor Response

The sensor R_P vs. target distance is shown in Figure 9. The R_P changes in a similar way to the inductance. As the target gets closer to the sensor, the amount of energy dissipated in the target increases; this manifests as a decrease in the sensor R_P. The shape of the response is similar to the inductance shift, and it also scales with the target diameter. The magnitude of the shift is a function of the target conductivity and geometry. If the sensor R_P gets too low, then the LDC will not be able to properly maintain the sensor oscillation signals. For the LDC1312, 1 kΩ is a practical minimum for R_P.

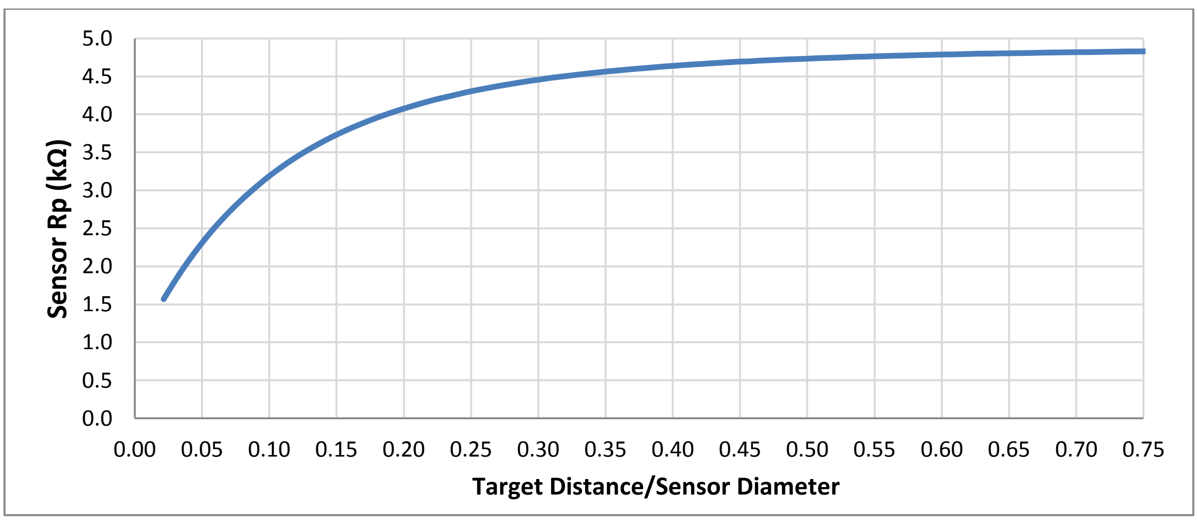


Figure 9: Sensor R_P vs. Target Distance

6.3 Lateral shift in Target Position

Inductive sensing can also measure lateral shifts in a target position. A sensor and target configuration which can perform this type of measurement is shown in Figure 10. For this measurement, the target is not centered over the sensor, but moves so that it covers a variable portion of the sensor. The target is held at a fixed Z-distance with respect to the sensor. The sensor inductance shift is proportional to the amount of target area covering the sensor.

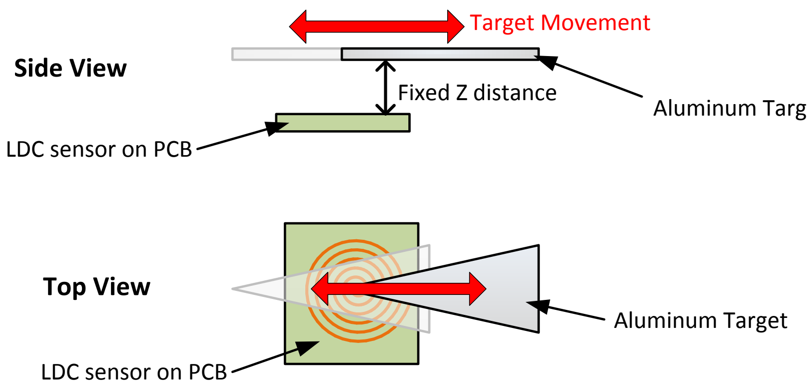


Figure 10: Lateral Position Sensing with LDC

This lateral position sensing is the principle employed by TIDA-00615 to detect knob rotation.

6.4 LDC1312 Operation

As shown in the LDC1312 block diagram in Figure 11, the LDC1312 drives an alternating current, I_{DRIVE}, across the INAx and INBx pins which are connected to an LC resonating sensor. This current injects sufficient energy to compensate for the sensor R_P loss. The recommended sensor voltage, which is based on the IDRIVE and sensor R_P, is between 1.2 V_P to 1.8 V_P.

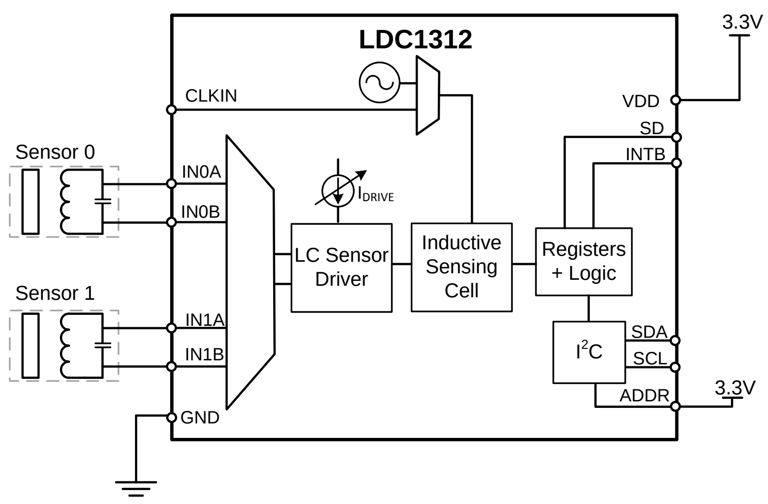


Figure 11: LDC1312 Block Diagram

The LDC1312 then measures the sensor inductance by measuring the oscillation frequency. The resonance oscillation frequency, f_{SENSOR}, can be determined from the sensor inductance and capacitance by:

$$f_{SENSOR} = \frac{1}{2\pi\sqrt{LC}} \quad (2)$$

The sensor frequency has an inverse square root relationship to the sensor inductance – if the inductance decreases by 10%, the sensor frequency increases 4.9%. The LDC131x returns the sensor frequency as a 12bit output code that is the ratio of the sensor frequency to the reference frequency:

$$\mathbf{DATAx} = \frac{2^{12} \times f_{SENSORx}}{f_{REFERENCE}} \quad (3)$$

The reference frequency can either be provided from an external source of up to 40 MHz or the LDC can use its internal oscillator as a reference frequency. An external source can provide improved effective resolution, but for many applications the internal oscillator is sufficient.

The LDC131x device, while providing only a 12 bit output word, internally converts with 16 bits of resolution. The output gain and offset of the LDC are used to access the additional bits of resolution:

$$f_{SENSORx} = CHx\_FIN\_DIVIDER * f_{REFx}\left[\frac{DATAx}{2^{(12+OUTPUT\_GAIN)}} + \frac{CHx\_OFFSET}{2^{16}}\right] \quad (4)$$

Where:

- $DATA_X$ = Conversion result from the DATA_CHx register
- CHx_ OFFSET = Offset value set in the OFFSET_CHx register
- f_{REFx} is the channel X reference frequency, which is f_{CLK}/CHx_FREF_DIVIDER.
- CHx_FIN_DIVIDER is the programmed channel input divider
- OUTPUT_GAIN is the LDC resolution programmed by RESET_DEV:OUTPUT_GAIN.

Refer to the Analog Wire blog post Improve the ENOB of a multichannel LDC by 4 bits in 3 simple steps for more information on this functionality.

The output code is accessed via I2C. The LDC1312 channels are sequentially sampled. Channels are only active while sampling, and inactive channels are shorted to prevent coupling with the active channel.

6.5 Inductive Incremental Position Operation

A rotary encoder provides a set of outputs which indicate when a change in the angle of the knob occurs, and the direction of rotation (clockwise or counter-clockwise). The encoder firmware maintains a state which corresponds to total change in knob position since initialization.

For example, if the encoder state is position 3, and the knob is rotated 2 positions in a clockwise direction, the new encoder state would be 5. This state could correspond to a stereo volume setting or a desired temperature setting.

6.6 4 Position LDC Encoder Implementation

Consider an LDC system with a 2 sensors separated by 90° with a semicircular rotating target. Figure 12 and Figure 13 illustrate how target position maps to the LDC channel outputs. Note that for the purpose of this discussion, the outputs are represented as binary, but in the actual system the outputs will display an analog characteristic.

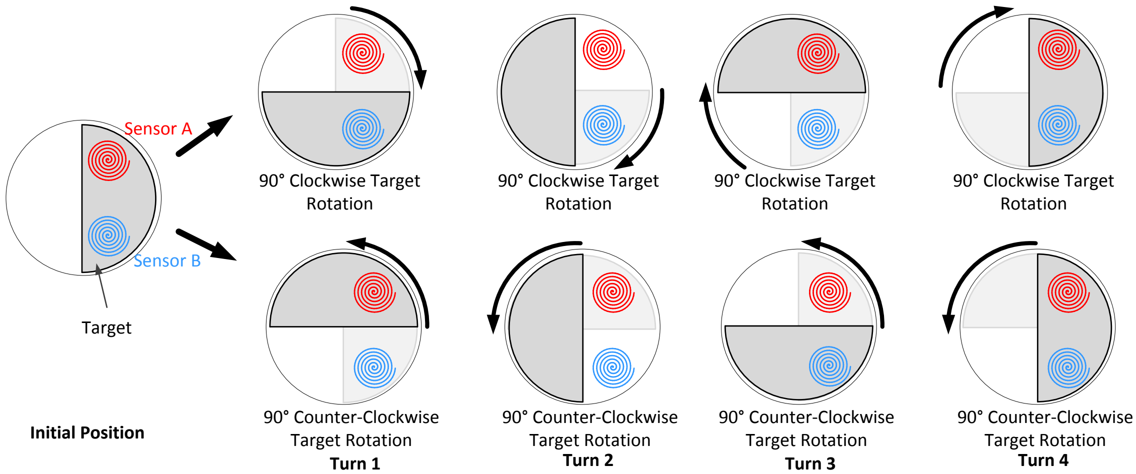


Figure 12: Sensor and Target configuration

With the target initial position as shown in Figure 12, the target fully covers both sensors, and so the inductance of both sensors is at a minimum, as shown in Figure 13.

Should a 90° clockwise rotation of the target occur, Sensor A is not covered by the target and so its inductance increases to its maximum value (which means the sensor frequency is then at its lowest value). Sensor B remains covered, and so there is no change in its output.

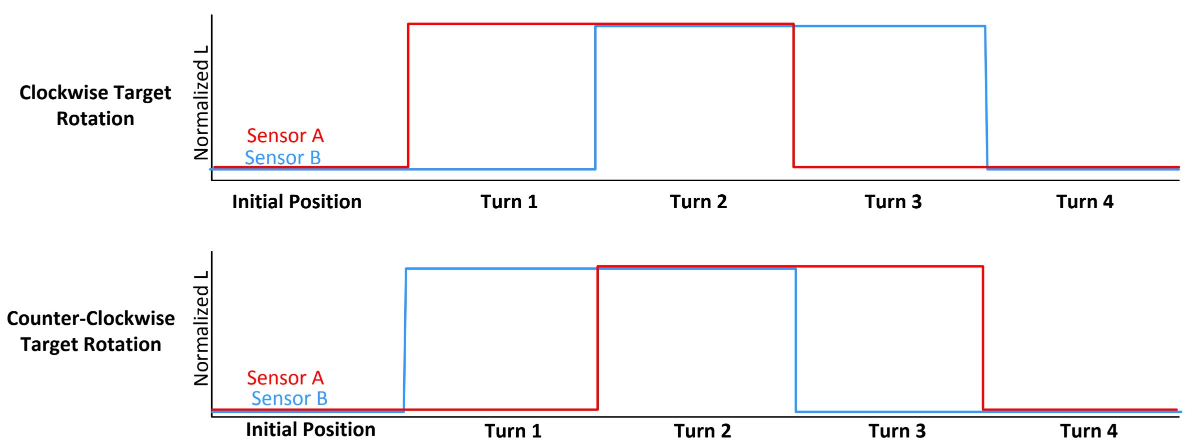
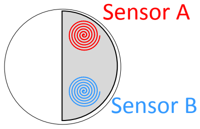
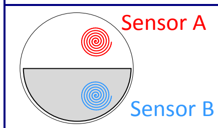
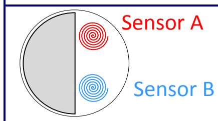
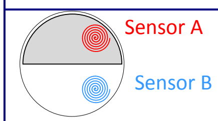


Figure 13: Normalized Inductance changes

If a 90° counter-clockwise rotation of the target occurs, returning the target to the initial position, Sensor A and Sensor B are both covered and their inductances are at the corresponding minimum value.

Additional turns will shift the inductance of the two sensors as shown. For every turn of the target, one of the sensors shifts. After 4 turns in the same direction, the target returns to its initial position. Note that the inductance shift is inversely related to the frequency shift of the sensor.

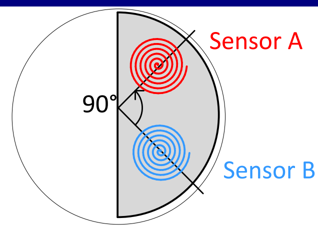
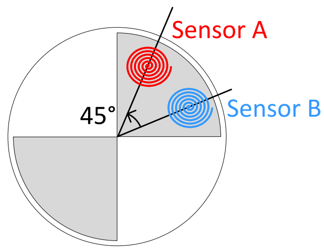
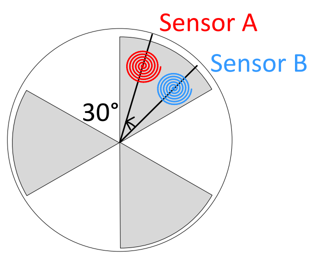
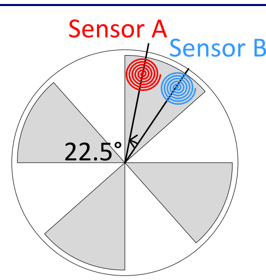
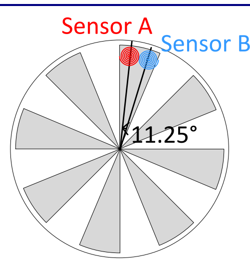
Table 3: Target Movement and Sensor Measurement change

Starting Target Position		Clockwise Rotation		Counter-Clockwise Rotation	
Target Starting Position	**Angle**	**Target Movement**	**Sensor Inductance Change**	**Target Movement**	**Sensor Inductance Change**
	0°	0°→90°	Sensor A: Increase Sensor B: No change	0°→270°	Sensor A: No Change Sensor B: Increase
	90°	90°→180°	Sensor A: No Change Sensor B: Increase	90°→0°	Sensor A: Increase Sensor B: No Change
	180°	180°→270°	Sensor A: Decrease Sensor B: No Change	180°→90°	Sensor A: No Change Sensor B: Decrease
	270°	270°→0°	Sensor A: No Change Sensor B: Decrease	270°→180°	Sensor A: Decrease Sensor B: No Change

6.7 N-Position Encoder

The LDC solution can scale in the number of encoded positions per rotation by multiples of 4. By cutting the target into multiple evenly-sized sections, the number of positions can be increased.

Table 4: Scaling to 4 × N Positions

Number of Positions	Target Shape + Sensor Positioning	Target Geometry	Sensor Positioning
4		1 section covering 180°	90° Separation
8		2 sections, each 90°, separated by 90°	45° Separation
12		3 sections, each 60°, separated by 60°	30° Separation
16		4 sections, each 45°, separated by 45°	22.5° Separation
32		8 sections, each 22.5°, separated by 22.5°	11.25° Separation
4 × N	Varies	N Sections, each 180°/N, separated by 180°/N	90°/N Separation

As the number of positions increases, the angular separation between sensors decreases. If the encoder diameter is held constant, the decreased angular separation results in a smaller area available for each sensor. If the sensor cannot be reduced in size (due to inductance restrictions or sensing range requirements), then the encoder diameter must be increased. The sensor minimum size is a function of the PCB manufacturing – the trace width, spacing, and number of layers affect the size. For example, with a 4 mil (0.102 mm) trace width and spacing using 4 layers, the minimum sensor size is around 5 mm in diameter.

6.8 Equivalent Positioning of Sensors

The positioning of the 2 sensors can be considered as a quadrature configuration. When there are multiple sections to the target, there are multiple positions which have equivalent phase relationships, and a sensor will return the same response as a sensor in another equivalent position.

As shown in Figure 14, with a 4 section target, there are 4 optional positions for each sensor which provide equivalent responses. Placing Sensor A at any of the indicated A_X locations will produce the same response, and any of these positions can be selected as the sensor A position. This flexibility in placement also applies to the B sensor, in that any of the B_Y sensor positions can be used for the B sensor. Any combination of A_X and B_Y sensor positions can be selected and will provide the same response. As the number of target sections increase, the number of potential sensor positions increases correspondingly.

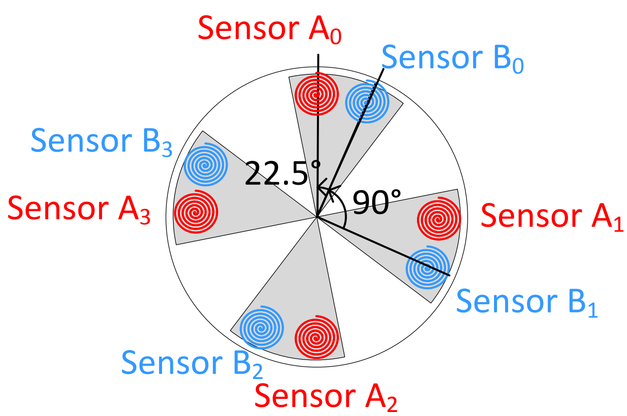


Figure 14: Equivalent Sensor placement for 16 position encoder

6.9 Sensor Design

For proper operation, the LDC131x device requires sensors to have R_P>1kΩ. The sensor inductance has a large effect on the R_P, and higher inductance sensors will have a higher R_P. Sensor inductance can be increased by increasing the sensor area and increasing the number of turns used to form the inductor.

The maximum area for the sensor is limited by the size of the target section; otherwise the sensor response is significantly reduced. Using a trapezoidal shaped sensor section, as shown in Figure 15 provides a larger inductance compared to a circular sensor.

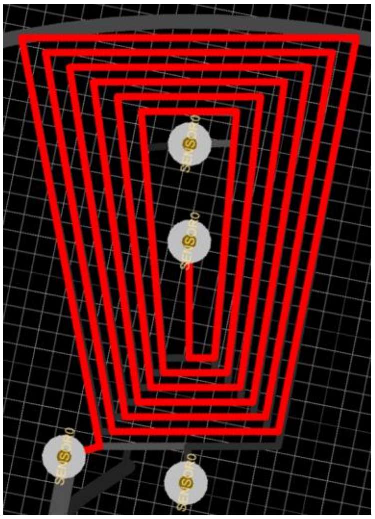


Figure 15: Trapezoidal Sensor configuration

Increasing the number of turns is achieved by using a finer trace and space for the PCB manufacturing. Using 4 mil (0.102 mm) trace width and spacing, the inductor can be routed with 6 turns. Increasing the number of turns further can be achieved by adding multiple layers, as shown in Figure 16.

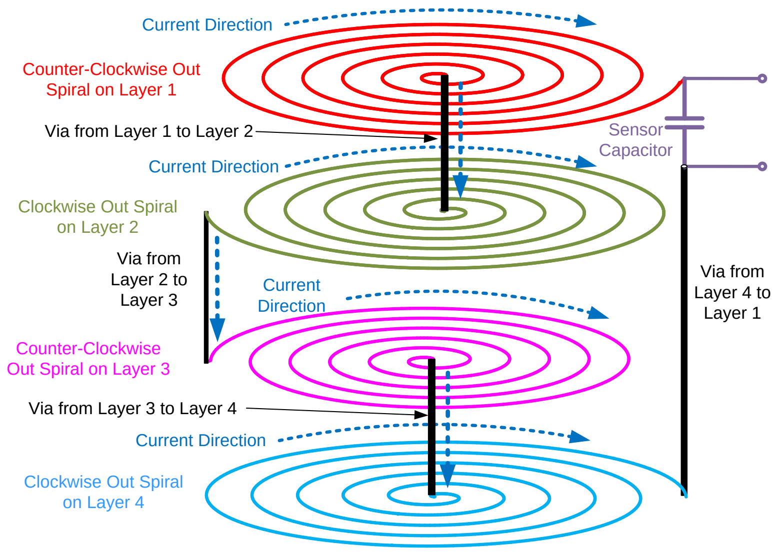


Figure 16: 4-Layer Inductor physical construction

An additional method to increase sensor inductance is to use multiple series inductors. Each of the series elements are placed at an equivalent quadrature positions as described previously. The multiple sections of the target are symmetrical and each segment of the sensor is placed in an equivalent position. As a result, each section of the target interacts with each segment of the inductor in a similar manner, providing larger sensor signal amplitude, as shown in Figure 17.

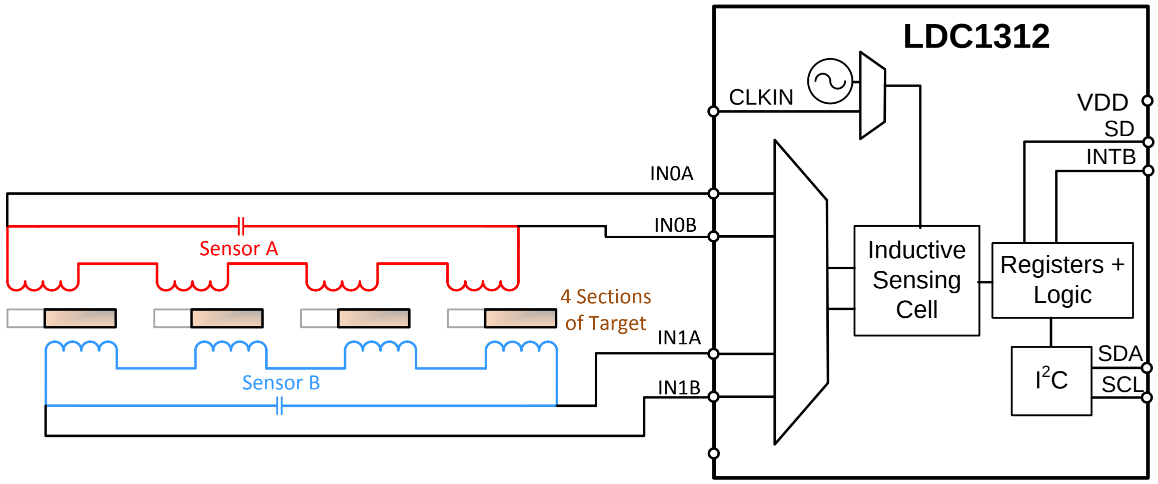


Figure 17: Multiple Section Sensor Connection

The physical placement of the two sensors is arranged so that the each sensor segment is positioned across an inner diameter of 13.7mm and extends to 25.4mm. The 8 total segments are arranged so that they are positioned at equivalent sensing positions for the 2 sensors, as shown in Figure 18.

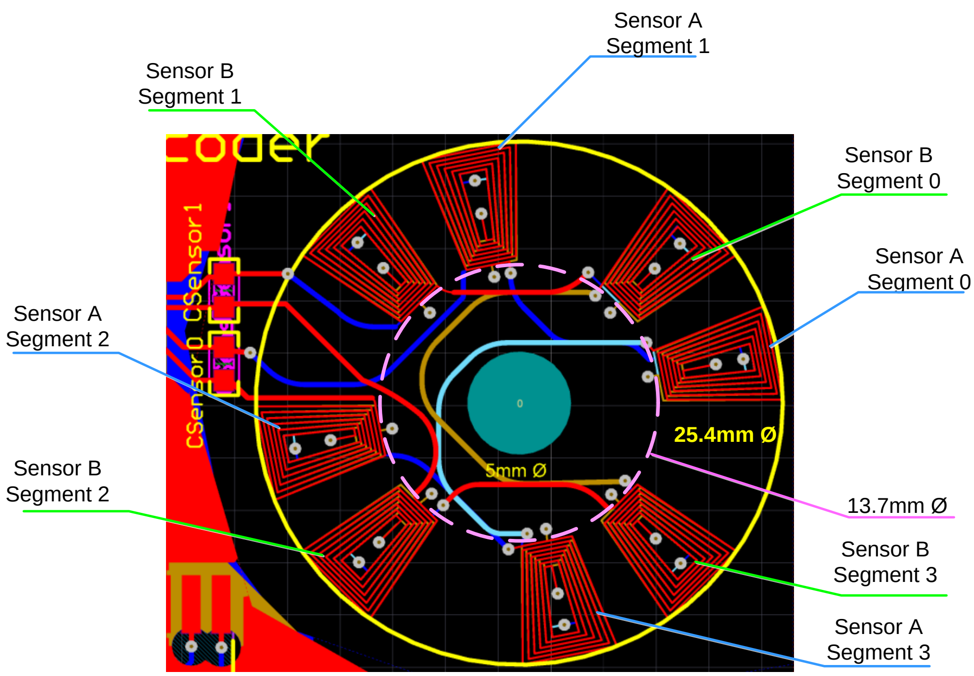


Figure 18: Multiple Sensor Segment Geometry

Table 5: Sensor Segment Angles

Segment	Sensor A	Sensor B
0	11.25°	45°
1	101.25°	135°
2	191.25°	225°
3	281.25°	315°

6.10 Target Design

To implement a 32-position, the target contains 8 conductive regions, each covering 22.5° and separated by voids of 22.5°. Figure 19 shows the target geometries, where the red indicates 1oz. ENIG plated copper (37 µm thick) covered by soldermask. The conductive regions are only present on the top layer of the target PCB. The cyan colored regions indicate the two mechanical holes – the first, at the center of the target, is a 5 mmØ hole, while the second hole is 2 mmØ placed 300 mils (7.62 mm) from the center hole at an angle of -11.25°, at a void in the metal. This smaller hole is used to mechanically align the knob to the target.

The target is manufactured as a 1.6 mm thick PCB; note that the PCB thickness does not affect system performance.

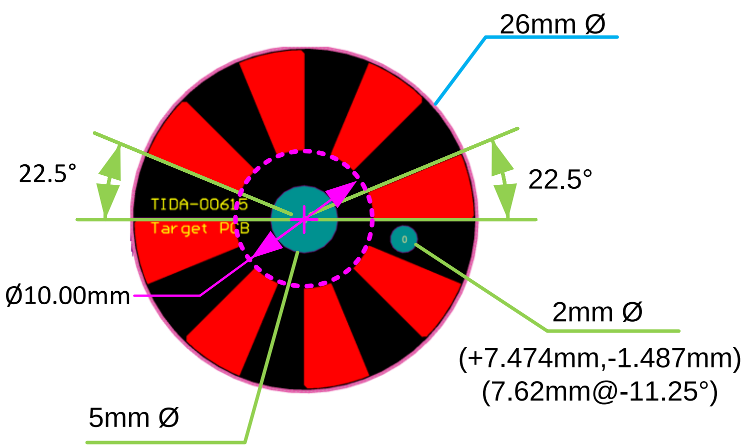


Figure 19: Target Dimensions

6.11 LDC1312 Configuration

The reference frequency for LDC1312 is provided by the LDC1312's internal oscillator. The nominal value of the internal oscillator is 40 MHz.

The sensor parameters, f_{SENSOR}= 3.7 MHz, Q = 12.5, R_P = 1.9 kΩ are used to calculate appropriate values for each register. Table 6 lists the LDC1312 register settings used in the reference design.

Sensor A is connected to channel 0 of the LDC, and Sensor B is connected to channel 1.

Table 6: Register Settings for LDC1312

Address	Value	Register Name	Comments
0x08	0x0100	RCOUNT_CH0	RCOUNT to set sample rate = 4.9kSPS
0x09	0x0100	RCOUNT_CH1	RCOUNT to set sample rate = 4.9kSPS
0x10	0x000C	SETTLECOUNT_CH0	Settling time needed by TIDA-00615 sensor
0x11	0x000C	SETTLECOUNT_CH1	Settling time needed by TIDA-00615 sensor
0x14	0x1001	CLOCK_DIVIDERS_CH0	CH0_FIN_DIVIDER = 1, CH0_FREF_DIVIDER = 1
0x15	0x1001	CLOCK_DIVIDERS_CH1	CH1_FIN_DIVIDER = 1, CH1_FREF_DIVIDER = 1
0x19	0x0000	ERROR_CONFIG	Can be changed from default to report status and error conditions
0x1A	0x1C01	CONFIG	Utilize internal oscillator, and set sensor drive current as indicated in datasheet.
0x1B	0x820D	MUX_CONFIG	Enables Ch0 and Ch1 (sequential mode), Input deglitch bandwidth set to 10MHz
0x1E	0xD800	DRIVE_CURRENT_CH0	Sets sensor drive current on Ch0
0x1F	0xD2800	DRIVE_CURRENT_CH1	Sets sensor drive current on Ch1
0x1C	0x0600	RESET_DEV	Sets the gain to 16
0x0C	0x2000	OFFSET_CH0	Offset value for Channel 0
0x0D	0x2000	OFFSET_CH1	Offset value for Channel 1
0x1A	0x1601	CONFIG	Conversion configuration

6.11.1 LDC1312 Configuration Details

The LDC1312 register settings are configured in the following manner:

1. **Set Measurement resolution**

   Setting RCOUNT to 0x0100 provides approx. 14 bits of resolution, which is sufficient for this application. Both channel 0 and channel 1 RCOUNT registers need to be set to this value.

2. **Set the settling count for sensor activation**

   Based on the datasheet recommendations, the settlecount is set as:

   $CHx\_SETTLECOUNT \geq Q \times f_{REF} / (16 \times f_{SENSOR}) \rightarrow 8.4$

   To provide margin to account for system tolerances, the settle count is set to 12 (decimal), and the SETTLECOUNT_CHx registers (0x10 & 0x11) are set to 0x000C.

3. Set Input and Reference Dividers

The sensor frequency is 3.7 MHz, which allows the sensor divider to be 1. The register field CHx_FIN_DIVIDER is therefore set to 0x1.

The LDC1312 provides the highest sample rate when the reference divider is 1. There is a device constraint that $4 \times f_{SENSOR} < f_{REF}$. With 3.7 MHz sensor and an approximately 42 MHz reference frequency, this constraint is satisfied. Therefore the reference divider can be set to 1, which is done by setting the CHx_FREF_DIVIDER field to 0x01.

The input divider and reference dividers settings share a register, which results in a combined value for the CHx divider registers (0x14 and 0x15) of 0x1001.

4. Set Clock source and interrupts

The Internal Reference oscillator is appropriate as the resolution is acceptable; therefore REF_CLK_SRC=0.

By default, no interrupts are enabled. The setting for ERROR_CONFIG results in 0x0000.

5. Set LDC1312 to continuously sample on Channel 0 and 1

MUX_CONFIG enables the continuous conversion on both channels. The input deglitch filter is set at 10 MHz, lowest setting that exceeds sensor oscillation frequency. The combined value for MUX_CONFIG register (0x1B) results in 0x1001.

6. Set sensor current drive

The drive currents are fixed as recommended by the datasheet (RP_OVERRIDE_EN=1 and AUTO_AMP_DIS=1). The drive current is set based on R_P = 1.9 kΩ. The corresponding decimal value of 27 is translated to hexadecimal 0xD800.

7. Enable higher gain setting

RESET_DEV sets the gain for the LDC1312. Setting the gain and offset registers increases the effective resolution of the LDC1312. The highest gain setting of 16 is used to achieve the maximum resolution. More information on utilizing this feature can be found on the analog wire blog post https://e2e.ti.com/blogs_/b/analogwire/archive/2015/06/24/inductive-sensing-improve-the-enob-of-a-multichannel-ldc-by-4-bits-in-3-simple-steps.

8. Set offset value

An offset value is subtracted from each DATA value to maximize the dynamic range of the sample data and allow the use of GAIN =16 without entering saturation. The offset is found during prototyping.

CONFIG register disables auto-amplitude correction and auto-calibration, enables full current drive during sensor activation, selects external clock source, and wakes up device to start conversion. This register write must occur last because device configuration is not permitted while the LDC is in active mode. The combined value results in 0x1C01.

7 Test Data

7.1 Sensor Electrical Characteristics

Sensor characteristics of inductance, quality factor, and series AC resistance were measured on an impedance analyzer over the frequency range of 0.1MHz to 14MHz. The two sensors are well-matched over that range.

Table 7: Sensor Characteristics

Parameter	EVM Sensor Value
Outer Diameter of 1 segment, long side	226 mils (5.7 mm)
Inner Diameter of 1 segment, long side	129 mils (3.28 mm)
Number of Sections	4
Number of Turns (on one layer)	6
Trace Width	4 mils (0.102 mm)
Trace Spacing	4 mils (0.102 mm)
Number of layers	4
Trace Thickness	1 oz-cu (35 µm)
Inductance@ 3 MHz	5.6 µH
Sensor Capacitance	330 pF
f_{SENSOR} (no target)	3.7 MHz
R_p@ 3 MHz (no target)	1.9 kΩ
Q@ 3 MHz	12.5
Approx. $C_{PARASITIC}$	3.4 pF
Self-Resonant Frequency (SRF)	36 MHz

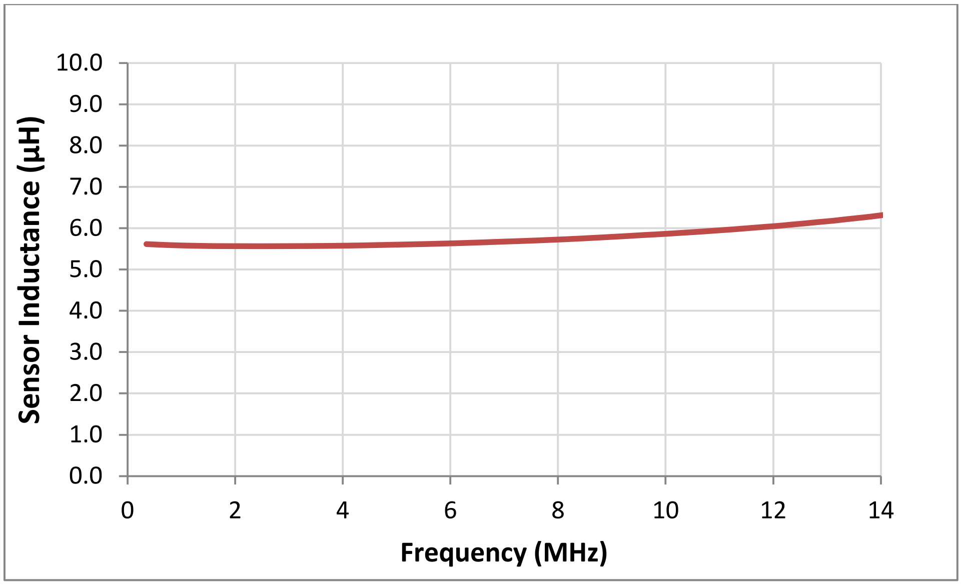


Figure 20: Inductance (μH) vs. Frequency (MHz) of sensors

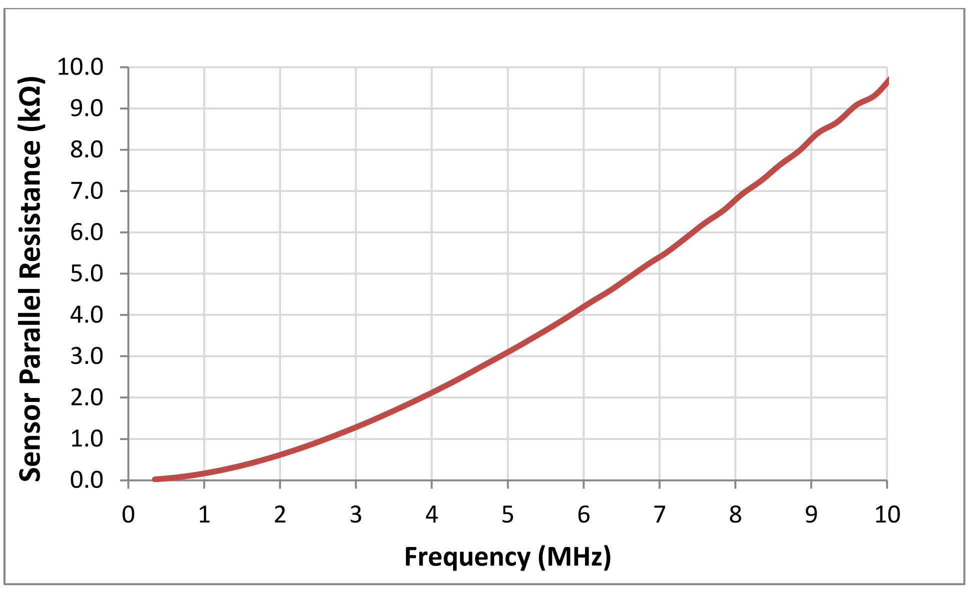


Figure 21: Parallel Resistance [Ω] vs. Frequency sweep of each coil series

At the operating frequency of 3.7 MHz, the sensors have a Q of 12.5 and a series resistance of 8.6 Ω. This corresponds to an R_P of 1.9 kΩ, which can be easily driven by the LDC1312.

7.2 Angular Resolution

The change in sensor inductance over a full rotation was evaluated using a precision rotation stage as shown in Figure 22. The target PCB and sensor PCB were isolated from any conductive materials and precisely positioned.

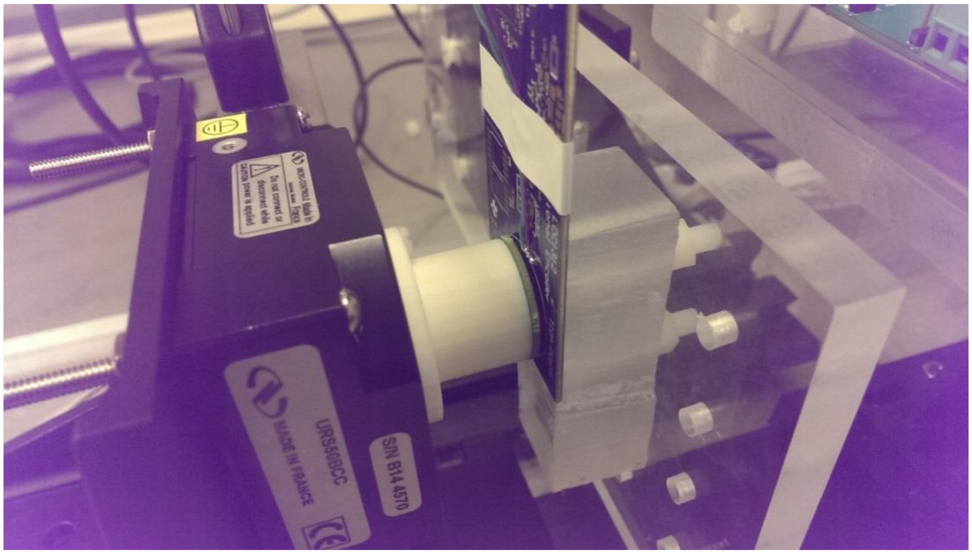


Figure 22: System used to measure rotational accuracy

The sensors response vs. knob angle is shown in Figure 23. The 8 sections of the target result in 8 sinusoidal responses across a 360° rotation of the target.

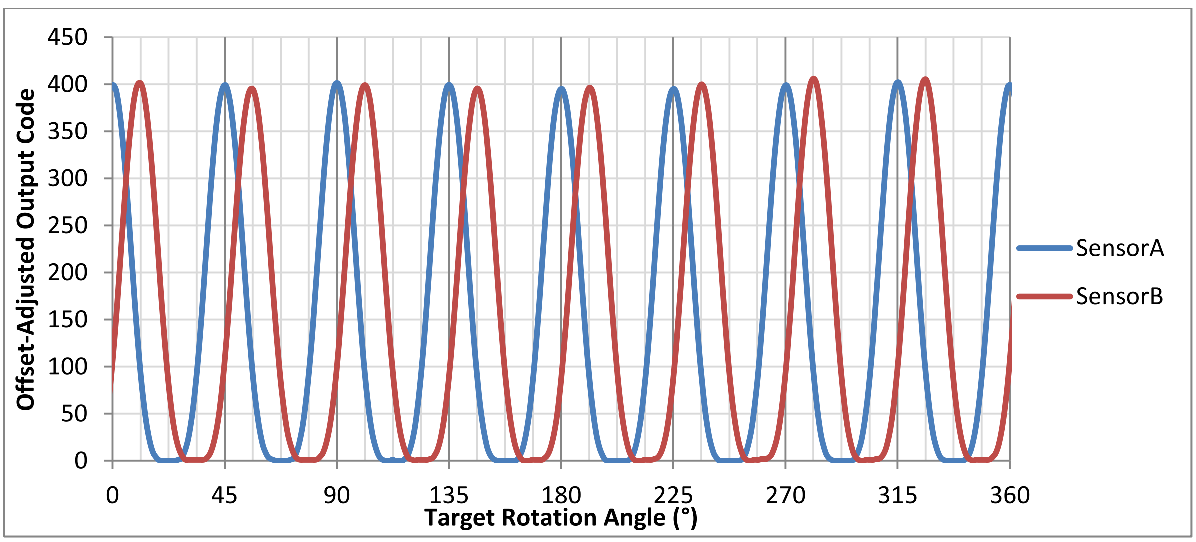


Figure 23: Output code variation due to target rotation at 0.5mm distance

By performing an FFT on the two waveforms, we find that the angular separation between Sensor A and Sensor B response is 88.7°.

The shift in output codes corresponds to a change of inductance of 0.749µH when the target is 0.5mm from the sensor.

When the target-sensor distance is increased to 1.0mm, the signal amplitude decreases by 57% (Sensor A drops from 99.7 codes to 56.8 codes), as shown in Figure 24.

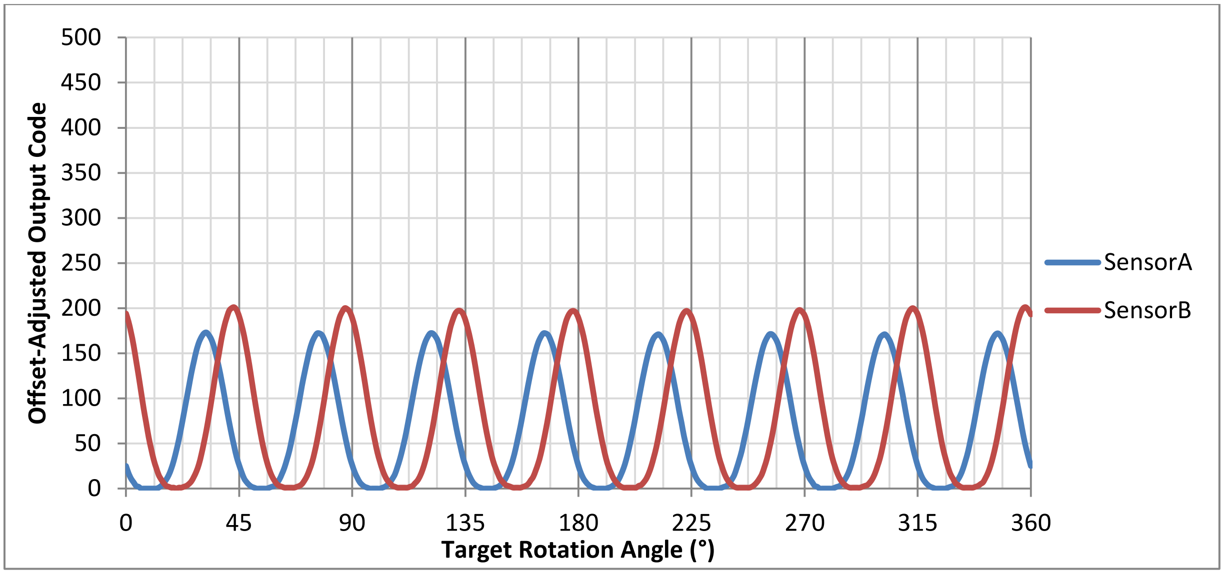


Figure 24: Output code variation due to target rotation at 1.0mm distance

The sensor noise floor is measured simply by measuring the standard deviation of the outputs when the knob is held in a static position, and is shown in Figure 25 and Figure 26. The sensors have a standard deviation of less than 0.5 codes, which corresponds to a standard deviation of less than 1 nH; this is results in a SNR of ~750:1 when the sensor-target distance is 0.5mm. At 1 mm distance, the SNR is 344:1, which provides a clear differentiation between the encoder signal and any noise.

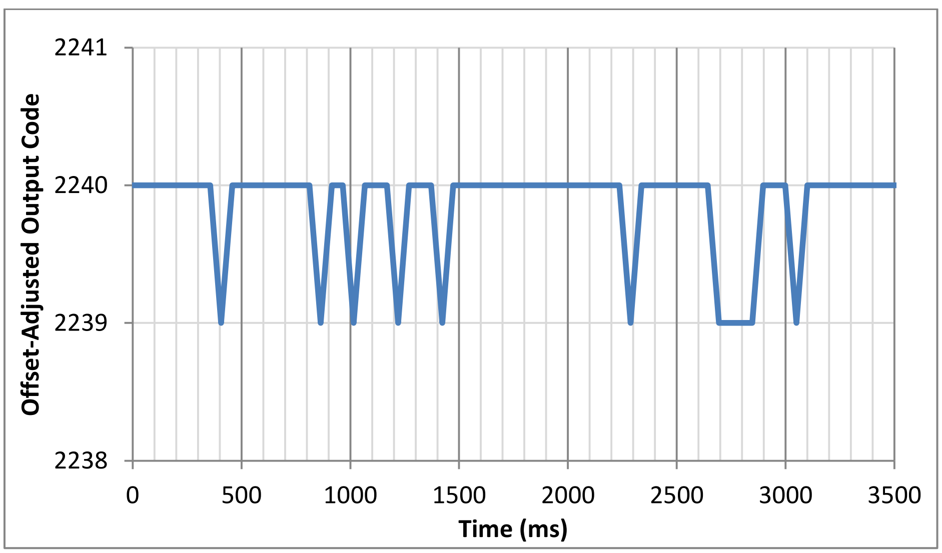


Figure 25: Sensor A Noise Level

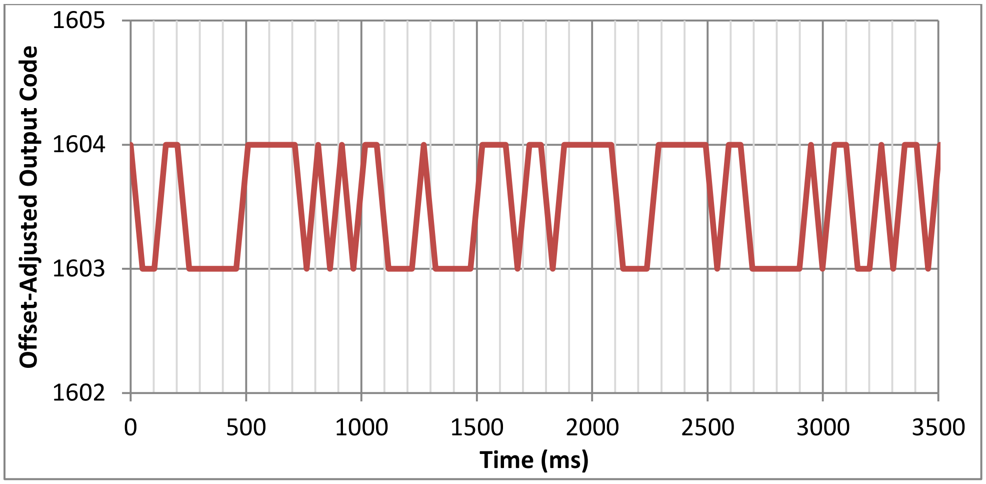


Figure 26: Sensor B Noise Level

8 Signal Processing

8.1 Microcontroller Requirements

TIDA-00615 uses a MSP430F5528 microcontroller as its central processor. The primary consideration for this selection was to maintain build environment consistency with the LDC1312EVM and other LDC EVMs. The MSP430F5528 has more than sufficient memory, processor power, and peripherals necessary to support the LDC1312 encoder knob, and also provides a USB interface to a PC.

Since most systems will not require a USB peripheral, the microcontroller requirements can be reduced significantly. Minimum microcontroller requirements are:

1. Flash Memory Used: <800 Bytes
2. RAM/FRAM Used: 40 Bytes (5x UINT16_t and 5x UINT8_t)
3. Peripherals: 1 I2C interface

8.2 Algorithm

The algorithm used in TIDA-00615 is straight-forward. The LDC1312 continuously samples the 2 sensors, and if the conversion result changes by a sufficient magnitude, the algorithm determines which sensor is at a peak or valley, and the phase difference between the two channels. This data is sufficient to determine an event occurrence and also the direction of rotation.

Some of the advantages of this algorithm are that it requires no calibration, handles any slow moving drift which can occur due to temperature variation, and it requires minimal RAM and Flash. Using an average of 490 instructions to execute one cycle of algorithm on the MSP430 MCU, the algorithm can support 300RPM+ rotation rates for a 5ms response with only 0.1 MIPS.

The algorithm can operate reliably with angular offsets between the target sensor array, and also imperfect quadrature positioning of the sensors.

The flowchart of the algorithm is shown in Figure 27.

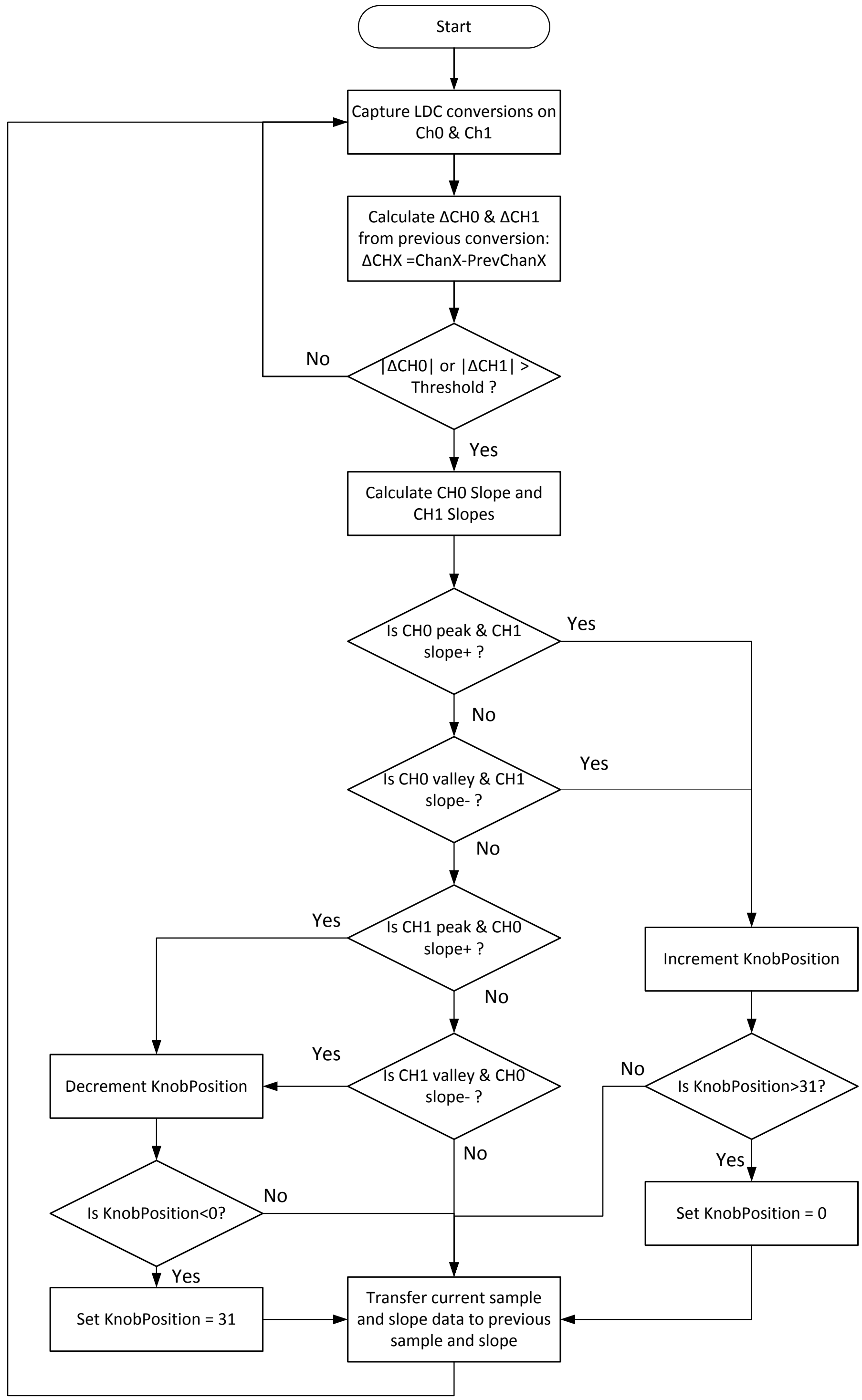


Figure 27: Algorithm Flowchart

Table 8: Firmware Variables list

Variable	Type	Functionality
meas_ch0	uint16_t	current LDC output code for channel 0 (Sensor A)
meas_ch1	uint16_t	current LDC output code for channel 1 (Sensor B)
previous_ch0	uint16_t	previous LDC output code for channel 0 (Sensor A)
previous_ch1	uint16_t	previous LDC output code for channel 1 (Sensor B)
diff_ch0	uint16_t	difference between meas_ch0 and previous_ch0
diff_ch1	uint16_t	difference between meas_ch1 and previous_ch1
knob_position	uint8_t	Current position of knob
direction_ch0	Boolean	slope of channel 0 (increasing or decreasing)
direction_ch1	Boolean	slope of channel 1 (increasing or decreasing)
prev_direction_ch0	Boolean	previous slope of channel 0 (increasing or decreasing)
prev_direction_ch1	Boolean	previous slope of channel 1 (increasing or decreasing)
threshold	constant	Minimum LDC code change needed to indicate position change

8.3 System Response with example data

Figure 28 shows the LDC1312 output codes and the calculated knob position vs. time. At ~0.4 sec, the Sensor B trace has a step which corresponds to a clockwise rotation of the knob. The algorithm therefore increments the knob position based on this step. At time 1.3 sec, the change in sensor A indicates a second rotation on the knob. The falling edge on Sensor B at 1.75 sec corresponds to a third rotation.

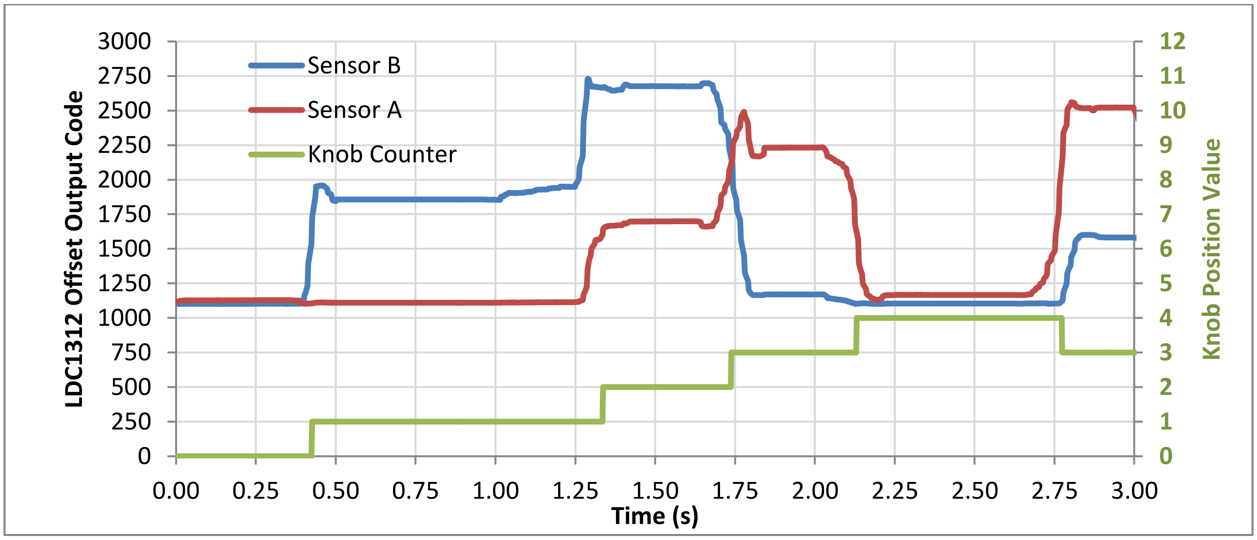


Figure 28: Example Sensor Data with Knob Position Value

9 Design Files

These materials are provided at http://www.ti.com/tool/TIDA-00615

9.1 Schematics

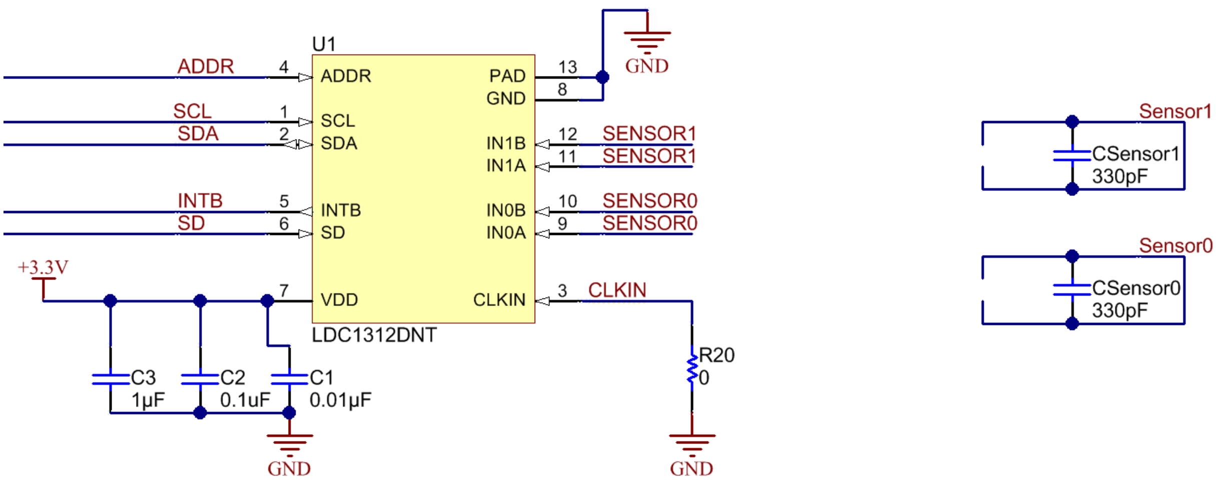


Figure 29: LDC1312 and Sensor

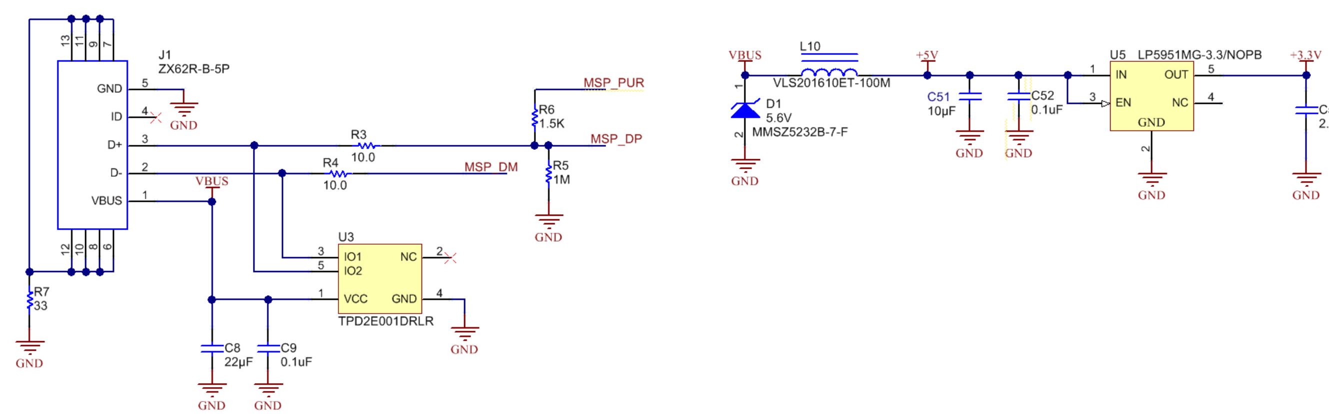


Figure 30: USB Interface and Power Management

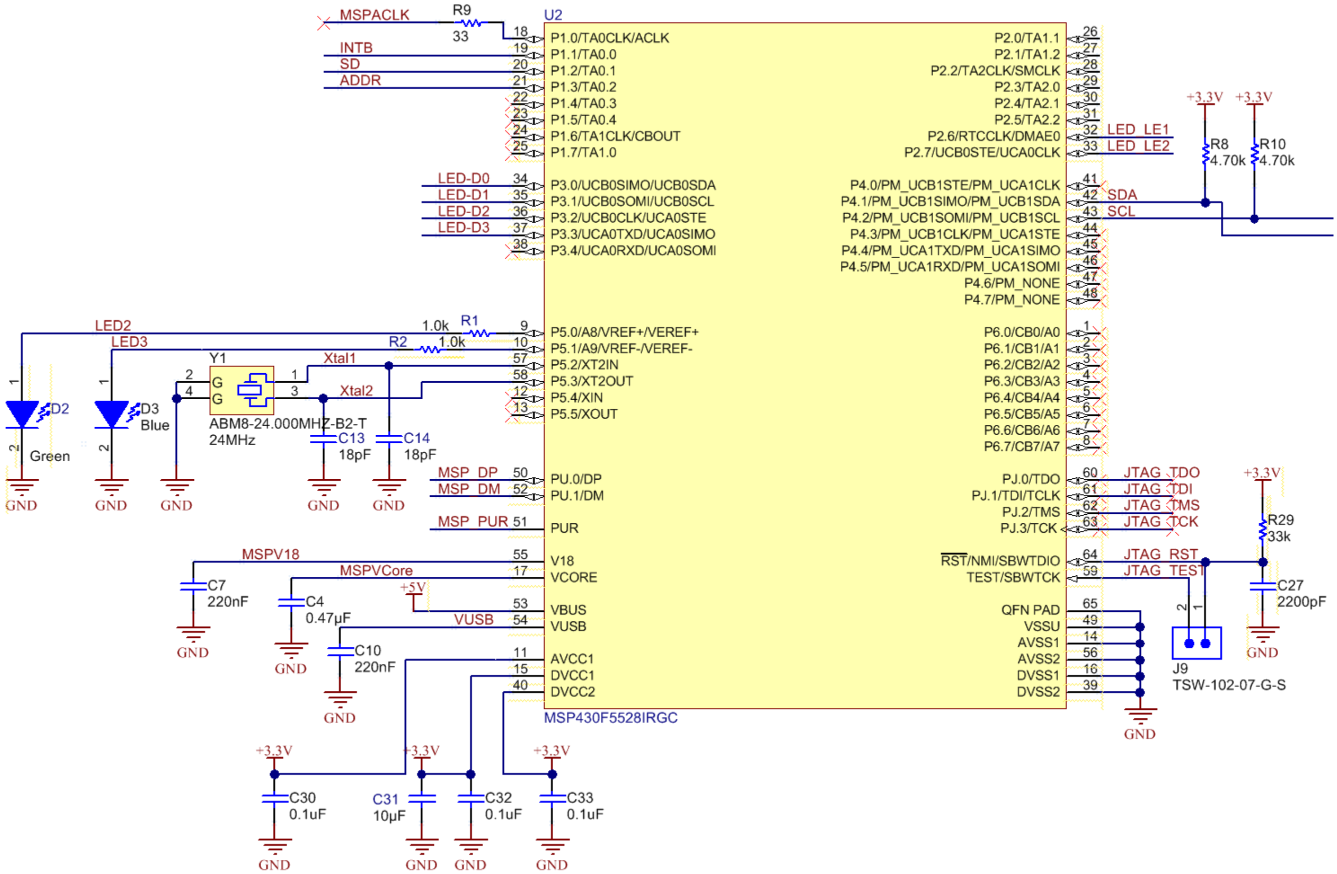


Figure 31: MSP430 Connections

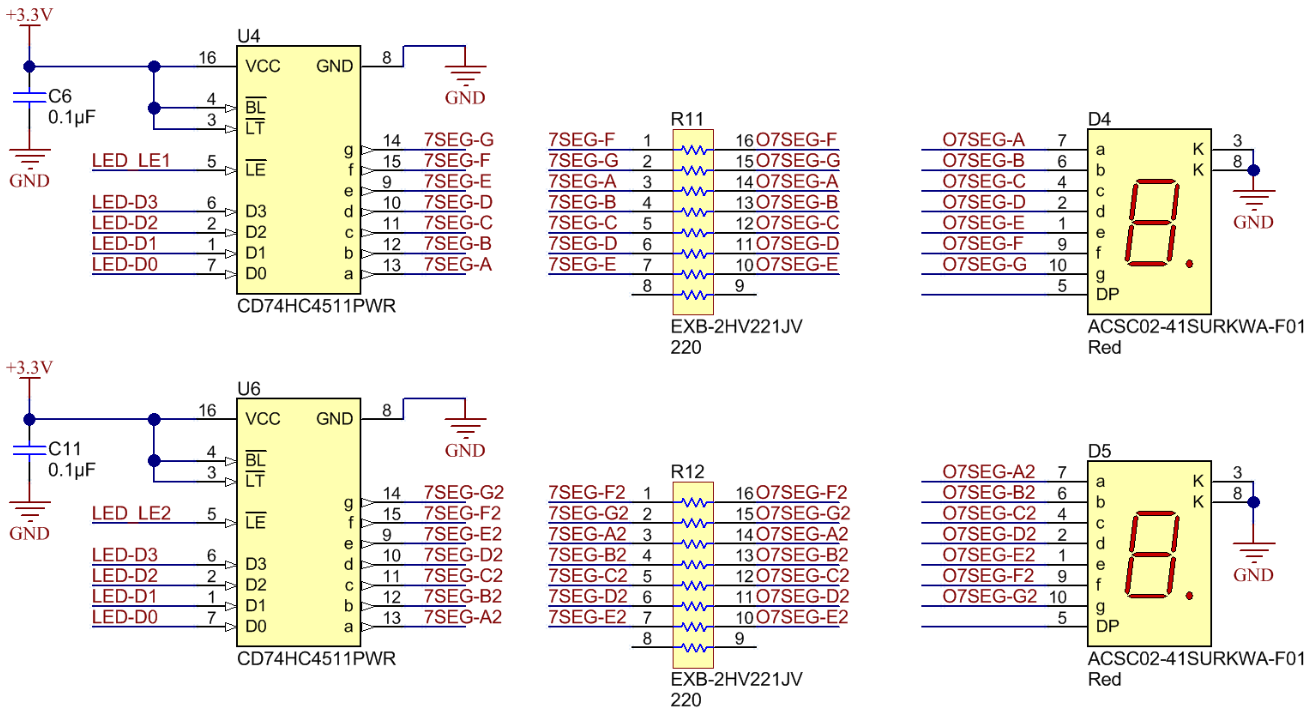


Figure 32: 7 Segment Displays and Drivers

9.2 Bill of Materials

Table 9: Sensor PCB BOM

Item	Designator	Description	Manufacturer	Part Number	Qty
1	!PCB1	Printed Circuit Board	Any	TIDA-00615	1
2	C1	CAP, CERM, 0.01 µF, 16 V, +/- 10%, X7R, 0402	TDK	C1005X7R1C103K	1
3	C2	CAP CER 0.1UF 16V 5% X7R 0402	Murata Electronics North America	GRM155R71C104JA88D	1
4	C3	CAP, CERM, 1uF, 10V, +/-10%, X5R, 0402	MuRata	GRM155R61A105KE15D	1
5	C4	CAP, CERM, 0.47 µF, 6.3 V, +/- 10%, X5R, 0402	MuRata	GRM155R60J474KE19D	1
6	C6	CAP, CERM, 0.1 µF, 50 V, +/- 10%, X7R, 0402	TDK	C1005X7R1H104K	1
7	C7	CAP, CERM, 220nF, 10V, 10%, X7R, 0402	TDK Corporation	C1005X7R1A224K050BB	1
8	C8	CAP, CERM, 22uF, 16V, +/-10%, X5R, 0805	TDK	C2012X5R1C226K125AC	1

Item	Designator	Description	Manufacturer	Part Number	Qty
9	C9	CAP CER 0.1UF 16V 5% X7R 0402	Murata Electronics North America	GRM155R71C104JA88D	1
10	C10	CAP, CERM, 220nF, 10V, 10%, X7R, 0402	TDK Corporation	C1005X7R1A224K050BB	1
11	C11	CAP, CERM, 0.1 µF, 50 V, +/- 10%, X7R, 0402	TDK	C1005X7R1H104K	1
12	C13	CAP, CERM, 18pF, 100V, +/-5%, C0G/NP0, 0603	MuRata	GRM1885C2A180JA01D	1
13	C14	CAP, CERM, 18pF, 100V, +/-5%, C0G/NP0, 0603	MuRata	GRM1885C2A180JA01D	1
14	C27	CAP, CERM, 2200pF, 50V, +/-10%, X7R, 0603	Kemet	C0603X222K5RACTU	1
15	C30	CAP CER 0.1UF 16V 5% X7R 0402	Murata Electronics North America	GRM155R71C104JA88D	1
16	C31	CAP, CERM, 10uF, 10V, +/-20%, X5R, 0603	TDK	C1608X5R1A106M	1
17	C32	CAP CER 0.1UF 16V 5% X7R 0402	Murata Electronics North America	GRM155R71C104JA88D	1
18	C33	CAP CER 0.1UF 16V 5% X7R 0402	Murata Electronics North America	GRM155R71C104JA88D	1
19	C51	CAP, CERM, 10uF, 10V, +/-20%, X5R, 0603	TDK	C1608X5R1A106M	1
20	C52	CAP CER 0.1UF 16V 5% X7R 0402	Murata Electronics North America	GRM155R71C104JA88D	1
21	C53	CAP, CERM, 2.2uF, 10V, +/-10%, X5R, 0603	Kemet	C0603C225K8PACTU	1
22	CSensor0	CAP, CERM, 330pF, 50V, +/-1%, C0G/NP0, 0603	TDK	C1608C0G1H331F080AA	1
23	CSensor1	CAP, CERM, 330pF, 50V, +/-1%, C0G/NP0, 0603	TDK	C1608C0G1H331F080AA	1
24	D1	Diode, Zener, 5.6V, 500mW, SOD-123	Diodes Inc.	MMSZ5232B-7-F	1
25	D2	LED, Green, SMD	OSRAM	LG L29K-G2J1-24-Z	1
26	D3	LED, Blue, SMD	OSRAM	LB Q39G-L2N2-35-1	1
27	D4	LED, Red, SMD	Kingbright	ACSC02-41SURKWA-F01	1
28	D5	LED, Red, SMD	Kingbright	ACSC02-41SURKWA-F01	1
29	J1	Connector, Receptacle, Micro-USB Type B, SMT	Hirose Electric Co.	ZX62R-B-5P	1

Item	Designator	Description	Manufacturer	Part Number	Qty
30	L10	Inductor, Shielded, Ferrite, 10 µH, 0.4 A, 1.38 ohm, SMD	TDK	VLS201610ET-100M	1
31	LBL1	Thermal Transfer Printable Labels, 0.650" W x 0.200" H - 10,000 per roll	Brady	THT-14-423-10	1
32	R1	RES, 1.0k ohm, 5%, 0.063W, 0402	Vishay-Dale	CRCW04021K00JNED	1
33	R2	RES, 1.0k ohm, 5%, 0.063W, 0402	Vishay-Dale	CRCW04021K00JNED	1
34	R3	RES, 10.0, 1%, 0.063 W, 0402	Vishay-Dale	CRCW040210R0FKED	1
35	R4	RES, 10.0, 1%, 0.063 W, 0402	Vishay-Dale	CRCW040210R0FKED	1
36	R5	RES,1M ohm, 5%, 0.063W, 0402	Yageo	RC0402JR-071ML	1
37	R6	RES 1.5K OHM 1/16W 5% 0402 SMD	Vishay Dale	CRCW04021K50JNED	1
38	R7	RES, 33 ohm, 5%, 0.1W, 0603	Vishay-Dale	CRCW060333R0JNEA	1
39	R8	RES, 4.70 k, 1%, 0.1 W, 0402	Panasonic	ERJ-2RKF4701X	1
40	R9	RES, 33 ohm, 5%, 0.1W, 0603	Vishay-Dale	CRCW060333R0JNEA	1
41	R10	RES, 4.70 k, 1%, 0.1 W, 0402	Panasonic	ERJ-2RKF4701X	1
42	R11	RES, 220, 5%, 0.0625 W, Resistor Array - 8x1	Panasonic	EXB-2HV221JV	1
43	R12	RES, 220, 5%, 0.0625 W, Resistor Array - 8x1	Panasonic	EXB-2HV221JV	1
44	R29	RES, 33k ohm, 5%, 0.063W, 0402	Vishay-Dale	CRCW040233K0JNED	1
45	U1	Multi-Channel 12/16-Bit Inductance to Digital Converter with I2C, DNT0012B	Texas Instruments	LDC1312DNT	1
46	U2	Mixed Signal Microcontroller, RGC0064B	Texas Instruments	MSP430F5528IRGC	1
47	U3	Low-Capacitance + / - 15 kV ESD-Protection Array for High-Speed Data Interfaces, 2 Channels, -40 to +85 degC, 5-pin SOT (DRL), Green (RoHS & no Sb/Br)	Texas Instruments	TPD2E001DRLR	1
48	U4	High Speed CMOS Logic BCD-to-7-Segment Latch / Decoder / Driver, 2 to 6 V, 16-pin SOP, Green (RoHS & no Sb/Br)	Texas Instruments	CD74HC4511PWR	1
49	U5	Micropower, 150mA Low-Dropout CMOS Voltage Regulator, 5-pin SC-70, Pb-Free	Texas Instruments	LP5951MG-3.3/NOPB	1

Item	Designator	Description	Manufacturer	Part Number	Qty
50	U6	High Speed CMOS Logic BCD-to-7-Segment Latch / Decoder / Driver, 2 to 6 V, 16-pin SOP, Green (RoHS & no Sb/Br)	Texas Instruments	CD74HC4511PWR	1
51	Y1	Crystal, 24.000MHz, 18pF, SMD	Abracon Corp	ABM8-24.000MHZ-B2-T	1
52	J9	Header, TH, 100mil, 2x1, Gold plated, 230 mil above insulator	Samtec, Inc.	TSW-102-07-G-S	0
53	R20	RES, 0 ohm, 5%, 0.1W, 0603	Vishay-Dale	CRCW06030000Z0EA	0

9.3 PCB Layout Recommendations

Table 10: Sensor PCB Layer Usage

Layer	Functionality
Top	Signals, Components, and ground-fill
Mid-layer 1	Ground
Mid-layer 2	Power
Bottom	Signals and ground-fill

Table 11: Sensor PCB Stack-up

Layer	Name	Material	Thickness	Constant	Board Layer Stack
1	Top Overlay				
2	Top Solder	Solder Resist	0.40mil	3.5	
3	Top Layer	Copper	1.40mil		
4	Dielectric1	FR-4	12.60mil	4.8	
5	Mid-Layer 1	Copper	1.40mil		
6	Dielectric3	FR-4	32.00mil	4.8	
7	Mid-Layer 2	Copper	1.40mil		
8	Dielectric2	FR-4	12.60mil	4.8	
9	Bottom Layer	Copper	1.40mil		
10	Bottom Solder	Solder Resist	0.40mil	3.5	
11	Bottom Overlay				

9.3.1 Layout Prints

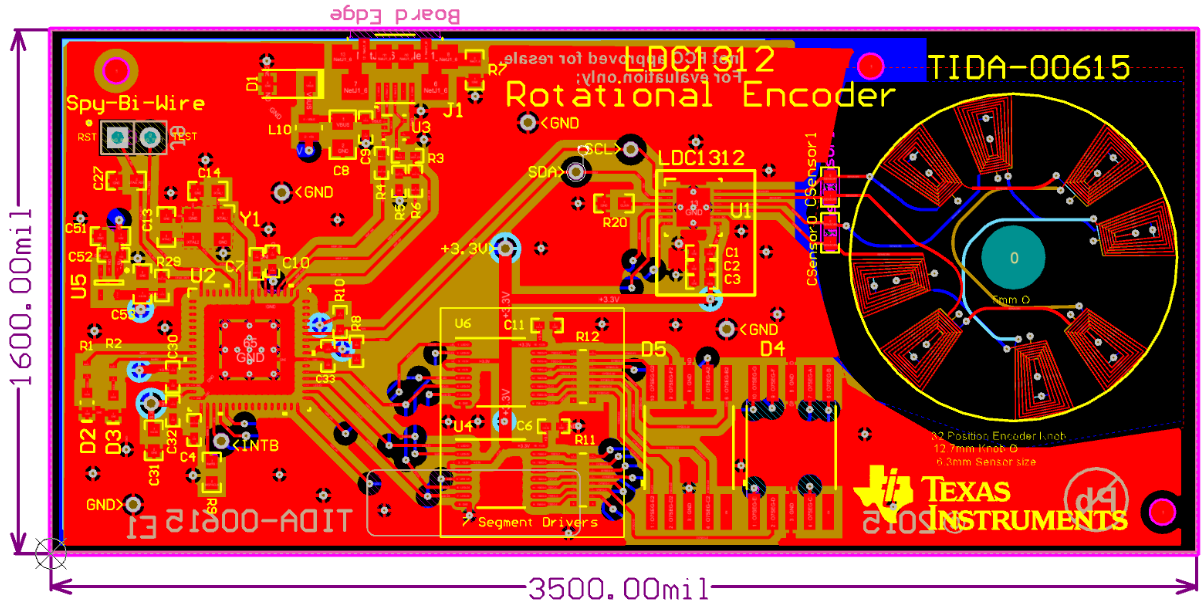


Figure 33: Multi-layer Sensor Print

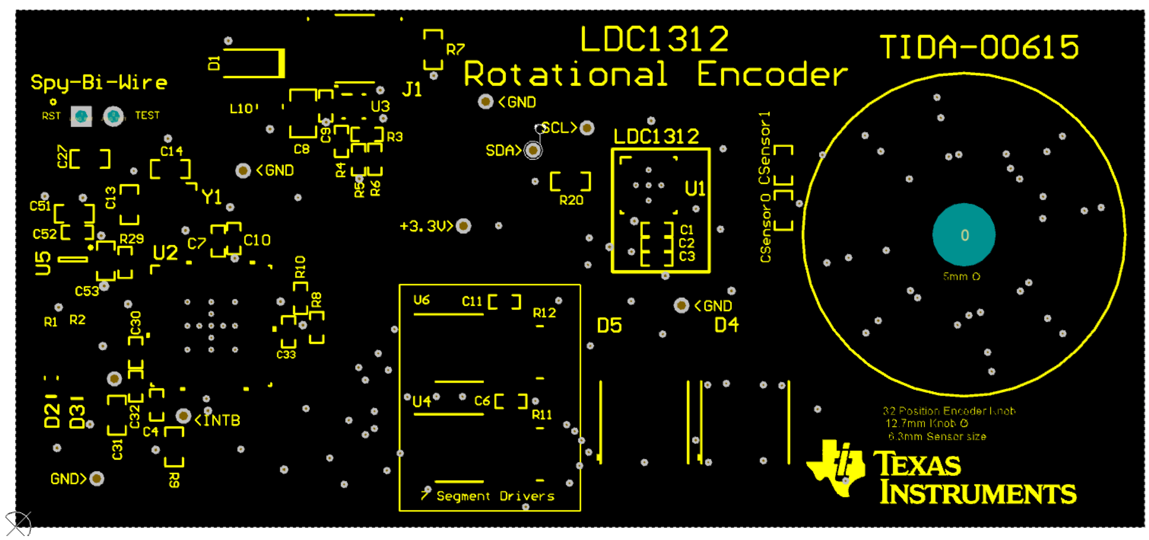


Figure 34: Sensor PCB Top Silkscreen

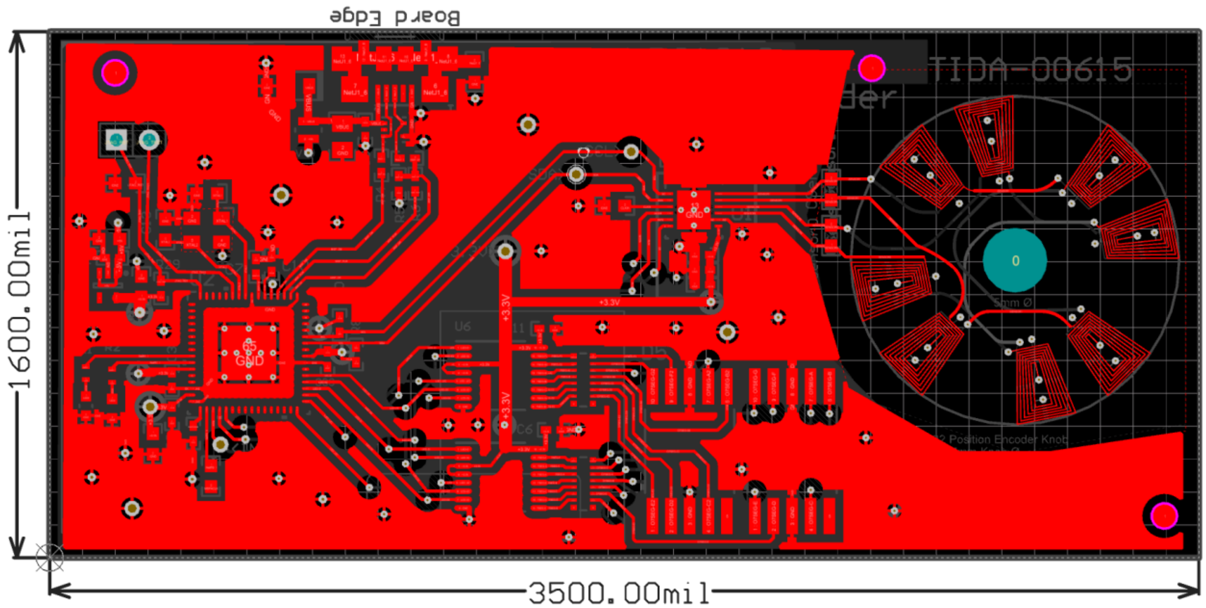


Figure 35: Sensor PCB Top Layer Routing

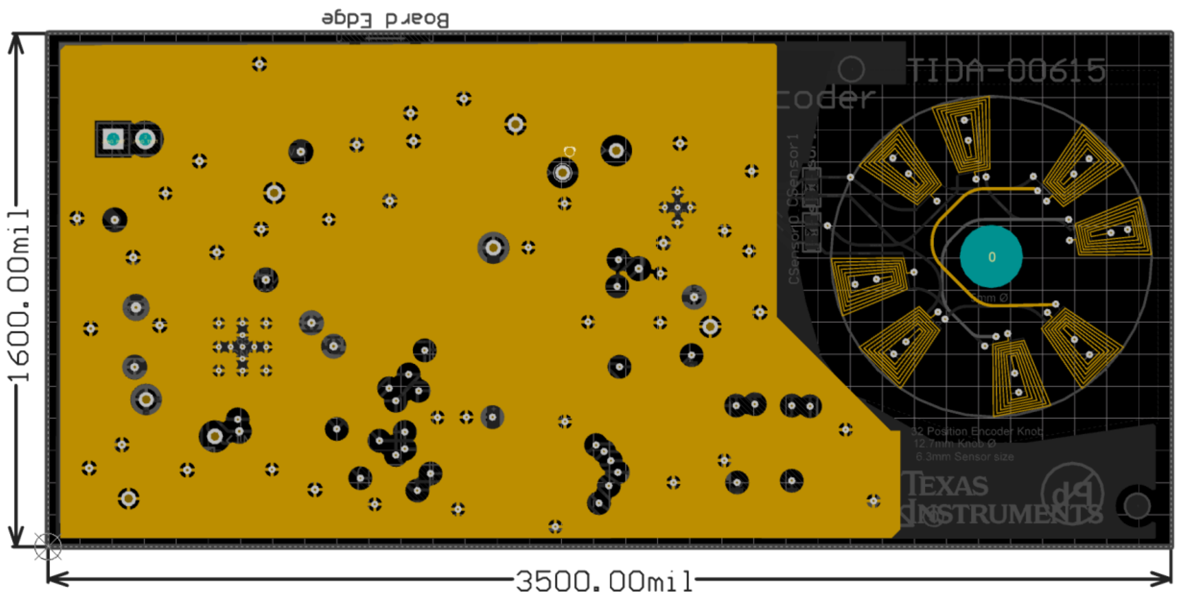


Figure 36: Sensor PCB Midlayer1 Routing

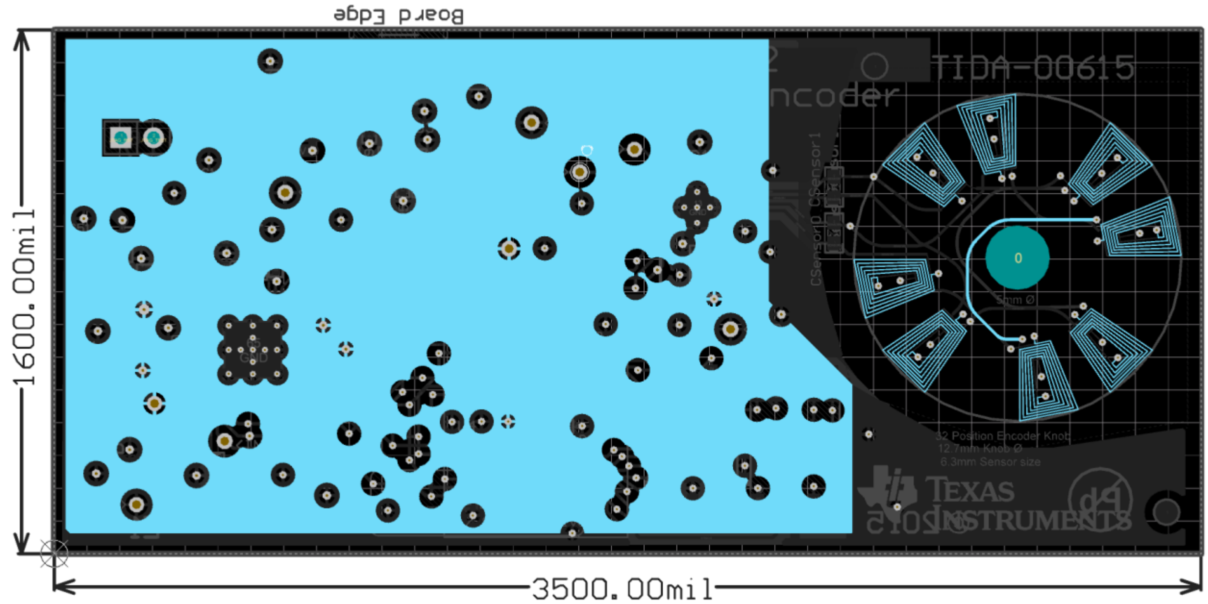


Figure 37: Sensor PCB Midlayer2 Routing

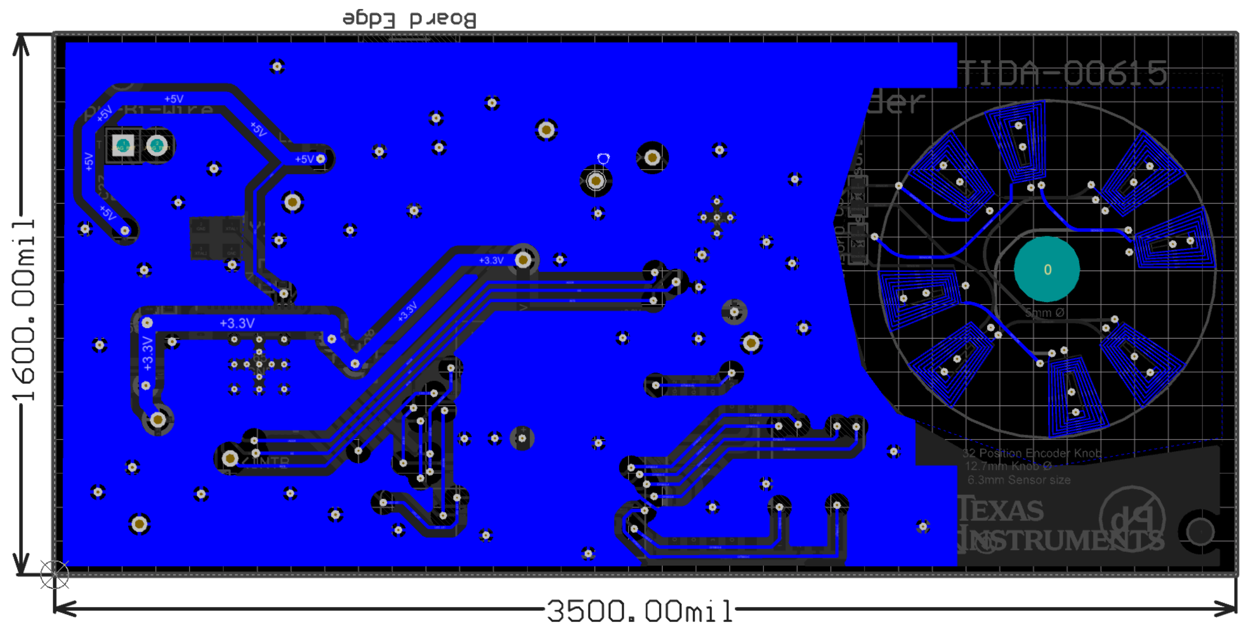


Figure 38: Sensor PCB Bottom Layer Routing

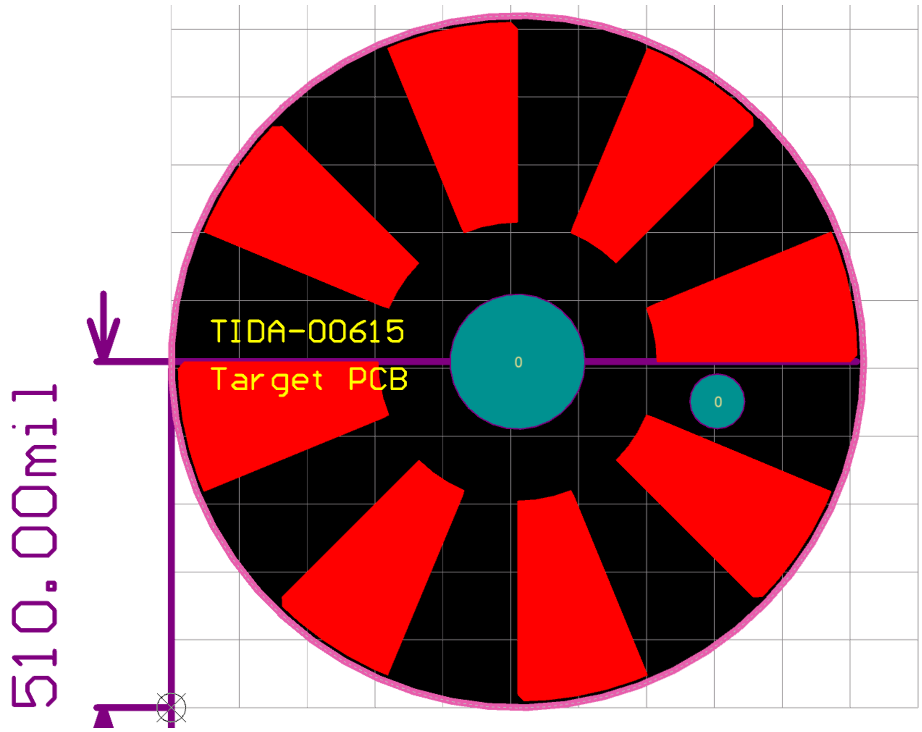


Figure 39: Target PCB Top Layer Routing

9.4 Altium Project

To download the Altium project files for each board, see the design files at http://www.ti.com/tool/TIDA-00615.

9.5 Layout Guidelines

Sensor routing uses 4 mil (0.102 mm) trace width and spacing. For designs using 5 mil (0.128 mm) geometries, the sensor inductance will decrease. This can be compensated for by increasing the area of the inductors (which would increase the size of the knob), adding additional series inductor sections, or increasing the sensor frequency.

Minimize the amount of traces and board fills near the sensor. Place the sensor capacitors as close as possible to the inductor.

9.6 Assembly Drawings

To download the Assembly Drawings for each board, see the design files at http://www.ti.com/tool/TIDA-00615

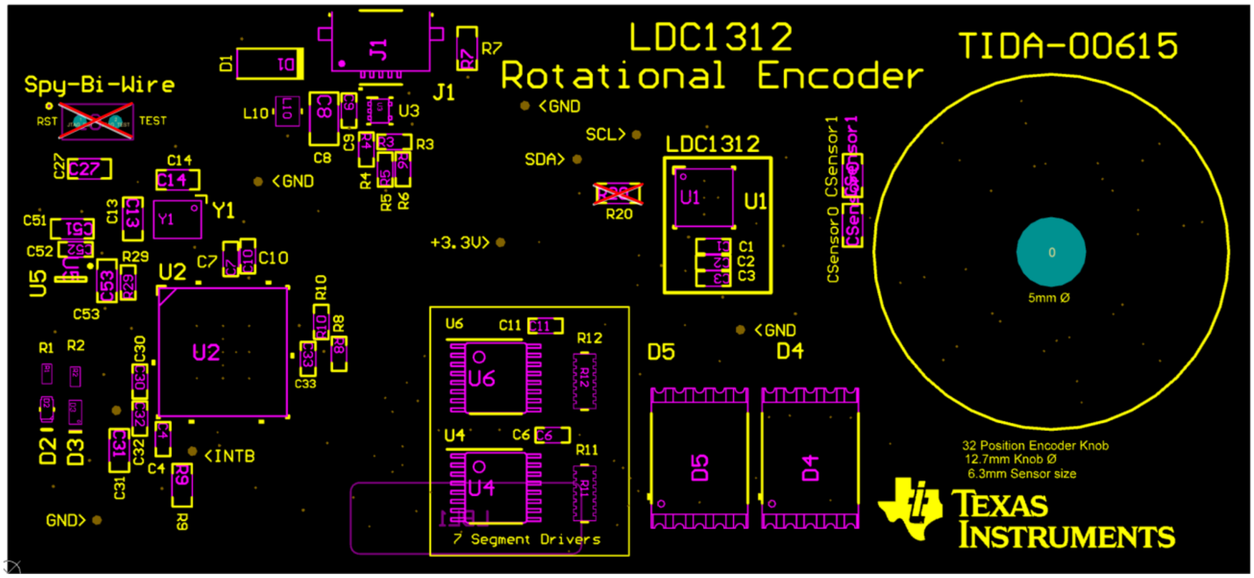


Figure 40: Sensor PCB Assembly Drawing

10 Mechanical Design Files

To download the mechanical design files, see the design files at http://www.ti.com/tool/TIDA-00615

10.1 Mechanical Components

The knob is composed of 5 pieces, as shown below. All dimensions in mm. Mechanical components were designed and selected to provide basic functionality and were not optimized for reliability or manufacturing.

Table 12: Component Material Composition

Item	Description	Composition
1	Knob	ABS Plastic
2	Target PCB	FR4
3	Sensor PCB	FR4
4	Index Wheel	ABS Plastic
5	Indexer	Nylon

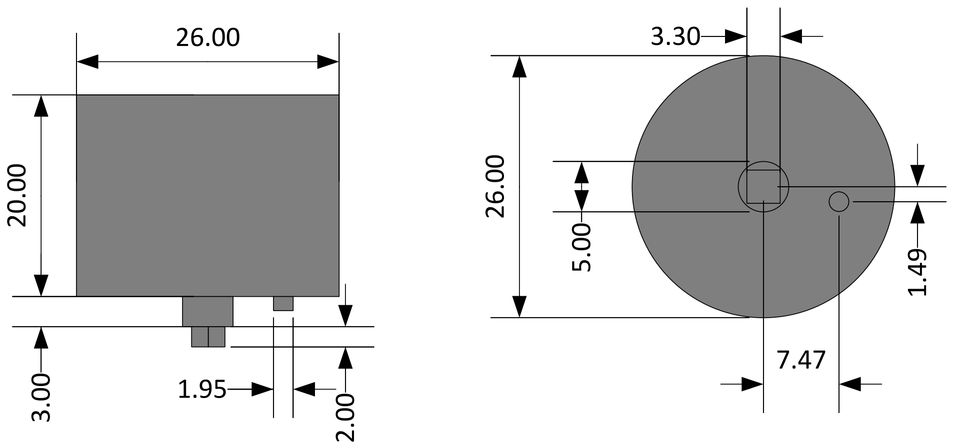


Figure 41: Knob

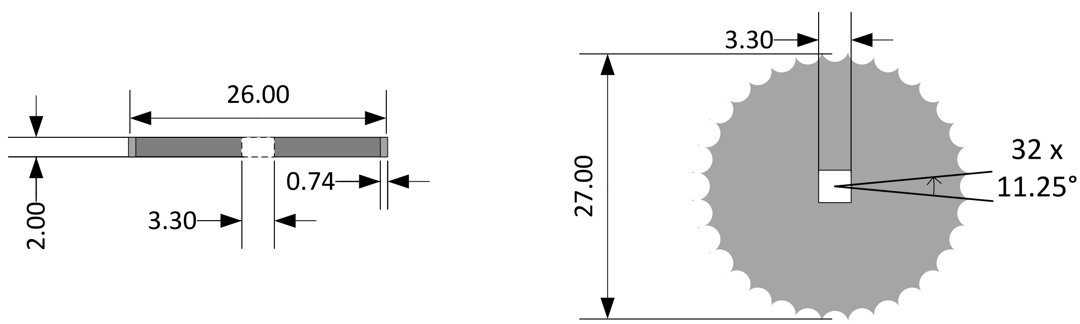


Figure 42: Index Wheel

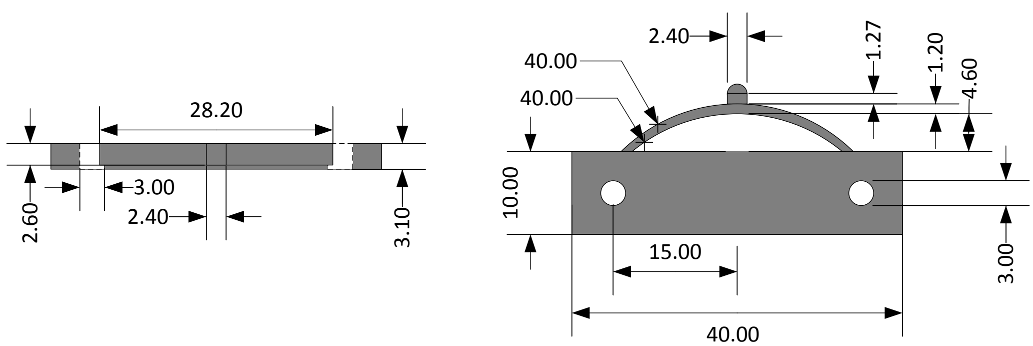


Figure 43: Indexer

10.2 Mechanical Assembly Sequence

Assembly is performed in the following sequence:

1) The Target PCB is attached to the Knob using double-sided adhesive tape. Note that the Target PCB and the Knob are keyed for proper alignment.
2) The Knob+Target PCB assembly is then inserted into the 5mm diameter hole on the Sensor PCB.
3) The Index Wheel is attached to the Knob+Target PCB assembly and adhered using cyanoacrylate.
4) The Indexer is aligned to the index wheel and attached to the bottom of the Sensor PCB using double-sided adhesive.

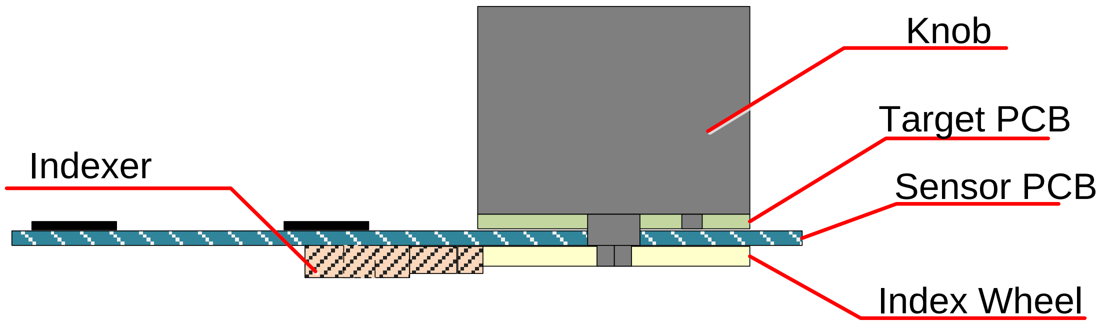


Figure 44: Mechanical Assembly

11 Software Files

To download the software files for this reference design, please see the link at http://www.ti.com/tool/TIDA-00615

12 References

1. S. S. Mohan, M.del Mar Hershenson, S. P. Boyd, and T. H. Lee, "Simple Accurate Expressions for Planar Spiral Inductances," IEEE JOURNAL OF SOLID-STATE CIRCUITS, vol. 34, no. 10, pp 1419-1424, Oct. 1999.
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3. Texas Instruments WEBENCH® Design Center, http://www.ti.com/webench
4. Texas Instruments E2E Community, http://e2e.ti.com/

13 About the Author

Chris Oberhauser is an Applications Engineer at Texas Instruments, where he is responsible for supporting Inductive sensing applications and developing reference designs and new products. Chris has extensive experience in mixed-signal, analog, and RF device level testing and applications expertise. Chris earned his Bachelors of Science in Electrical Engineering (BSEE) from the Rochester Institute of Technology, Rochester, NY, and has worked at Texas Instruments for over 11 years.

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