TI Designs

LDC0851 Incremental Rotary Encoder

Design Overview

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

Design Resources

TIDA-00828	Design Folder
LDC0851	Product Folder
MSP430F5500	Product Folder
LP5951	Product Folder
TPD2E001	Product Folder

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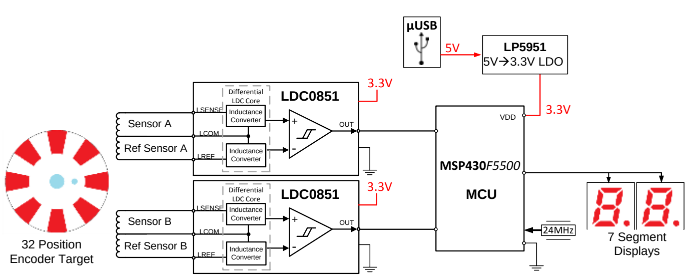
Design Features

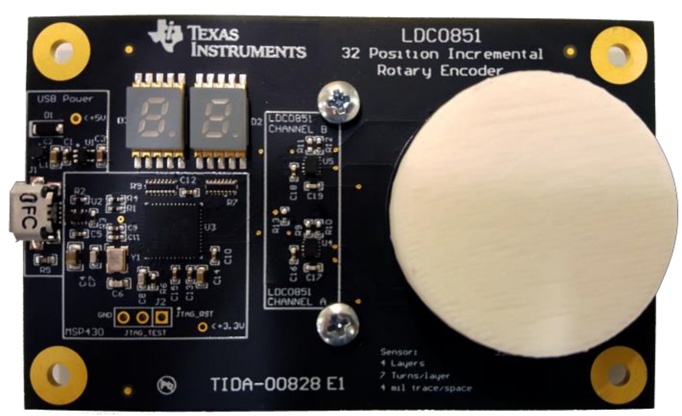
- Contactless, high reliability incremental position knob using LDC technology
- No calibration required
- Power consumption of <6mA (excluding MCU & LED indicators)
- Sensor and knob can be placed remotely with respect to LDC0851 device
- 32 steps/rotation
  - design can scale to support multiples of 4 positions
- Rotation Speed Measurement of >2000 RPM
- External magnets will not affect functionality
- Minimal MCU memory and instructions:
  - 1 byte of RAM
  - 208 bytes of ROM/Flash

Featured Applications

- Automotive Center Control Panels
- Rolling jog wheels
- Appliance interfaces, including cooktops and cleaning appliances
- Home audio and consumer electronics
- Industrial System control

Block Diagram





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1 Key System Specifications

Parameter	Specification
Physical Dimensions	86.6 x 54 x 19.5 mm
Knob Dimensions	35 Ø x 10 mm
Sensor Geometry	2 x 8.6 mm matched trapezoidal inductors
Sensor Inductance (no target interaction)	2.32 µH
Sensor Frequency (no target interaction)	16.7 MHz
Sensor Inductance (maximum target interaction)	2.09 µH
Sensor Frequency (maximum target interaction)	17.6 MHz
Total Sensor Capacitance	78 pF
Rotational Resolution	32 Positions/Revolution (11.25° /Position)
Target to Sensor distance	0.82 mm
Total current consumption (excluding 7-segment LED)	6.23 mA
LDC0851 Current consumption	2.7 mA (per device)
Operating Temperature	-40°C to +85°C

2 System Description

Historically, rotary encoder knobs have been implemented using mechanical contact-based systems. These systems are prone to reliability issues and consequently may require expensive replacement over their lifetimes due to wear of moving parts. Alternate solutions using optical sensing are not immune to dirt and dust, which pose lifetime issues in many automotive and industrial applications. Magnetic sensing, while immune to dirt and dust, is affected by magnetic interference making it unreliable.

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. The *Incremental Rotary Encoder Using Inductive-to-Digital Converter Switch,* described in this design guide, offers a low cost and robust solution targeted for implementing knobs, dials, and encoders in various industrial, consumer, and automotive applications.

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

Two LDC0851s are used to sense the change in knob position. When the knob position causes the LDC0851 output to switch, the MCU determines the new knob position, and displays the new knob position using the 7 segment LED displays.

The design is composed of a sensor PCB, which contains all of the electrical components, a simple 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. For this design, power is supplied by the 5V USB connection and regulated to 3.3V for the MSP430 MCU and LDC0851.

Figure 1: System Assembly

2.1 Inductance Comparator Switch

The LDC0851, an Inductance Comparator switch, measures the inductive shifts of the reference and sense coils. The switch output is pulled down when the inductance of the sense coil drops below the inductance of the reference coil.

2.2 Microcontroller

The Microcontroller unit, MSP430F5500, monitors the outputs from the LDC0851 switches to determine relative position and direction of rotation. It also tracks the knob position and updates the 7-segment displays as appropriate.

2.3 Power Management

The hardware is powered from a standard USB port, which has a nominal voltage of 5V. The low-dropout (LDO) regulator, LP5951, regulates the available 5V down to 3.3V used as the main supply for all devices in the design. It provides sufficient output current using a small footprint SC70.

2.4 ESD Protection

The TPD2E001 protects the digital inputs of the MSP430F5500 that are attached to the USB interface from high voltage ESD transients.

3 Block Diagram

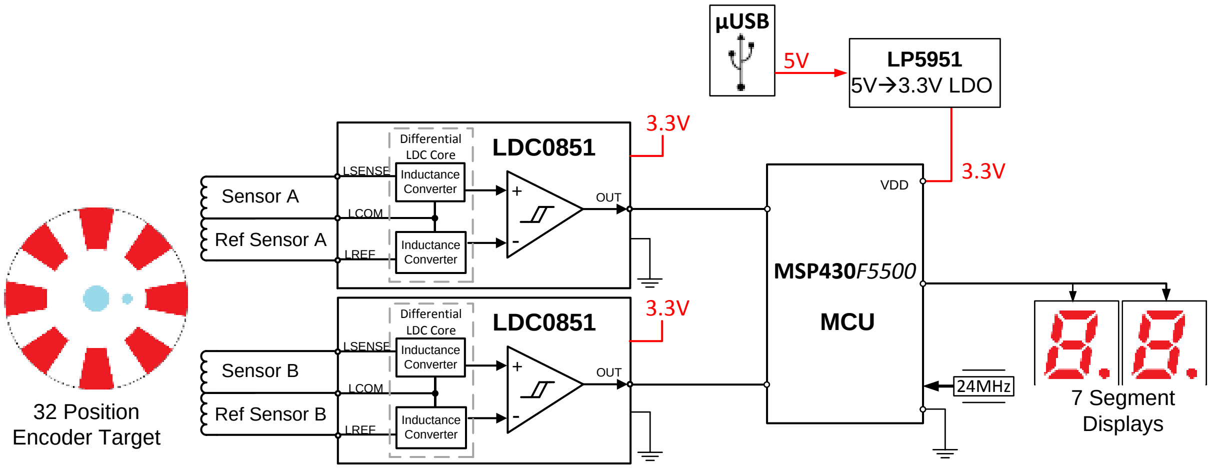

Figure 2: TIDA-00828 System Block Diagram

3.1 Highlighted Products

3.1.1 LDC0851

The LDC0851 is an inductance comparator with switch output. It utilizes a sensing inductor and a reference inductor to determine the relative inductance in a system. The push/pull output (OUT) switches low when the sense inductance drops below the reference inductance. It returns high when the reference inductance goes higher than the sense inductance.

Hysteresis is included to ensure a reliable switching threshold immune to noise or mechanical vibration. The performance is not affected by the presence of DC magnetic fields, making it very robust in tamper detection systems. Inductive sensing technology provides reliable and accurate sensing even in the presence of dirt, oil, or moisture making it ideal for use in harsh or dirty environments. The differential implementation prevents false triggering over environmental factors such as temperature variation or humidity effects.

A dedicated enable pin allows duty cycling to reduce power consumption.

3.1.2 MSP430F5500

The MSP430F5500 is an ultra-low power microcontroller with a USB interface. It features 8kB of Flash memory, 4kB RAM and 31 GPIOs, and operates at 24 MHz.

4 Getting Started

The operation of TIDA-00828 is simple – connect a micro-USB cable into J1 of the PCB, and connect the other end of the cable to a USB-based power supply as shown in Figure 3. Use of a PC USB port, a powered USB hub, or even a USB battery pack are all acceptable power sources for TIDA-00828.

A clockwise rotation of the knob increments the counter and the 7-segment displays show the new counter position. Similarly, a counter-clockwise rotation will decrement the counter value. The counter value is set to wrap-around after hitting the maximum value of 31 – for example, rotating the knob one position clockwise when the counter shows 31 will change the counted position to 00.

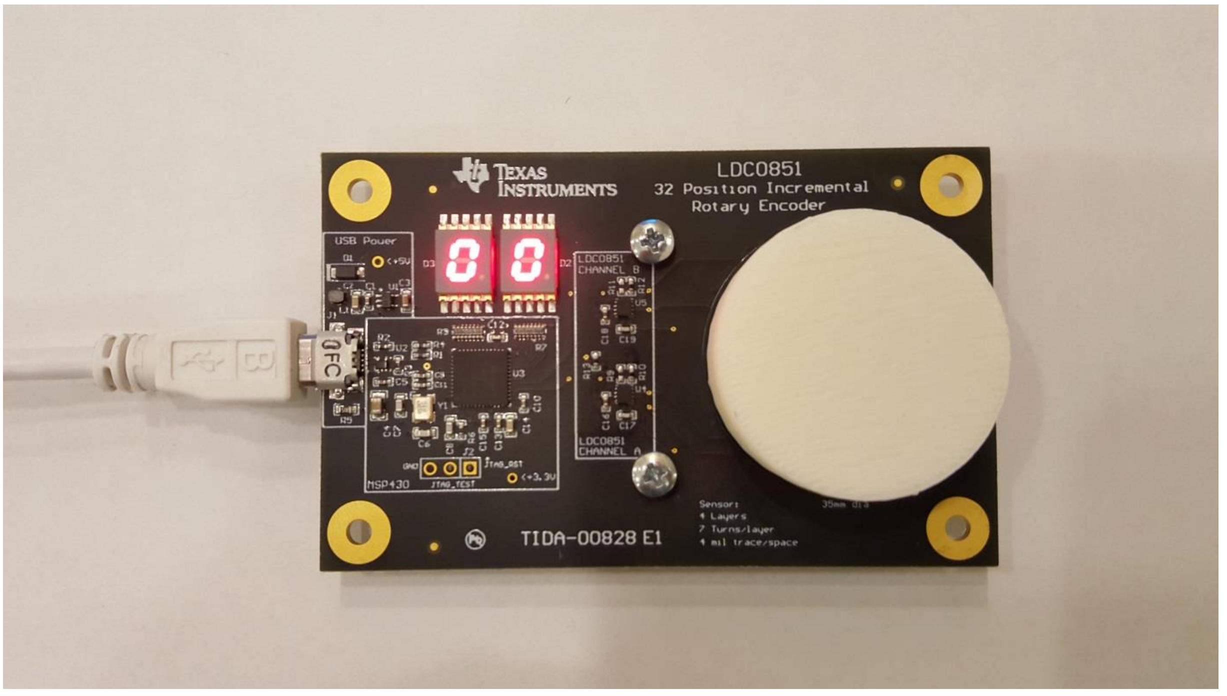

Figure 3: TIDA-00828 powered up by USB Connection

The wrap-around at 31 is a function of the firmware and other behaviors can be supported (such as halting the count or continuing further). A single 360° rotation however is limited to 32 counts, due to the sensor and target configuration used by TIDA-00828.

The continuous free rotation of the knob is due to the mechanical design; alternative mechanical designs which have a physical stop can be supported.

5 TIDA-00615 Comparison to TIDA-00508 and TIDA-00615

TIDA-00508 (http://www.ti.com/tool/TIDA-00508) and TIDA-00615 (http://www.ti.com/tool/TIDA-00615) are other TI rotational measurement reference designs based on LDC technology. They bring many of the same benefits of the TIDA-00828 – the contactless, hostile environment immunity and low cost implementation, but provide a set of features which may be more suitable for certain applications.

Table 1: Comparison of TIDA-00828, TIDA-00615, and TIDA-00508

	TIDA-00828	TIDA-00615	TIDA-00508
Functionality	32 Position Encoder Knob	32 Position Encoder Knob	1° Absolute angle measurement
LDC device compatibility	LDC0851	LDC1312 (or ½ of LDC1314)	LDC1314
Number of LDC channels	2 (2× LDC0851)	2 channels of LDC1312 or LDC1314	4 channels of LDC1314
Measurement output	Incremental change in position and direction	Incremental change in position and direction	Absolute position
Resolution	11.25° (is a function of the number of positions)	11.25° (is a function of the number of positions)	0.1°
Calibration	None	None	Required 1° accuracy; otherwise not needed for 3° accuracy
Maximum Rotation Speed	>2000 RPM, is a function of number of positions and sensor	>1000 RPM, is a function of number of positions	200 RPM
Sampling Requirements	Continuous – changes will not be detected without active LDC sampling	Continuous – changes will not be detected without active LDC sampling	As needed – 1 sample on 4 channels required
LDC current (excluding MCU and other components)	5.4 mA	3.4 mA	3.4 mA

6 System Design Theory

6.1 Inductive Sensing 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.

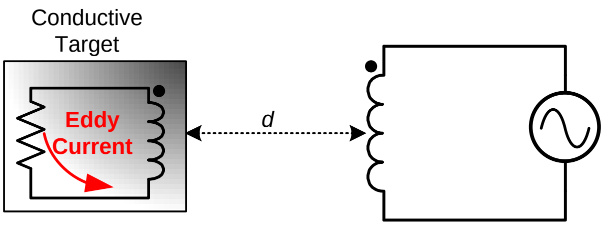

Figure 4: Conductor in AC Magnetic Field

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

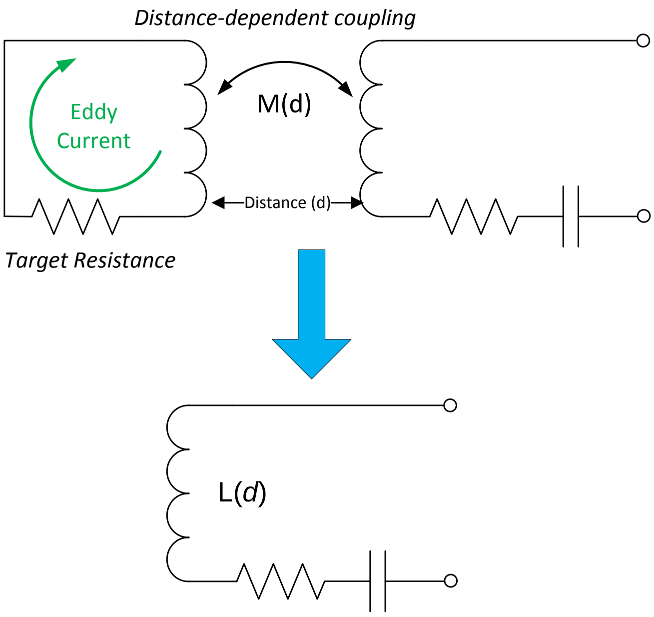

Figure 5: Electrical Model of Series Inductive Sensor

The circuit resonates at a frequency given by:

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

Any shift in the target position causes the inductance value, *L(d)*, to change, which in turn causes the resonant frequency to change. The LDC0851 uses this principle to determine a relative change between the sense and reference inductors.

6.1.1 Movement of a Conductive Target

Consider a flat conductive target is moving axially with respect to an L-C resonant circuit, as shown in Figure 6. The resonant L-C circuit consists of a planar circular spiral-wound trace with a parallel capacitor.

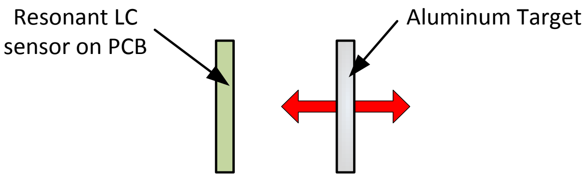

Figure 6: Aluminum Target moved axially with respect to LC resonant circuit

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.

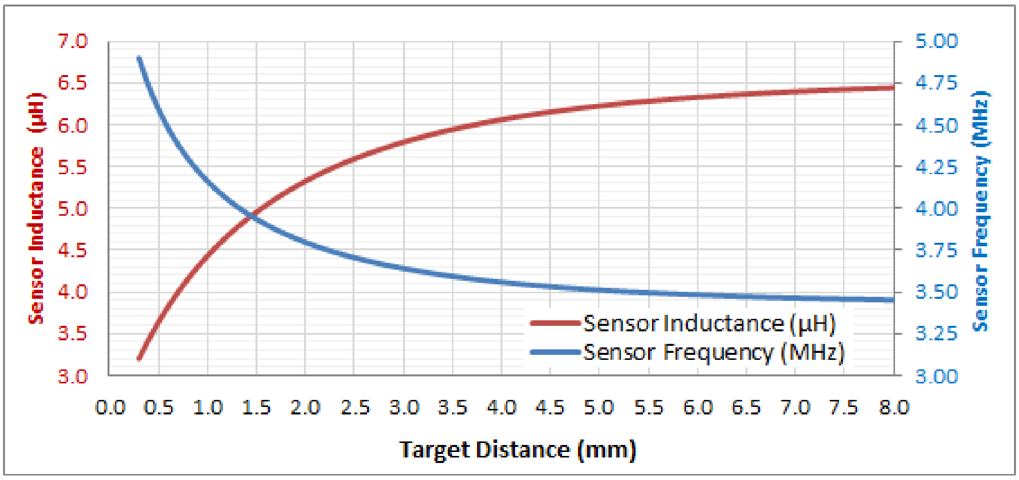

Figure 7: Example Sensor Response vs. Target Distance

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.

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.

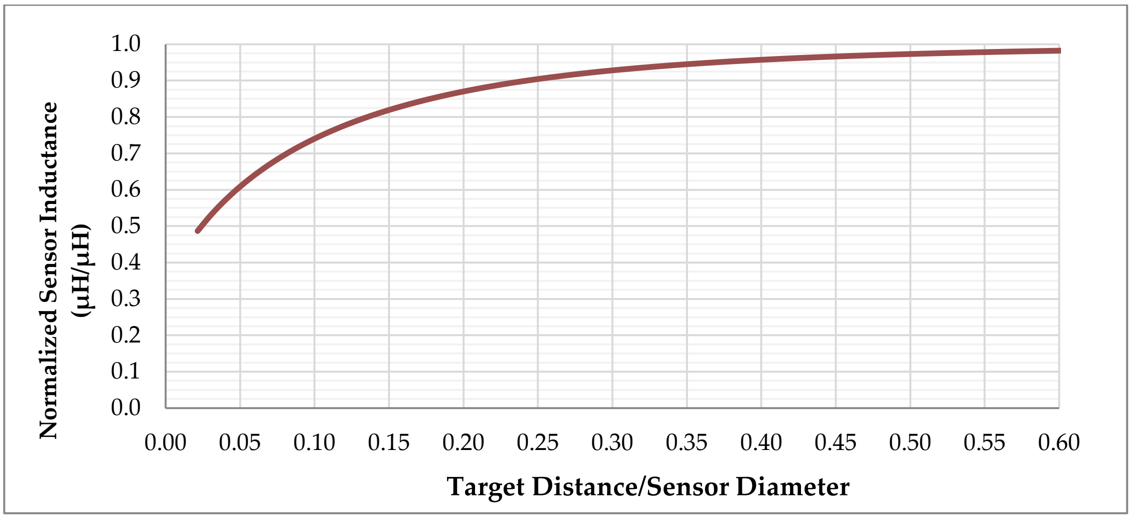

Figure 8: Normalized Sensor Response

6.1.2 Lateral shift in Target Position

Inductive sensing can also measure lateral shifts in a target position. For this measurement the target is not centered over the sensor, but moves so that it covers a portion of the sensor. The target is held at a fixed Z-distance with respect to the sensor.

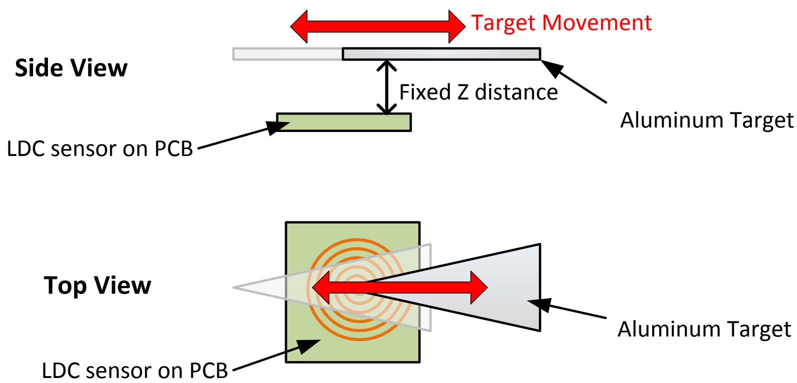

Figure 9: Lateral Position Sensing with LDC

The sensor inductance changes based on the proportion of sensor coverage – this change can be mapped to a lateral position. The more the target covers the sensor, the lower the inductance. The choice of target geometry can be changed to provide the appropriate change in inductance as the target moves.

6.2 LDC0851 Operation

The LDC0851 functions as an inductive comparator with a single digital output. The LDC0851 block diagram is shown in in Figure 10. The LDC0851 comes in a 2x2 mm, 8-pin DFN package and operates over a supply voltage range of 1.71 V to 3.46 V. It is rated for -40 to 125 °C, and has a maximum sample rate of 4 ksps.

Setting the EN pin low will put the LDC0851 into a shutdown mode where it draws typically less than 140 nA of current.

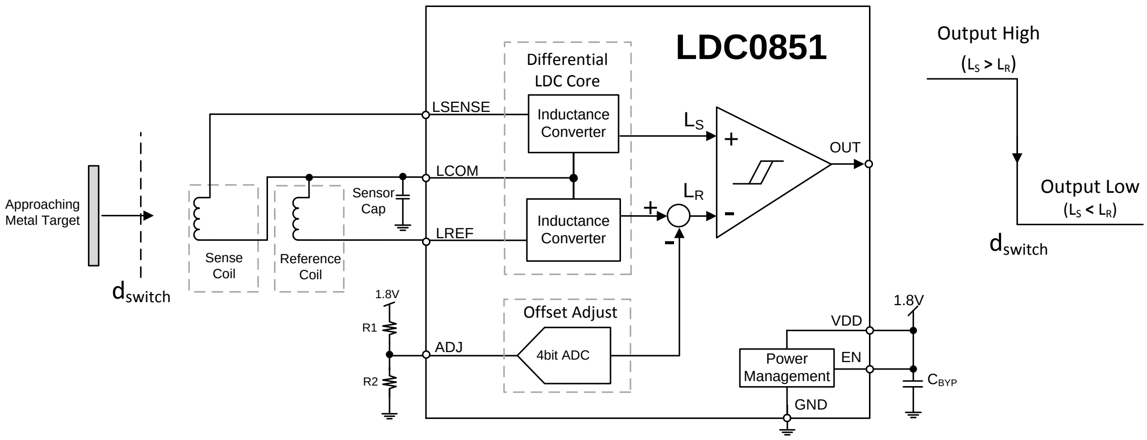

Figure 10: LDC0851 Block Diagram

The LDC0851 uses two sensors – a Reference sensor and a Sense sensor, where the Reference sensor is connected between LREF and LCOM pins, and the Sense sensor is across the LSENSE and LCOM pins. A sensor capacitor is connected from LCOM to GND. This capacitor is used to set the sensor frequency, which should be between 300 kHz and 19 MHz. The sensor operation frequencies are a function of the sensor inductances and sensor capacitance:

$$f = \frac{\sqrt{2}}{2\pi\sqrt{LC}} \qquad (2)$$

where the inductance L is the inductance of either the Sense inductor or the Reference Inductor.

Based on the target position, the two inductors generally have different operating frequencies. Note that any parasitic capacitance on the LCOM, LREF, and LSENSE pins will add to the sensor capacitor and change the actual operating frequency.

The inductance of the Sense inductor is compared to the Reference inductor, and the OUT pin indicates the current state, as shown in Figure 11. The Sense inductance shifts as a function of target distance, and so when the target moves closer to the Sense inductor than the set switching threshold, the OUT pin will shift low. When the target moves farther away from the Sense inductor, the inductance increases, and the OUT pin returns high. The LDC0851 uses hysteresis on switching threshold to produce a more stable output.

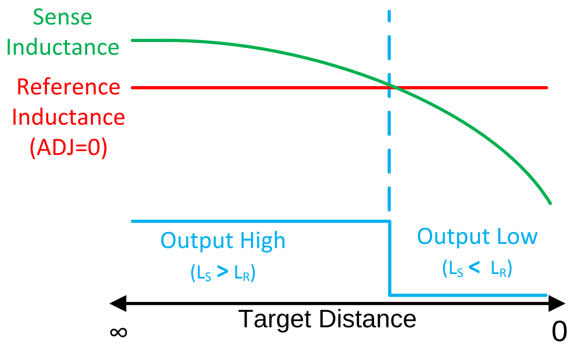

Figure 11: LDC0851 OUT functionality with ADJ=0

The Reference and Sense inductors should be closely matched to maintain a consistent switching distance over temperature and to compensate for other environmental factors. As the sensor capacitor is shared with both inductors instead a dedicated capacitor per sensor, there is no capacitor tolerance mismatch to consider.

The ADJ pin is used to offset the Reference inductance. If the ADJ pin is tied to ground, no offset is applied; this operation is shown in Figure 11. This approach is generally used for systems where identical inductors can be constructed for both the Reference and Sense inductors.

If the voltage applied to the ADJ pin is not 0.0V, an offset is applied to the Reference inductance, as shown in Figure 12. This offset functionality allows for control of the switch output based on the target position. It is recommended to use a voltage divider from the supply to set the ADJ pin voltage. A full description of the ADJ pin functionality and voltage levels can be found in section 8.3.2 of the LDC0851 datasheet.

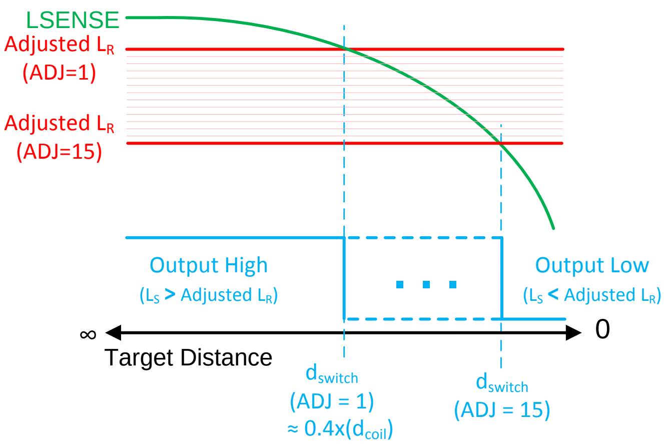

Figure 12: LDC0851 ADJ pin functionality

TIDA-00828 is an event counting application which uses symmetrical inductor designs and both the Sense and Reference inductors have matched target interactions. For this reason, TIDA-00828 achieves best performance with the ADJ pins of both LDC0851 devices connected to ground.

6.3 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 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.

For TIDA-00828, the physical knob is attached to a target PCB and rotates above a set of inductive sensors positioned on a sensor PCB, as shown in Figure 13. The target PCB has only a simple pattern of copper on the PCB and does not require any electrical components.

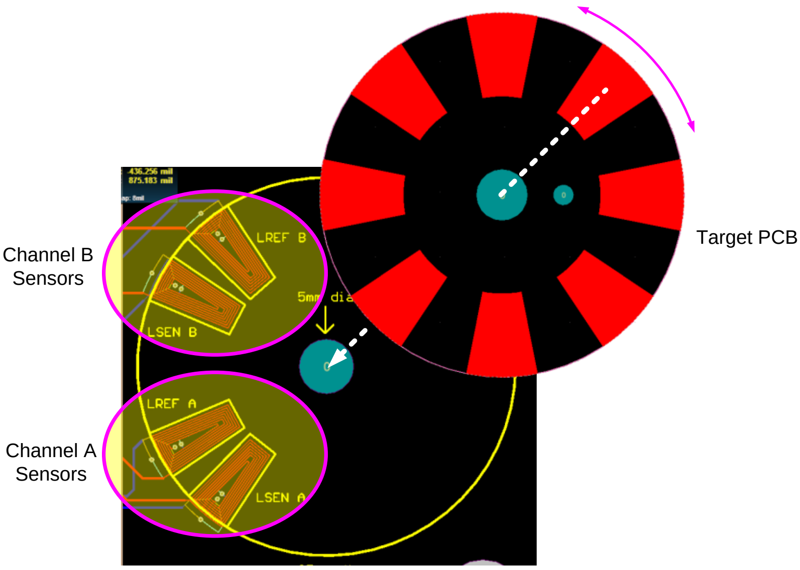

Figure 13: Sensor and Target configuration

6.4 Gray Coded Quadrature Outputs

At least 2 switches (indicated as A and B) are required to determine direction of rotation; therefore two LDC0851 devices are needed to implement an encoder. Each LDC0851 has a dedicated sense and reference inductor. The inductors and targets are arranged so that the output of the switch pair is Gray coded, which means that successive output values differ in only one bit. Table 2 shows output sequence.

Table 2: Possible Quadrature Outputs

Switch A	Switch B
0	0
0	1
1	1
1	0

Depending on the direction of this output sequence, the direction of rotation can be determined. For example, in TIDA-00828, the output sequence 00→01→11→10→00… signifies clockwise rotation. Similarly, the reverse sequence 00→10→11→01→00…indicates the counter clockwise rotation. It should be noted that such encoding limits the number of encoder positions to multiples of 4 to avoid discontinuities in the Gray coded outputs.

Generating the above sequence requires precise positioning of the targets and switch sensors, as discussed in the next section.

6.5 Target Design and Sensor Placement

As mentioned in Section 6.4, quadrature encoded switch outputs have 4 values: 00, 01, 11, and 10 which can be repeated multiple times to increase the number of positions as long as the sequence is maintained. Since the output signal repeats every 4 positions, each position is positioned within a 90° section of the output signal as shown by Figure 14. It can be seen that the Switch A and Switch B waveforms are out of phase by 90°.

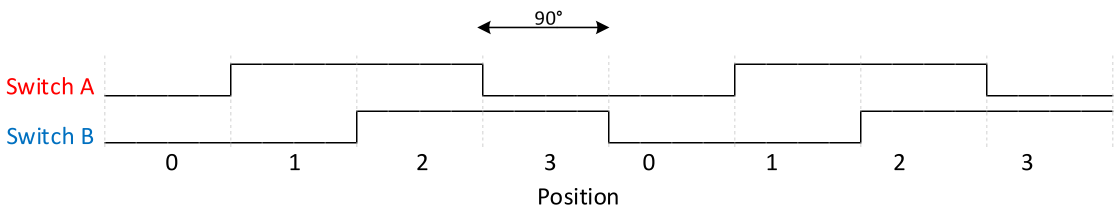

Figure 14: Quadrature output signals out of phase by 90°

To introduce a 90° phase difference in the output signals, the switch sense inductors need to be placed at a particular angle from each other. Consider the 8 position target disk design in Figure 15. Eight positions require each position to be 45° wide. By placing the sense inductors at 45° from each other while the target disk rotates above them, quadrature encoded output can be generated. It can be seen that the sense inductors need to be placed in consecutive position sectors to get a 90° phase difference in the output signals. As expected, a 45° rotation in either direction gives a new position.

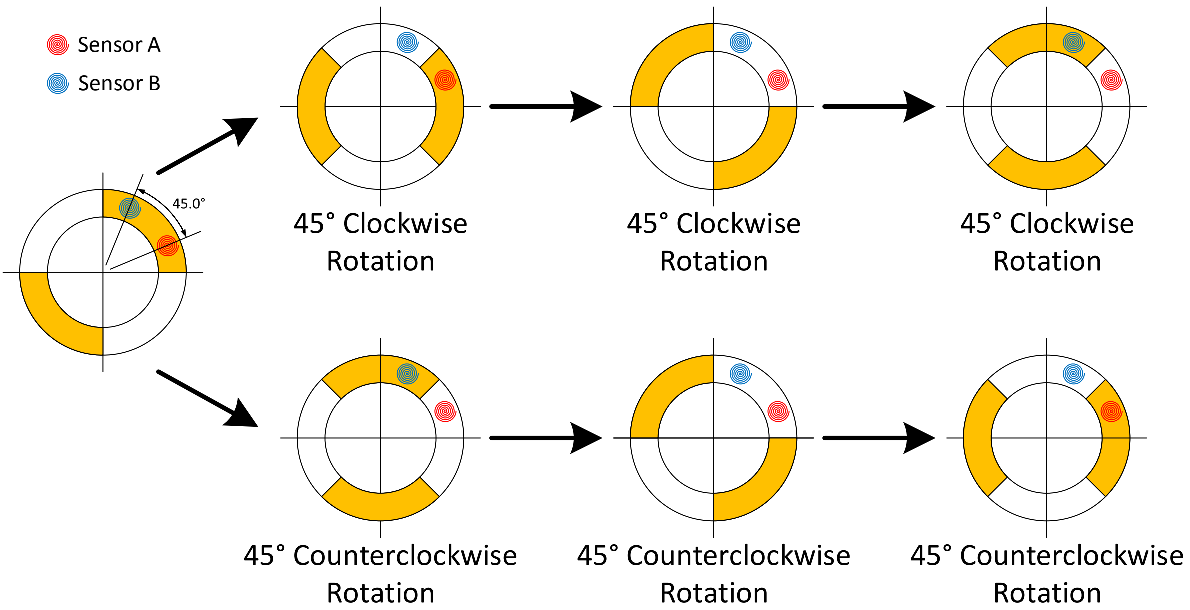

Figure 15: 8-Position target disk and sensor (SENSE coils) configuration

As long as the two sense inductors are placed in consecutive positions, a quadrature encoded output can be generated. This generalization can lead to easier inductor design. Consider the two configurations in Figure 16. In configuration B, the sense inductors are placed in consecutive positions but not next to each other. They are equivalent since they both generate the same output signals when the target disk is rotated.

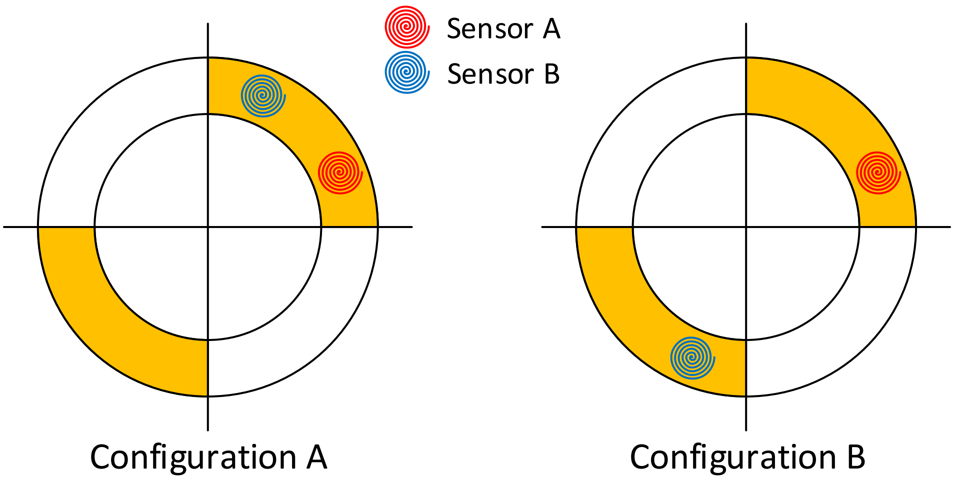

Figure 16: Equivalent configurations for sense inductors

Since the LDC0851 is configured for Basic Operation, the reference inductor needs to be placed such that it complements the quadrature encoding operation. It is therefore placed two positions away from its respective sense inductor. This configuration insures that only one inductor of each LDC0851 (the sense or the reference) is covered by the target at any instant. Figure 17 shows this configuration and respective inductances of the two coils.

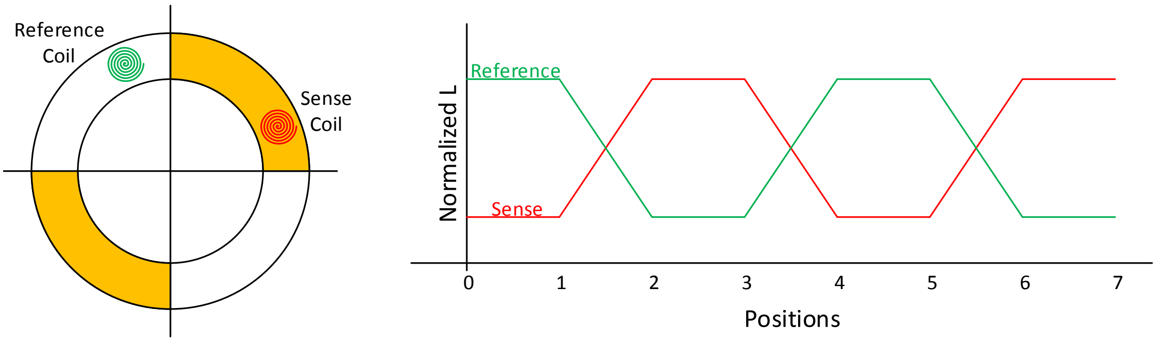

Figure 17: Reference coil placement and inductance shifts

To implement 32 positions, the target disk contains 8 conductive regions, each covering 22.5° and separated by gaps of 22.5°. A pair of conductive region and void makes up 4 positions. Each position is therefore 11.25° wide ($\frac{360°}{32} = 11.25°$). Figure 18 shows the target geometries and relative sensor positions on the sensor PCB. The red indicates 1oz. ENIG plated copper (35 µm thick) covered by solder mask. 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 5mm Ø hole, while the second hole is 2mm Ø placed 6mm from the center hole. This smaller hole is used to mechanically align the knob to the target. The thickness of the target disk PCB depends on the required spacing between the sensors and the targets on the disk; it will be discussed in the next section.

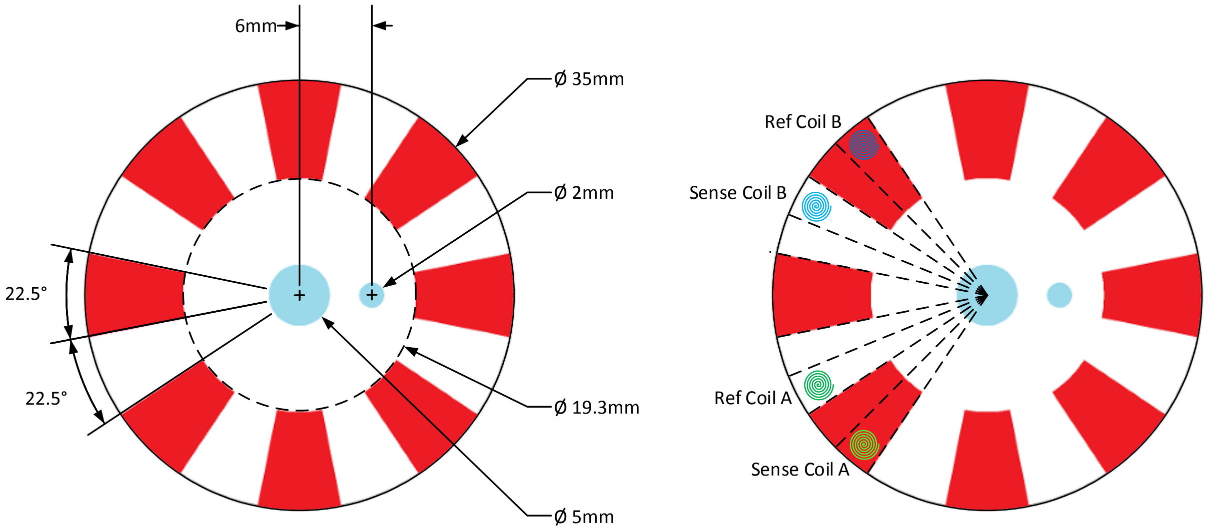

Figure 18: (Left) 32-Position target disk geometry, (Right) Sensor placement

The sensor positions shown in Figure 18 (Right) follow the sensor placement guidelines discussed in this section. Both reference coils are 2 positions (180°) away from their respective sense coils. The two sense coils are 1 position (90°) away from each other. It should be noted that the actual sensors on the sensor PCB are not circular spirals, but are instead trapezoidal. The sensor design for this application is discussed in the following section.

6.6 Sensor Design and Target Disk Placement

The LDC0851 relies on two sensors for proper operation. For TIDA-00828, two LDC0851 devices are used, which requires a total of 4 sensors, all of which are matched.

The design and matching of the inductors is very critical to ensure a proper switching operation. The following procedure can be followed to determine sensor characteristics.

1. Determine the outer diameter of the sensor. For a circular coil, this is the outer diameter, while for a trapezoidal coil the 'diameter' can be considered the length of the longer edge. All 4 sensors will have identical sizes.
2. Ensure that the target is within 33% of the sensor diameter, otherwise the change of inductance due to target movement may be too small for the LDC0851 to detect.
3. Determine the desired frequency (f_{SENSOR}), which should be between 300 kHz and 19 MHz.
4. Calculate the required inductance determined by

$$L_{SENSOR} \geq \frac{1}{0.029 \cdot (f_{SENSOR})} \tag{3}$$

Where:

- L_{SENSOR} is the inductance of the L_{SENSE} coil or L_{REF} coil

5. Calculate the sensor capacitance:

$$C_{SENSOR} = C_{TOTAL} - C_{BOARD} - C_{IN\_COM} \tag{4}$$

$$C_{TOTAL} = \frac{1}{(\pi \cdot f_{SENSOR})^2 (2 \cdot L_{SENSOR})} \quad \geq 33pF \tag{5}$$

Where:

- C_{BOARD} is the parasitic capacitance introduced by the board layout
- C_{IN_COM} is the parasitic pin capacitance of LCOM specified as 12pF in the data sheet.

Figure 19 shows the valid operating region with a 3.3V supply. The top and bottom edges of the valid region are bounded by equations (5) and (3) respectively.

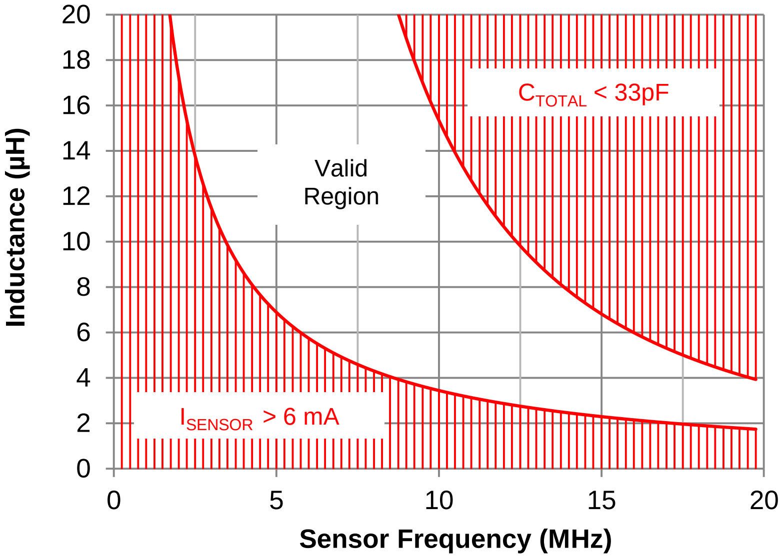

Figure 19: Inductance vs Sensor Frequency Design Space for 3.3V supply

6.6.1 Sensor Coil Geometry

Designing a small knob with many positions restricts the physical size of the sensors. These small sensors have a correspondingly low inductance. Without careful design, the inductance of the sensors will not be within the LDC0851 operating region.

TIDA-00828 utilizes trapezoidal sensors instead of circular ones to take advantage of the available space (sectors). Coupled with 4mil (0.102mm) trace width and spacing, a larger number of turns can be laid out. The sensors are also slightly wider than 11.25° (angle displacement per position) to allow one more turn thereby increasing the inductance even further. The sensor has 4 layers and 7 turns/layer. Figure 20 shows a single sensor layout layer-by-layer.

Table 3: Trapezoidal Sensor Design

Parameter	Value
Number of Turns	7
Trace Width	4 mils (0.102 mm)
Trace Spacing	4 mils (0.102 mm)
Number of Layers	4
Trace Thickness	1 oz-cu (35µm)

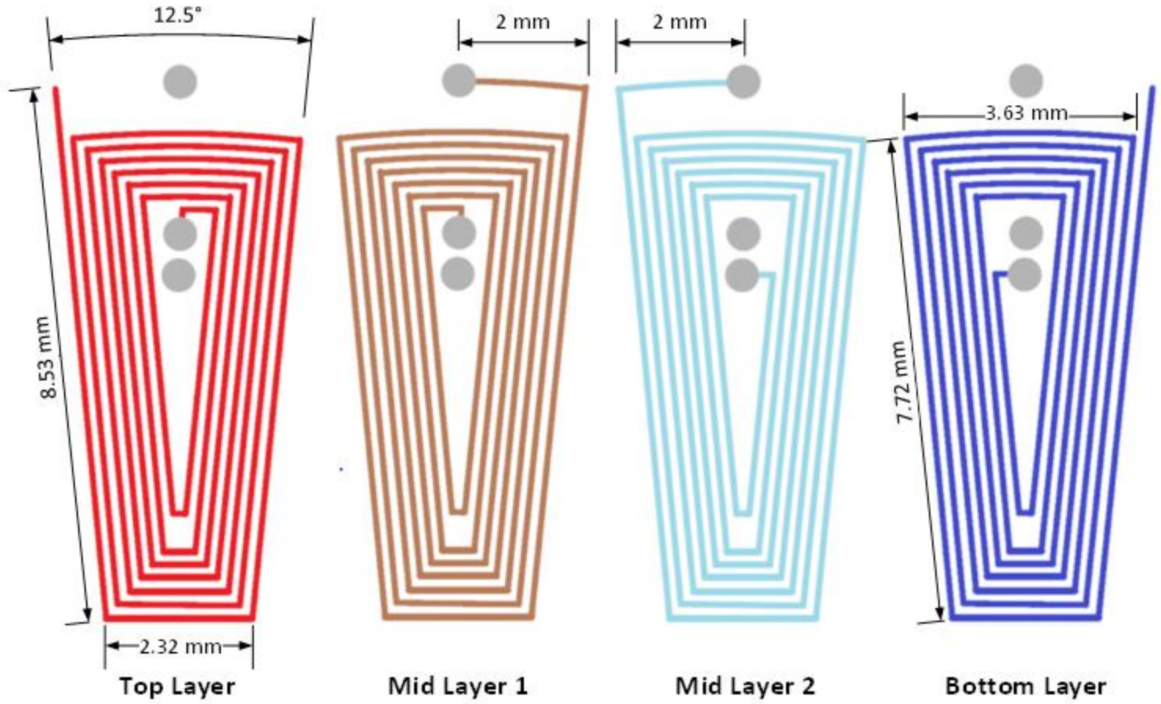

Figure 20: Trapezoidal Sensor Geometry and Layers

The placement of each sensor coil is based on Figure 18 (Right). The top and bottom pairs of coils form channels B and A respectively as seen in Figure 21. The reference coil is placed above the sense coil for simpler routing to the LDC0851.

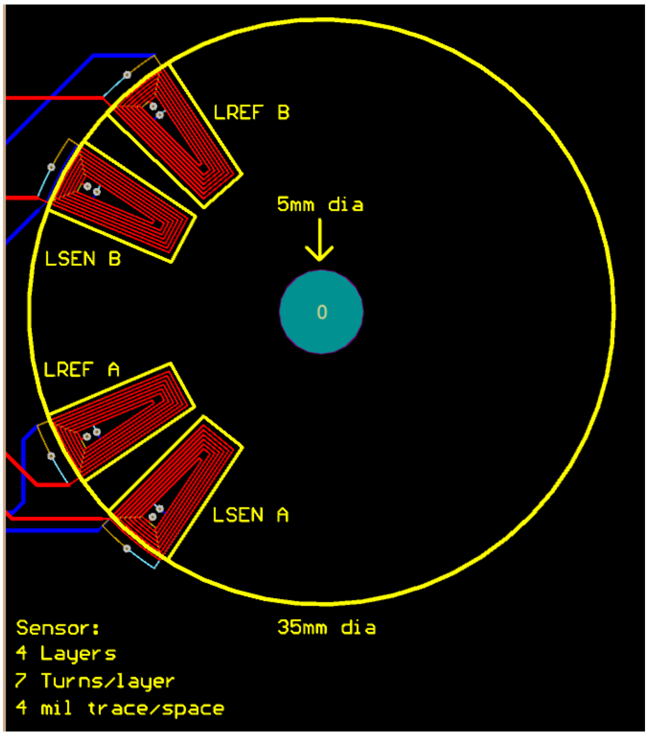

Figure 21: Trapezoidal sensors placed according to Figure 18 (Right)

The spiral orientation flips every layer to make sure the current flows in the same direction. This increases the mutual coupling between each coil section and enhances the total inductance for the set of coils. For example, the circular sensor in Figure 22 has current flowing clockwise through it in every layer. To this end the spiral traces in layers 1 and 3 are clockwise, and counter-clockwise in layers 2 and 4. As long as alternate layers have the same orientation and consecutive ones have opposite, the current direction will remain the same through every layer.

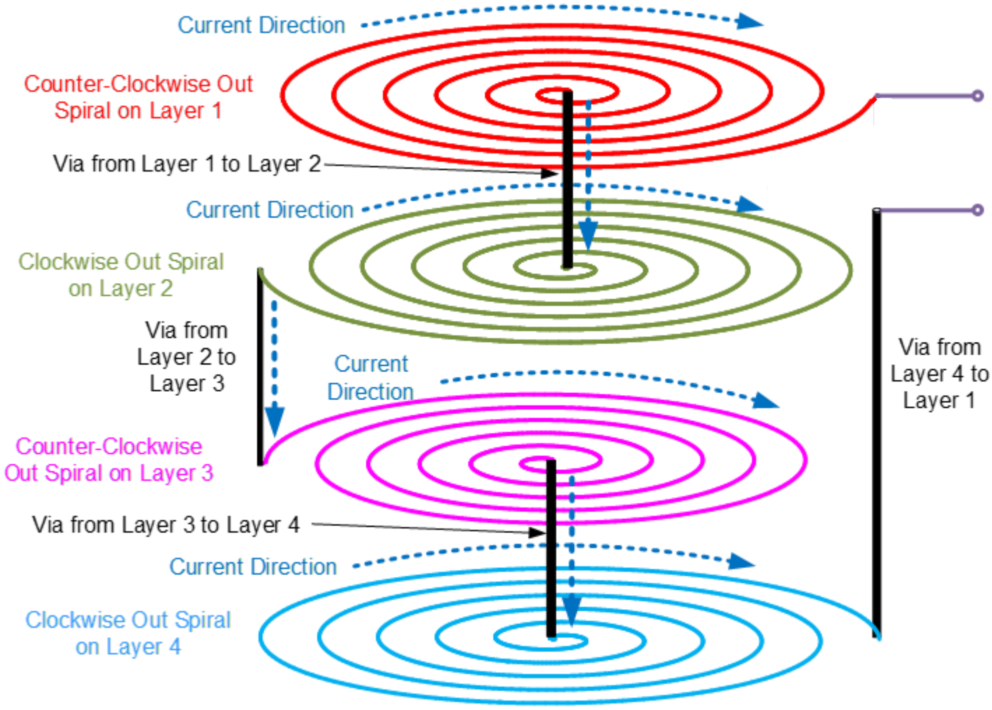

Figure 22: 4-Layer Inductor/sensor physical construction

6.6.2 Target Disk-Sensor Distance

The sensors have inductances of the order of 2.32 µH which reduces to 1.25 µH at maximum target interaction (when the metal target fully covers the sensor and is touching the sensor) as seen in Figure 23. According to Equation (3), the minimum allowed inductance is 1.81 µH; therefore the target interaction needs to be limited. The figure shows that there must be at least a 0.4 mm distance between the target and the sensor, so the inductance at full coverage is 1.87 µH to ensure the system falls within the LDC0851 operating region.

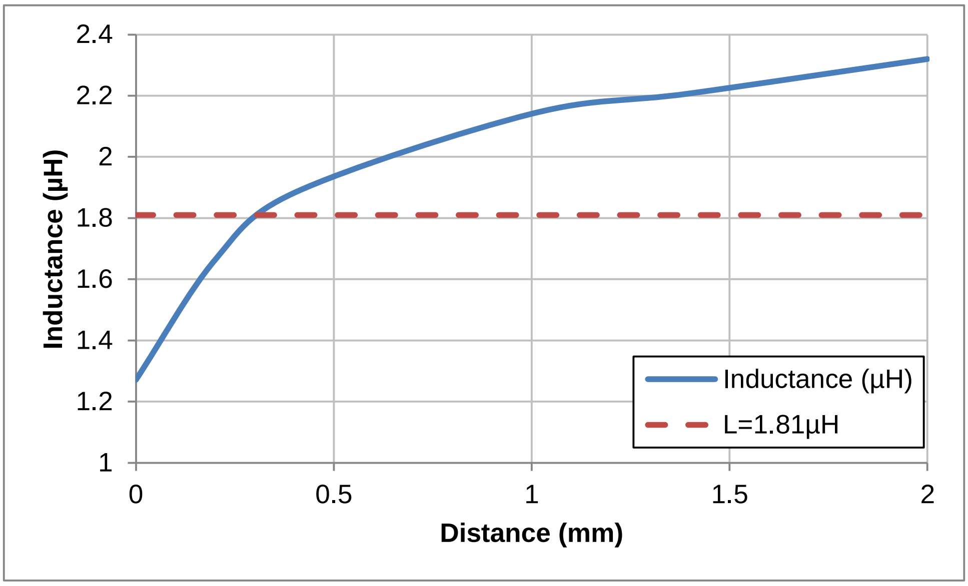

Figure 23: Sensor inductance vs target to sensor distance

By adjusting the thickness of the target disk PCB and placing it so that the conductive targets on the top layer face upwards towards the knob, a spacing of at least 0.4 mm can be maintained between the sensors and the targets as shown in Figure 24. The target disk PCB, excluding the top layer and solder mask, is designed to be 0.823mm thick. Even with a tolerance of ±10%, the minimum thickness will be at least 0.74mm, which satisfies the required spacing.

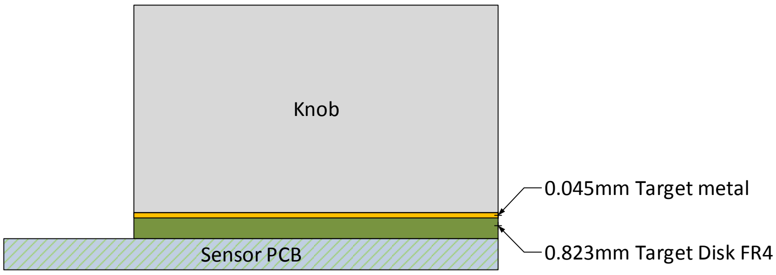

Figure 24: Target Disk – Sensor spacing using target disk PCB

The target cannot be arbitrarily far from the sensor; when the target distance is >40% of the sensor diameter, the LDC0851 switching is no longer robust and the Gray code output is no longer reliably generated. Based on the geometries of TIDA-00828's sensors, the target disk can be placed at a distance of 0.4mm to 1.4mm away from the sensors.

Applications requiring a larger sensing distance can achieve it by increasing the physical size of the sensors. Consequently, either the diameter of the knob would have to be increased or the number of positions per revolution would have to be decreased.

6.6.3 Sensor Frequency and Capacitance

According to equation (3), with a coil inductance of 2.32 µH at 3.3 V supply voltage the sensor frequency has the constraint: $f_{SENSOR} \geq 14.87$ MHz. Using a sensor capacitance, C_{SENSOR}, of 62 pF and assuming parasitic board (C_{BOARD}) and pin (C_{IN_COM}) capacitance to be 12 pF and 4 pF respectively, the total capacitance comes out to be C_{TOTAL} = 78 pF. Using equation (2), the sensor frequency is calculated to be 16.73 MHz.

At full coverage (0.82 mm spacing), the coil inductance drops to 2.09 µH and the total capacitance is unchanged, 78 pF. The L and C values give a senor frequency, f_{SENSOR} = 17.63 MHz, which is 5.4% higher and is greater than the 0.8% frequency hysteresis of the LDC0851. These numbers satisfy the condition in equation (3). Table 4 summarizes the above sensor characteristics.

Table 4: Calculated Sensor Characteristics

	No Coverage	Full Coverage @ 0.82mm
Total Capacitance, C_{TOTAL}	78pF	78pF
Coil Inductance, L	2.32µH	2.09µH
Sensor Frequency, f_{SENSOR}	16.73 MHz	17.63 MHz

6.6.4 Max Knob Rotation Speed

Though this TI Design represents an incremental encoder most suitable for human-machine-interface (HMI) applications, it can easily be adapted to applications where rotational speed measurement is the objective. The maximum possible RPM for the knob is a function of the conversion time (the interval of time for the LDC0851 to complete one conversion and update the output) of the LDC0851. The conversion time is given by the following equation:

$$t_{CONVERSION} = \frac{1}{231.0\ x\ 10^{-6} \cdot f_{SENSOR}} \quad (6)$$

Using a conservative f_{SENSOR} = 16.73 MHz, $t_{CONVERSION}$ is 0.258 ms. For robust and reliable operation, each position needs to be oversampled by at least 3 times and therefore the minimum time per position while spinning the knob is:

$$t_{MIN/POS} = 3 \times t_{CONVERSION} \quad (7)$$

Using $t_{CONVERSION}$ = 0.258 ms, $t_{MIN/POS}$ = 0.776 ms. The maximum RPM is therefore given by:

$$RPM_{MAX} = \frac{60}{t_{MIN/POS} \times Number\ of\ Positions} \quad (8)$$

With 32 positions, equation (8) produces a maximum of 2415 RPM for this specific system design. However, higher RPM values can be achieved by modifying system parameters such as f_{SENSOR} and the number of positions.

6.7 Signal Processing

6.7.1 Microcontroller Requirements

TIDA-00828 uses a MSP430F5500 microcontroller as its central processor. The primary considerations for this selection were a low cost and low power MCU with the ability to power the board via USB. The MSP430F5500 has more than sufficient memory and processor power necessary to support the rotary encoder. Minimum microcontroller requirements are:

1. Flash Memory Used: <250 bytes
2. RAM/FRAM Used: 1 Byte (1 UINT8_t)
3. GPIO Interrupts: 4 (Possible with 2: higher firmware complexity/flash memory used)

The enable pin (EN) on each LDC0851 is connected to a GPIO to allow the capability of power cycling the device. For systems which require always-on operation, the EN pin can be tied directly to +3.3V.

6.7.2 Algorithm

The algorithm used in TIDA-00828 is straight-forward. Each switch output from the LDC0851 is tied to a GPIO with interrupt capability. Table 5 summarizes the pin connections and interrupt configuration for each pin.

Table 5: Pin Connections and Interrupt Configuration

Pin	Interrupt Source	Interrupt Edge
P1.0	Channel/Switch A Output	Low-to-High
P1.1		High-to Low
P1.2	Channel/Switch B Output	Low-to-High
P1.3		High-to Low

After the initialization at power up, the algorithm is constantly in an idle state while waiting for interrupt triggers. When an interrupt is triggered due to one of the channel/switch outputs, the algorithm checks whether the other channel/switch output is high or low. Depending on the combination of interrupt triggered + state of the other output, the algorithm deduces the direction of rotation and increments/decrements the counter value accordingly. The counter value is then used to generate signals for the 7-segment displays to update it.

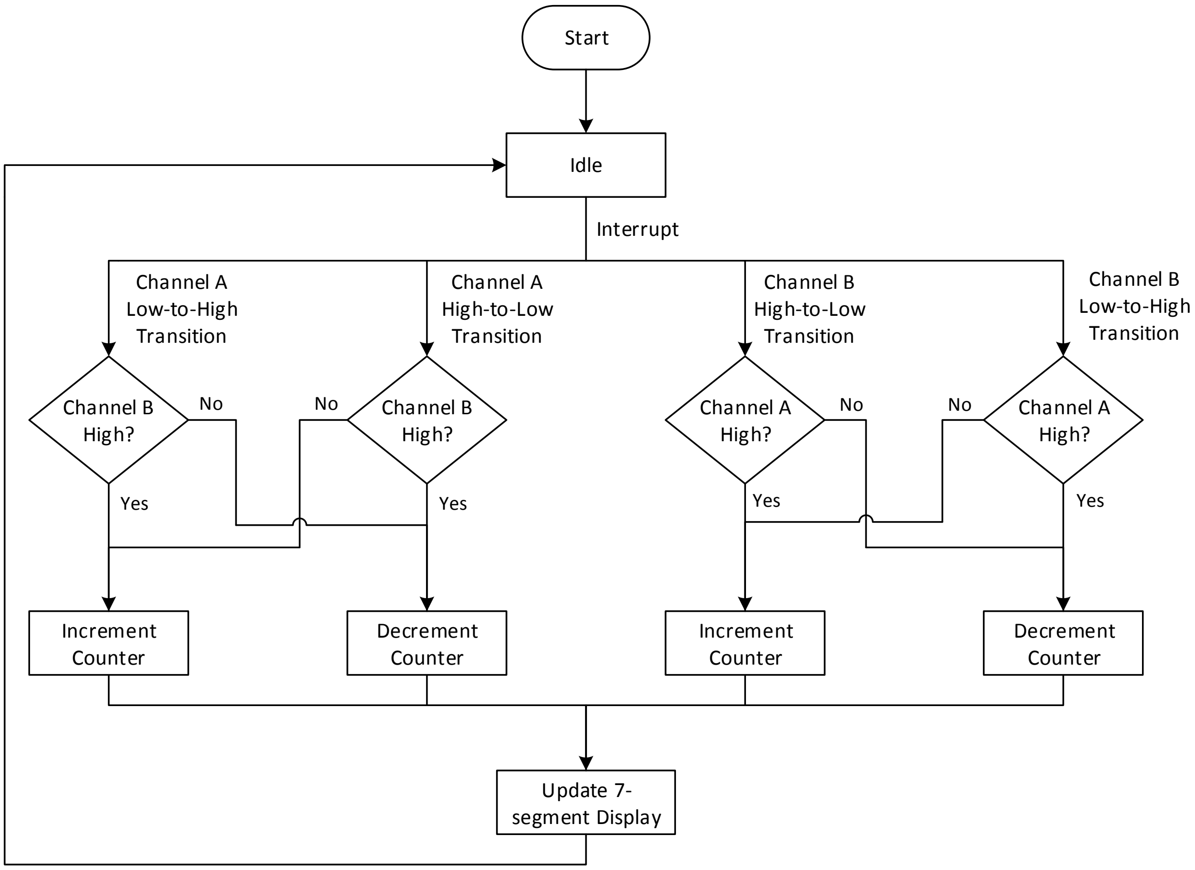

Figure 25: Algorithm Flowchart

7 Test Data

7.1 Sensor Electrical Characteristics

Table 6: Measured Sensor Characteristics

Parameter	Value
Inductance (no target interaction)	2.32 µH
Inductance (full target coverage @ 0.82mm)	2.09 µH
Sensor Capacitance	62 pF
$C_{BOARD}+C_{IN\_COM}$	14 pF
f_{SENSOR} (no target interaction)	16.9 MHz
f_{SENSOR} (full target interaction @ 0.82mm)	17.85 MHz

Using the impedance analyzer the inductances of the sense and reference coils are measured and plotted in Figure 26. The sense coil has slightly higher inductance to make sure the switch turns off in the absence of a target.

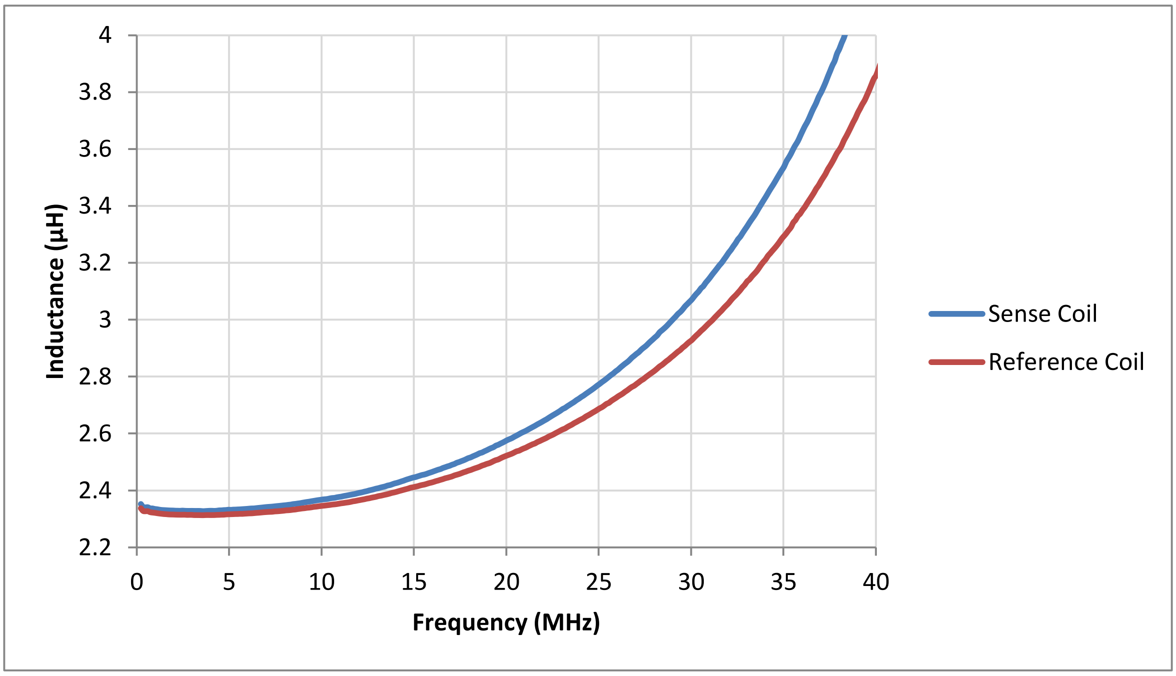

Figure 26: Coil characteristics using impedance analyzer

The sensor frequency differs from the calculated value due to tolerances in the capacitance values. At f_{SENSOR} = 16.9 MHz, the requirement in equation (3) is satisfied. This condition is also satisfied at full coverage by the target when the inductance decreases to 2.09µH and the f_{SENSOR} increases to 17.85 MHz. The total capacitance, C_{TOTAL}, is calculated to be 76 pF in both cases.

7.2 Angular Resolution

The switching pattern over a full rotation was evaluated using a precision rotation stage as shown in Figure 27. The target PCB and sensor board (manufactured separately for testing) were isolated from any conductive materials and precisely positioned.

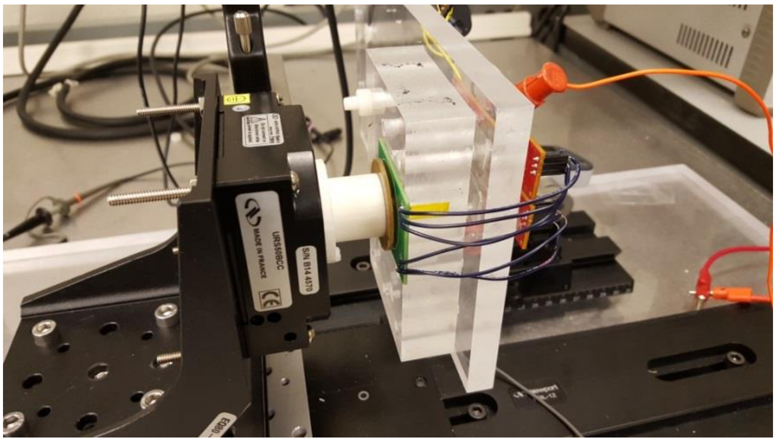

Figure 27: System used to measure rotational accuracy

The switching pattern was also measured for different distances between the sensors and the targets, and is summarized in Figure 28. To generalize the measurements, the distance is expressed as a fraction/percentage of the coil width (Outer edge: 4 mm).

Distances of 0% to 10% correspond to target distances of 0 mm to 0.4 mm in this design, which, as mentioned in section 6.6, reduces the coil inductance below 1.81µH when the target fully covers the sensor. The red region is therefore not suitable for operation.

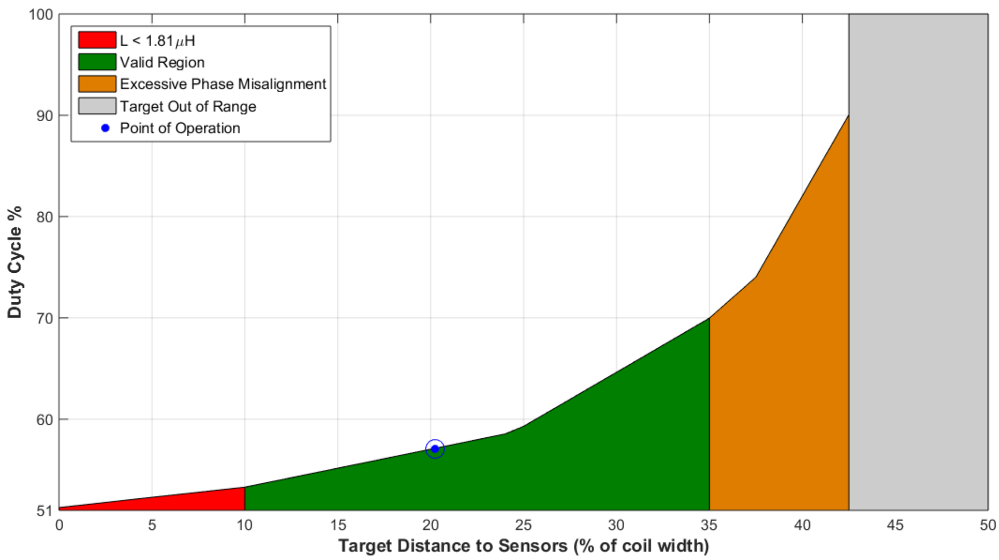

Figure 28: Target disk distance from sensors vs output duty cycles

The green region is the valid region of operation for this application. It ranges from 10% to 35% of the sensor diameter. The blue dot shows the operating point for TIDA-00828. At 20.25% or a target distance of 0.823 mm the duty cycle is roughly 57.1%.

The orange region corresponds to distances at which the LDC0851 switching is no longer correct. The larger target distance results in a smaller shift in frequency, and in the orange region the frequency shift is not greater than the minimum 0.8% hysteresis. This appears as an increased duty cycle on the OUT pins, and the comparators no longer reliably output the state 00. This misalignment is shown in Figure 29. The upper plot shows proper operation, while the lower plot shows that state 00 is not outputted.

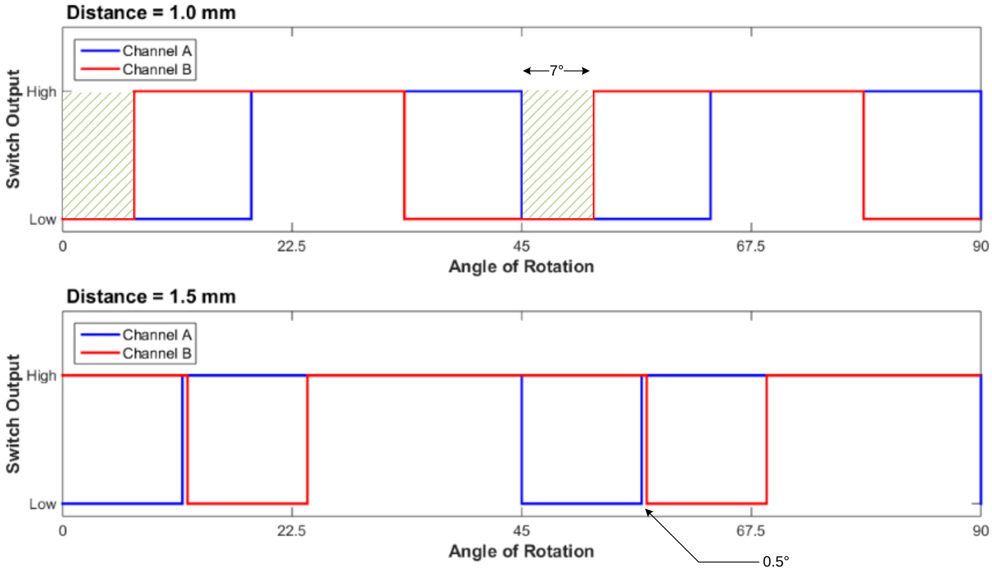

Figure 29: Channel trough overlaps

Targets at distances in the Gray region are out of the sensor range and do not switch the LDC0851. Since the output never goes low, the duty cycle is 100%.

7.3 Current Consumption

The total current consumption of TIDA-00828 is given by the following equation:

$$I_{TOTAL} = I_{LDC} + I_{MCU} + I_{7-SEG} \quad (9)$$

Where:

- I_{LDC} is the total current consumed by both LDC0851 devices
- I_{MCU} is the current consumed by the MSP430F5500
- $I_{7\text{-}SEG}$ is the total current consumed by both 7-segment displays

I_{LDC} and I_{MCU} are measured to be 5.4 mA and 0.83 mA respectively and do not vary significantly during operation. The 7-segment display current is a function of the illuminated segments and therefore varies with knob position.

7.3.1 Duty-cycling the LDC0851

Depending on how responsive the system needs to be, it may be acceptable to duty-cycle the LDC0851 devices to reduce current consumption. The LDC0851 has a 0.45ms start-up time, and sensors used in TIDA-00828 have a sample interval of 0.258ms. If the minimum sample interval of the system is 5 ms, then TIDA-00828 can be put into shutdown mode for 5 ms – 0.45 ms (startup time) – 0.258 ms (conversion time) = 4.29 ms.

When the LDC0851 devices are active, they consume 2.7 mA each for a total of 5.4 mA, and consume a total of <2 µA while in shutdown mode.

If the LDC0851 devices are active for 0.708 ms and in shutdown for 4.29 ms, the average current draw is < 0.8 mA

8 Design Files

8.1 Schematics

To download the Schematics, see the design files at http://www.ti.com/tool/TIDA-00828

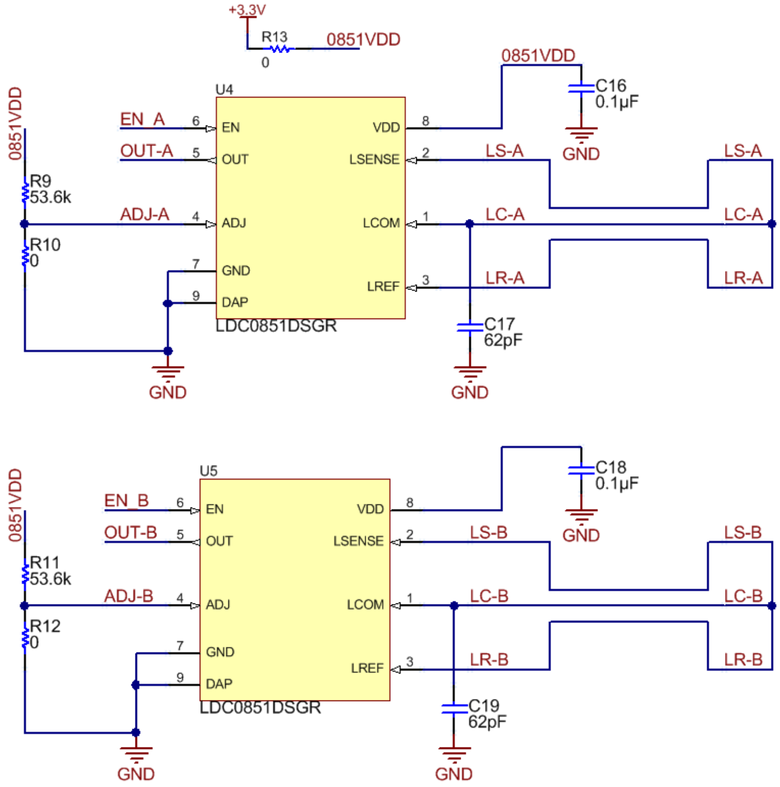

Figure 30: LDC0851 and Sensors. Channels A and B

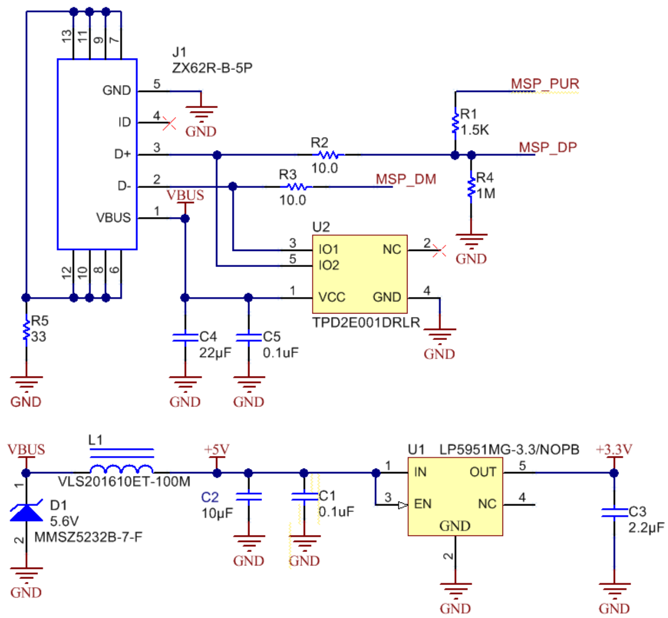

Figure 31: USB Interface and Power Management

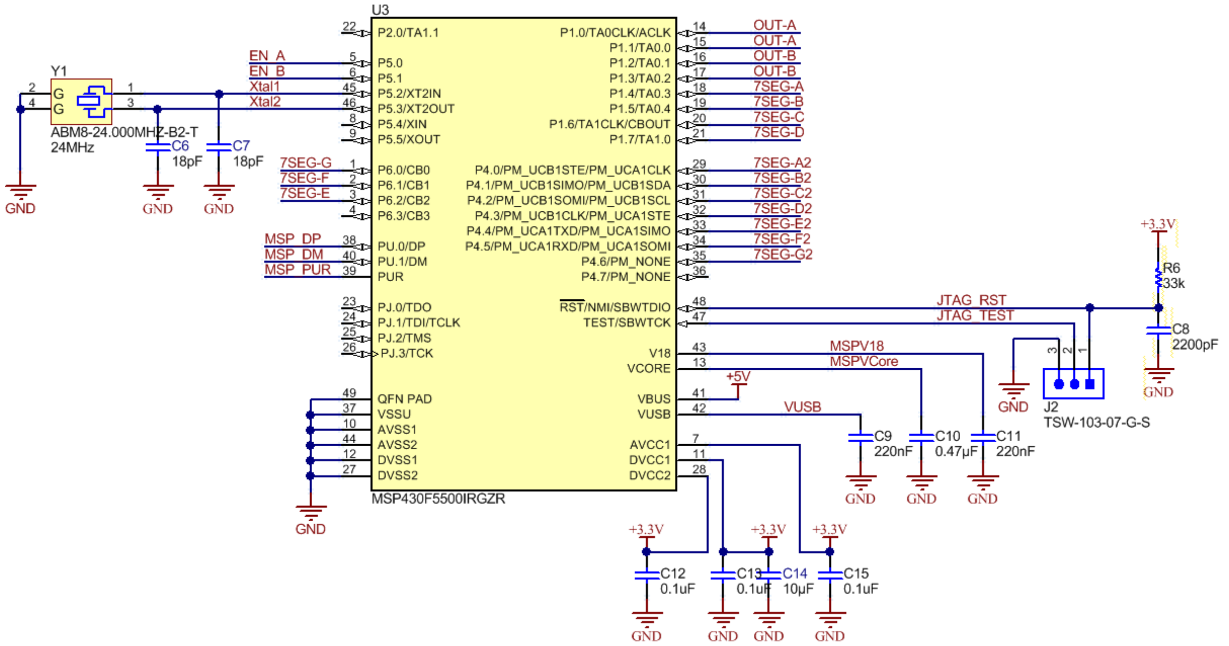

Figure 32: MSP430 Connections

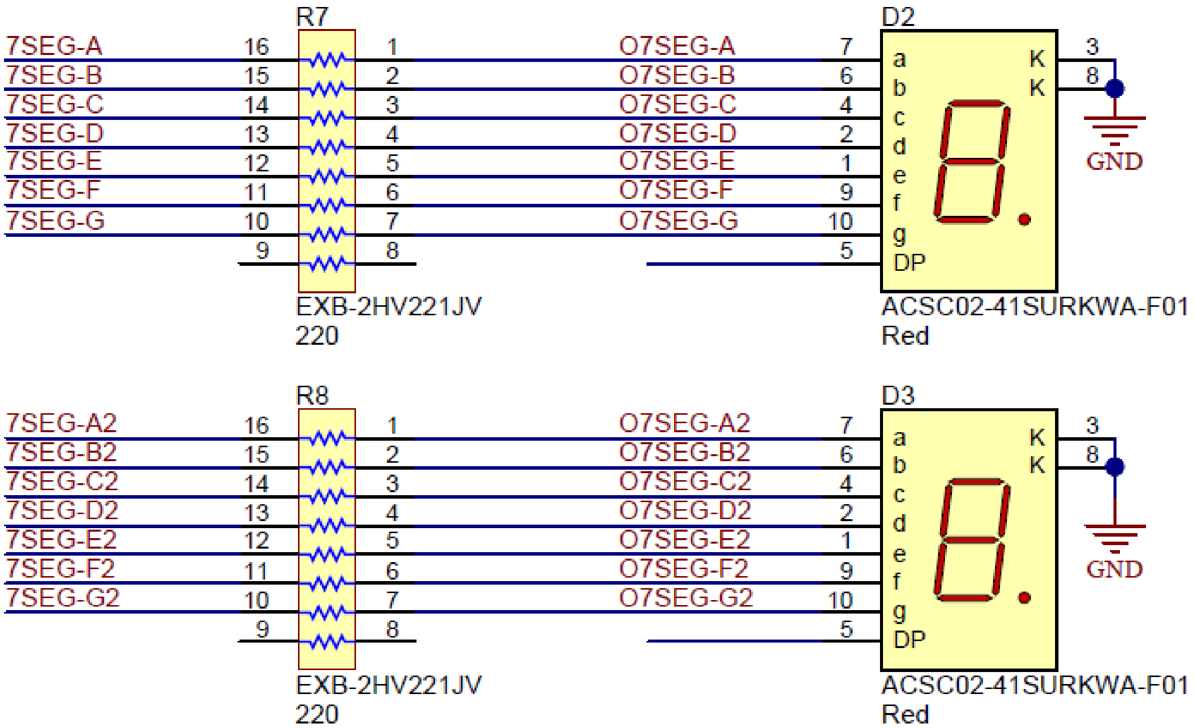

Figure 33: 7-Segment Displays

8.2 Bill of Materials

To download the Bill of Materials, see the design files at http://www.ti.com/tool/TIDA-00828

Table 7: Sensor PCB BOM

Designator	Value	Description	Package	Part Number	Manufacturer	Qty
!PCB1		Printed Circuit Board		TIDA-00828	Any	1
C1, C5, C12, C13, C15	0.1uF	CAP CER 0.1UF 16V 5% X7R 0402	0402	GRM155R71C104JA88D	Murata Electronics North America	5
C2, C14	10uF	CAP, CERM, 10uF, 10V, +/-20%, X5R, 0603	0603	C1608X5R1A106M	TDK	2
C3	2.2uF	CAP, CERM, 2.2uF, 10V, +/-10%, X5R, 0603	0603	C0603C225K8PACTU	Kemet	1
C4	22uF	CAP, CERM, 22uF, 16V, +/-10%, X5R, 0805	0805	C2012X5R1C226K125AC	TDK	1
C6, C7	18pF	CAP, CERM, 18pF, 100V, +/-5%, C0G/NP0, 0603	0603	GRM1885C2A180JA01D	MuRata	2
C8	2200pF	CAP, CERM, 2200pF, 50V, +/-10%, X7R, 0603	0603	C0603X222K5RACTU	Kemet	1
C9, C11	220nF	CAP, CERM, 220nF, 10V, 10%, X7R, 0402	0402	C1005X7R1A224K050BB	TDK Corporation	2
C10	0.47uF	CAP, CERM, 0.47 µF, 6.3 V, +/- 10%, X5R, 0402	0402	GRM155R60J474KE19D	MuRata	1
C16, C18	0.1uF	CAP, CERM, 0.1 µF, 16 V, +/- 10%, X7R, 0402	0402	GRM155R71C104KA88D	MuRata	2
C17, C19	62pF	CAP, CERM, 62 pF, 50 V, +/-5%, C0G/NP0, 0402	0402	GRM1555C1H620JA01D	MuRata	2
D1	5.6V	Diode, Zener, 5.6V, 500mW, SOD-123	SOD-123	MMSZ5232B-7-F	Diodes Inc.	1
D2, D3	Red	LED, Red, SMD	6.9x10mm	ACSC02-41SURKWA-F01	Kingbright	2
J1		Connector, Receptacle, Micro-USB Type B, SMT	Connector USB Mini B	ZX62R-B-5P	Hirose Electric Co. Ltd.	1
L1	10uH	Inductor, Shielded, Ferrite, 10 µH, 0.4 A, 1.38 ohm, SMD	2.0x0.95x1.6mm	VLS201610ET-100M	TDK	1
R1	1.5K	RES 1.5K OHM 1/16W 5% 0402 SMD	0402	CRCW04021K50JNED	Vishay Dale	1
R2, R3	10.0	RES, 10.0, 1%, 0.063 W, 0402	0402	CRCW040210R0FKED	Vishay-Dale	2
R4	1M	RES,1M ohm, 5%, 0.063W, 0402	0402	RC0402JR-071ML	Yageo	1
R5	33	RES, 33 ohm, 5%, 0.1W, 0603	0603	CRCW060333R0JNEA	Vishay-Dale	1
R6	33k	RES, 33k ohm, 5%, 0.063W, 0402	0402	CRCW040233K0JNED	Vishay-Dale	1
R7, R8	220	RES, 220, 5%, 0.0625 W, Resistor Array - 8x1	Resistor Array - 8x1	EXB-2HV221JV	Panasonic	2
R10, R12, R13	0	RES, 0, 5%, 0.063 W, 0402	0402	RC0402JR-070RL	Yageo America	3
U1		Micropower, 150mA Low-Dropout CMOS Voltage Regulator, 5-pin SC-70, Pb-Free	MAA05A	LP5951MG-3.3/NOPB	Texas Instruments	1
U2		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)	DRL0005A	TPD2E001DRLR	Texas Instruments	1

U3		25 MHz Mixed Signal Microcontroller with 8 KB Flash, 4096 B SRAM and 31 GPIOs, -40 to 85 degC, 48-pin QFN (RGZ), Green (RoHS & no Sb/Br)	RGZ0048A	MSP430F5500IRGZR	Texas Instruments	1
U4, U5		1.8-3.3V Inductive Switch, DSG0008A	DSG0008A	LDC0851DSGR	Texas Instruments	2
Y1		Crystal, 24.000MHz, 18pF, SMD	3.2x0.8x2.5 mm	ABM8-24.000MHZ-B2-T	Abracon Corportation	1
J2		Header, 100mil, 3x1, Gold, TH	3x1 Header	TSW-103-07-G-S	Samtec	0
R9, R11	53.6k	RES, 53.6 k, 1%, 0.063 W, 0402	0402	CRCW040253K6FKED	Vishay-Dale	0

8.3 PCB Layout Recommendations

Table 8: Sensor PCB Layer Usage

Layer	Functionality
Top	Signals and components
Mid-layer 1	Ground
Mid-layer 2	Power
Bottom	Signals

Table 9: 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	Dielectric 1	FR-4	10.00mil	4.1	
5	Signal Layer 1	Copper	1.40mil		
6	Dielectric 2	FR-4	36.00mil	4.1	
7	Signal Layer 2	Copper	1.40mil		
8	Dielectric 3	FR-4	10.00mil	4.1	
9	Bottom Layer	Copper	1.40mil		
10	Bottom Solder	Solder Resist	0.40mil	3.5	
11	Bottom Overlay				

Table 10: Target Disk 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	32.00mil	4.1	
5	Bottom Layer	Copper	1.40mil		
6	Bottom Solder	Solder Resist	0.40mil	3.5	
7	Bottom Overlay				

8.3.1 Layout Prints

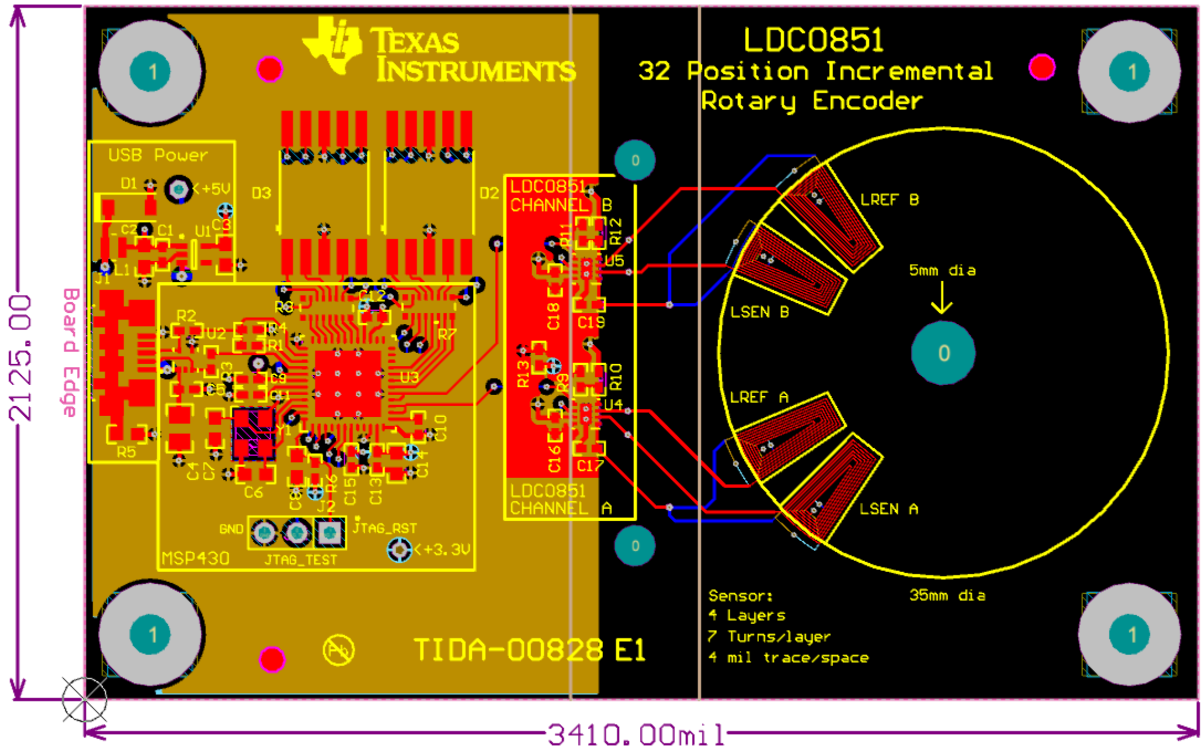

Figure 34: Sensor PCB Multi-layer

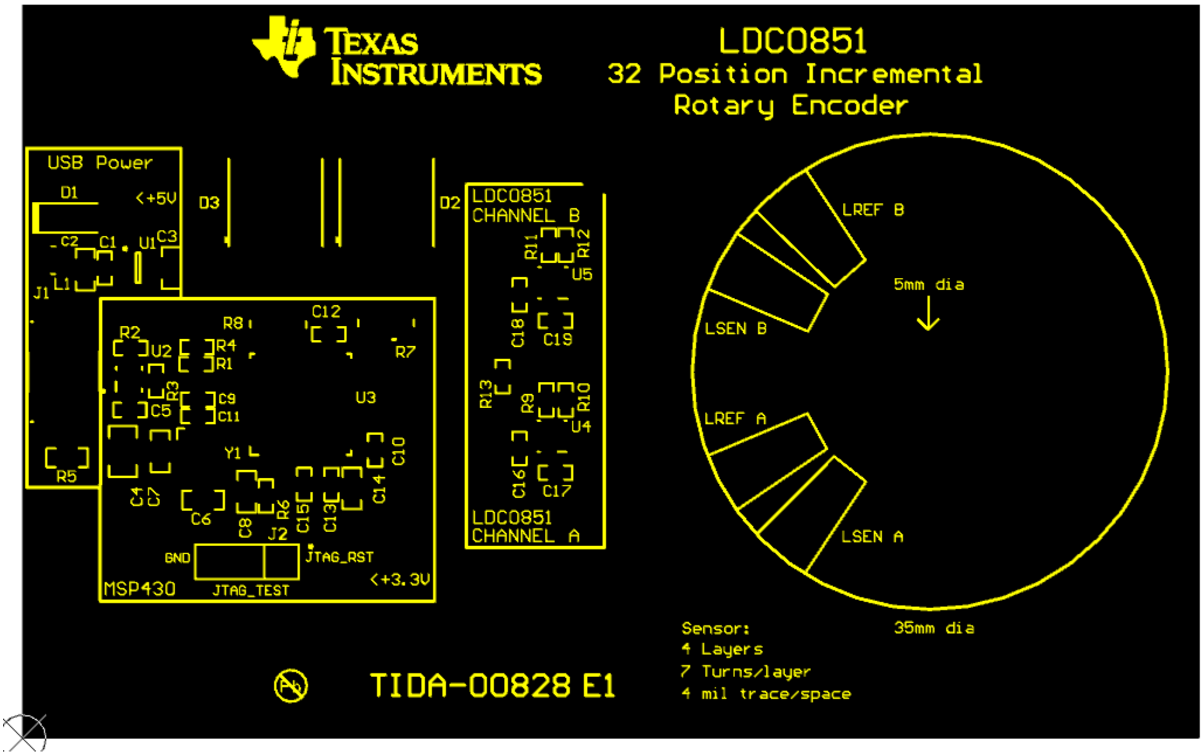

Figure 35: Sensor PCB Top Silkscreen

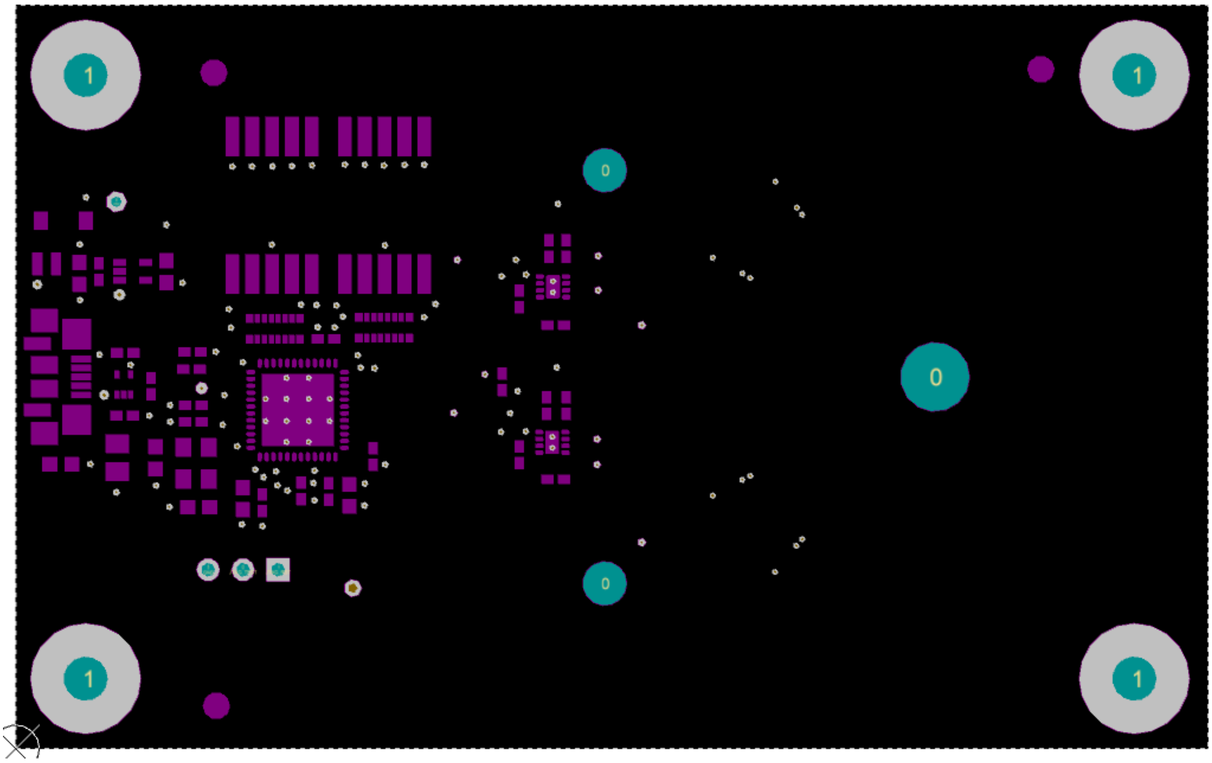

Figure 36: Sensor PCB Top Solder Mask

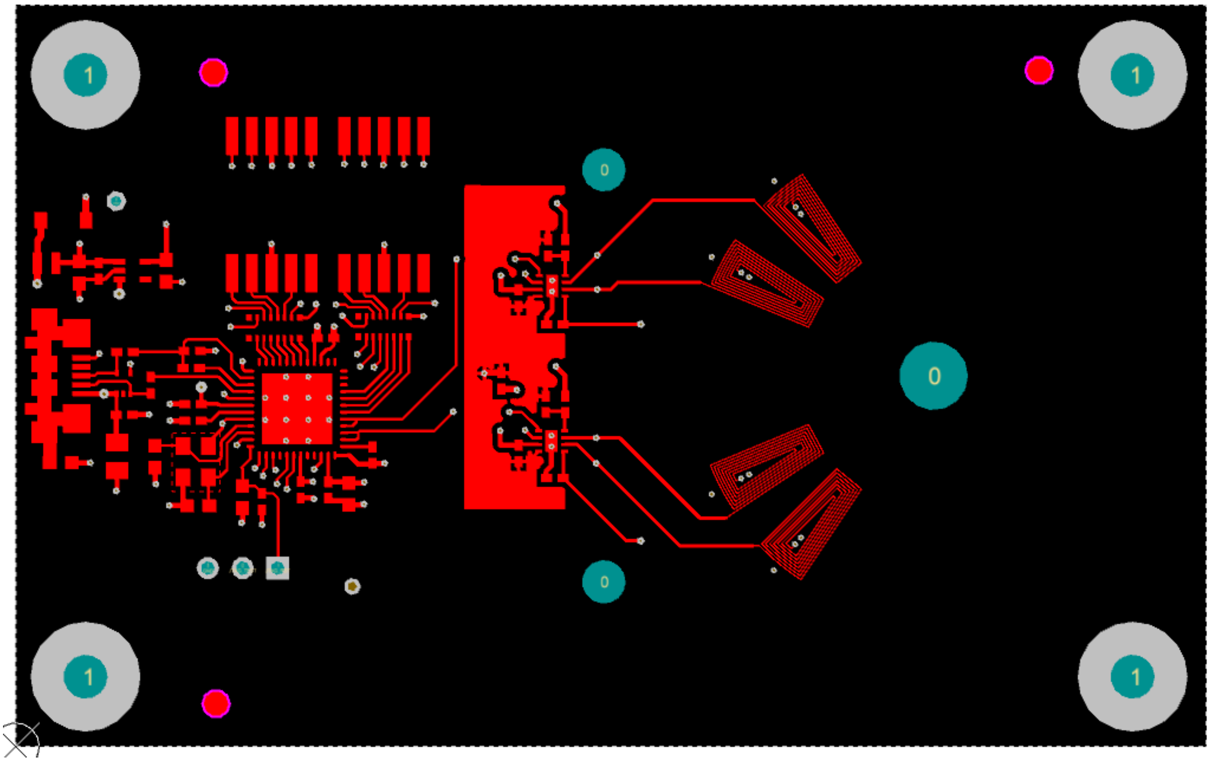

Figure 37: Sensor PCB Top Layer Routing

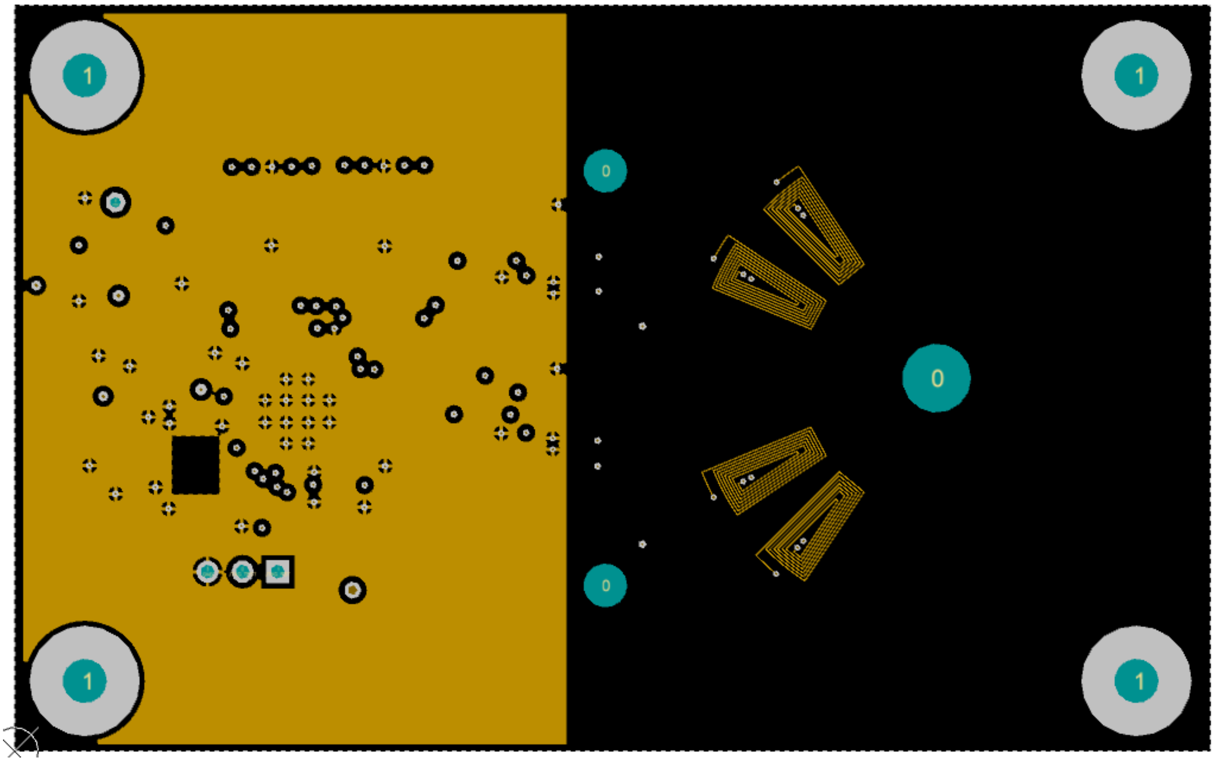

Figure 38: Sensor PCB Mid-layer 1

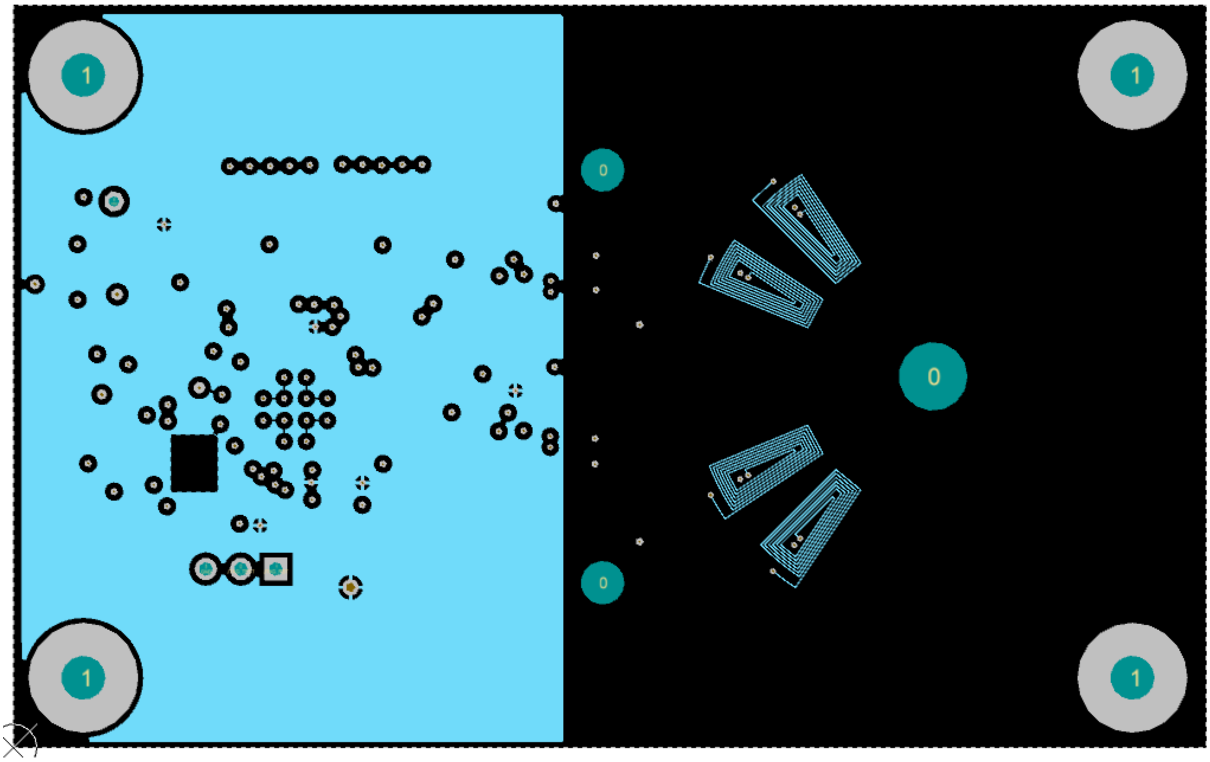

Figure 39: Sensor PCB Mid-layer 2

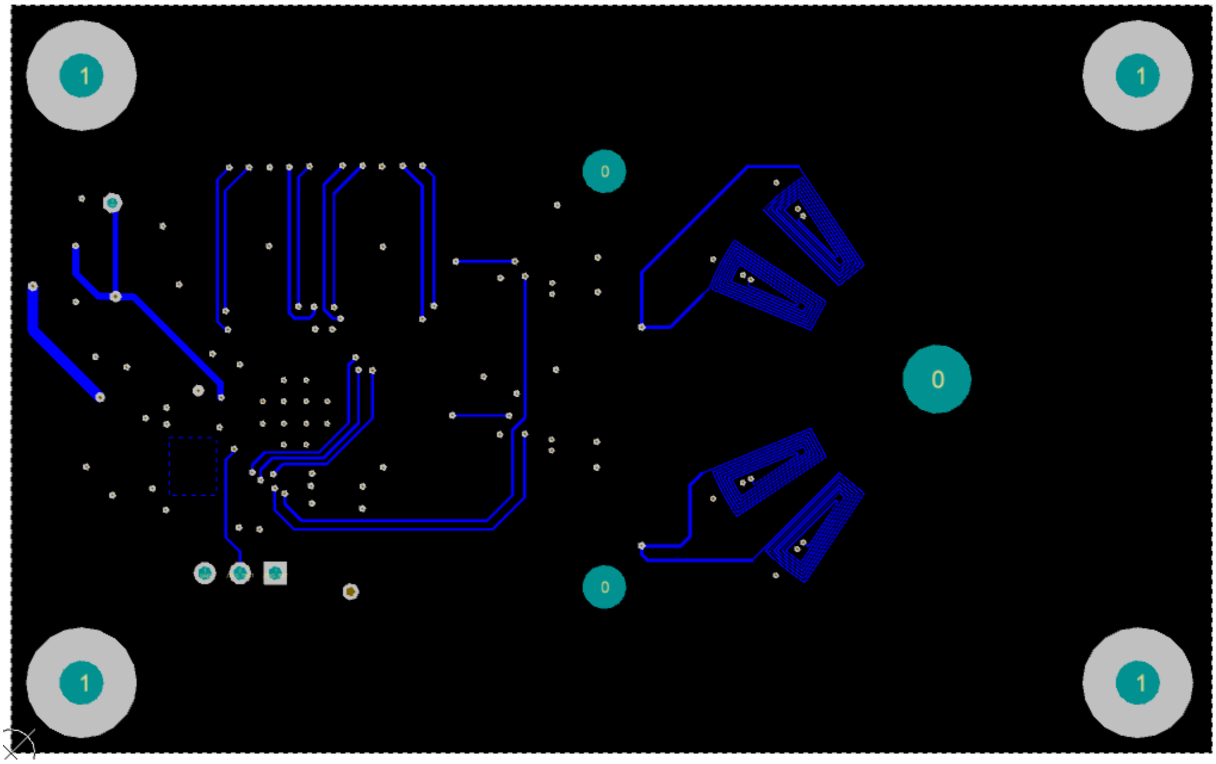

Figure 40: Sensor PCB Bottom Layer

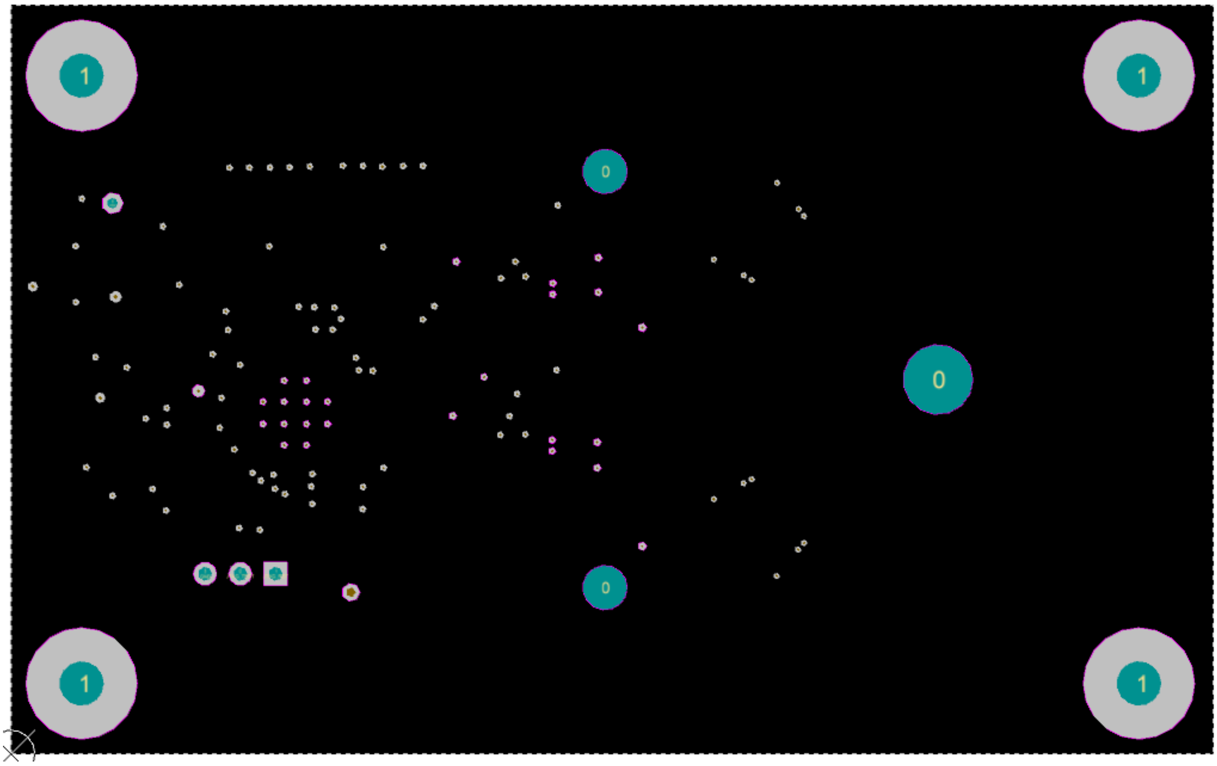

Figure 41: Sensor PCB Bottom Solder Mask

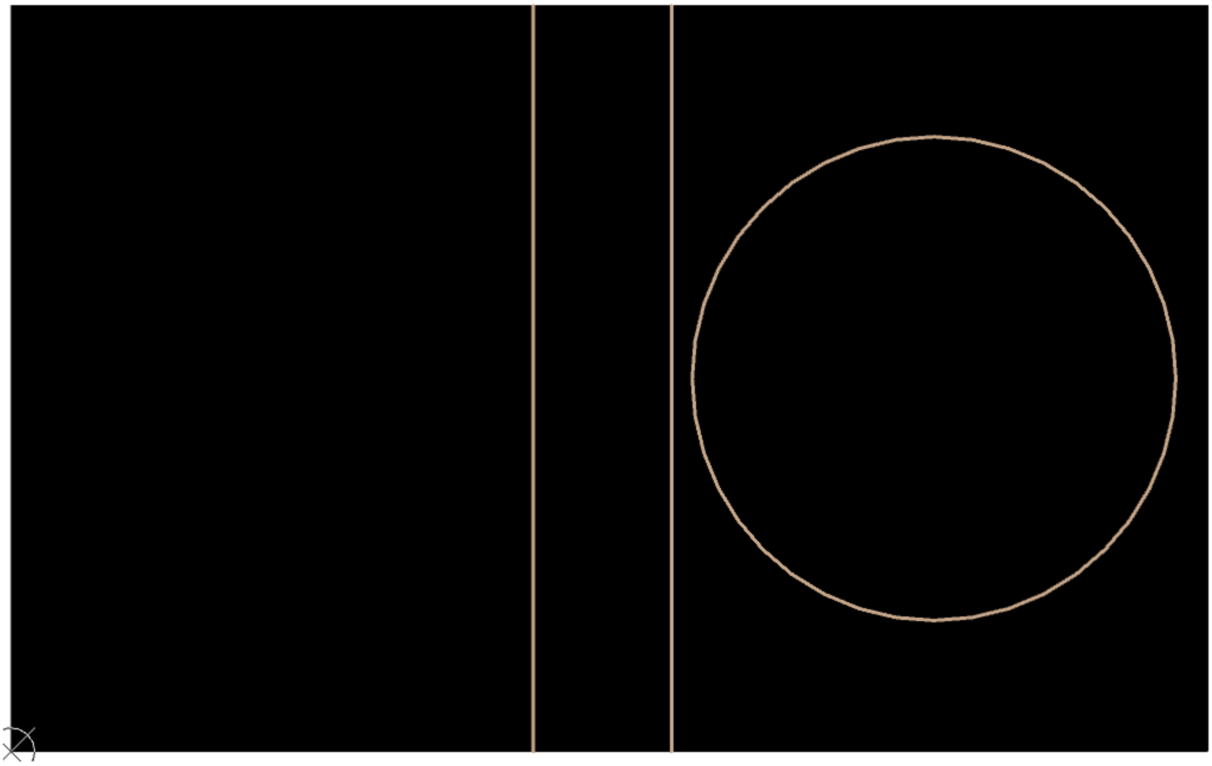

Figure 42: Sensor PCB Bottom Silkscreen

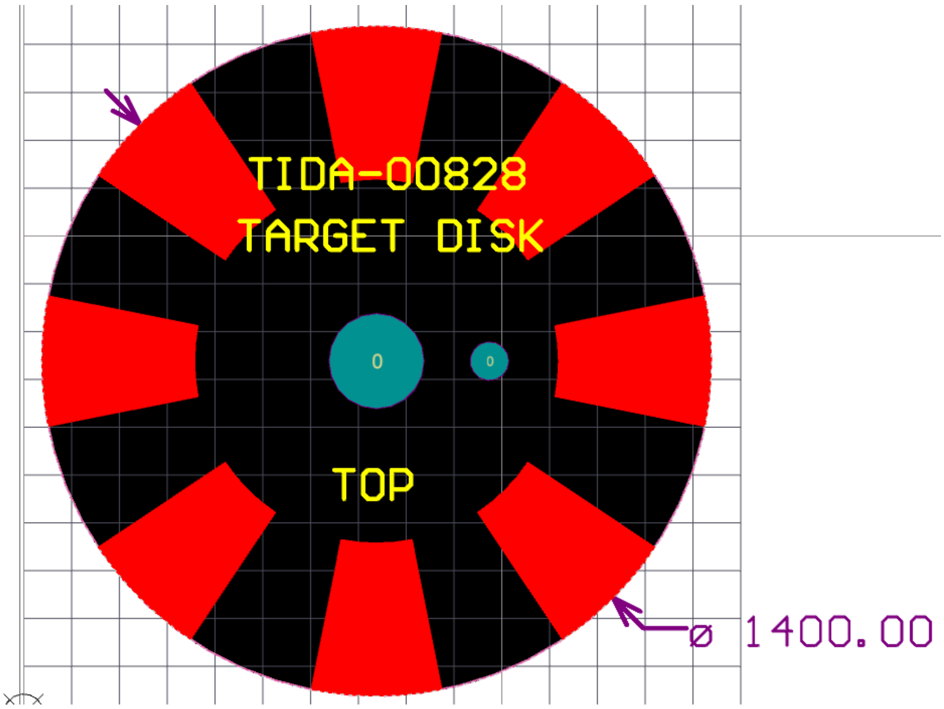

Figure 43: Target Disk PCB Top layer and Top Silkscreen

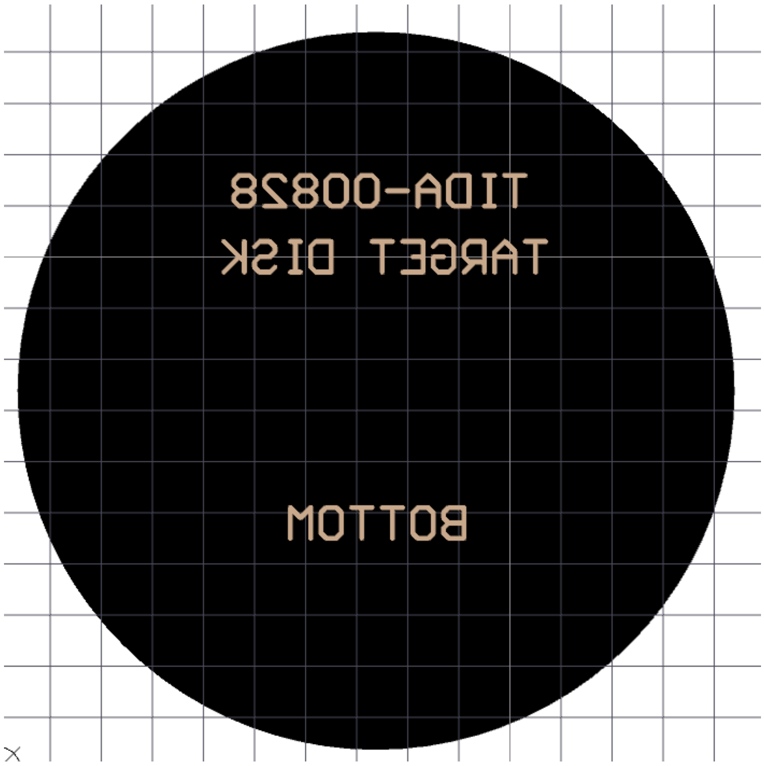

Figure 44: Target Disk PCB Bottom Silkscreen

8.4 Altium Project

To download the Altium project files, see the design files at http://www.ti.com/tool/TIDA-00828

8.5 Layout Guidelines

Sensor coil 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. Consequently, the size of the knob will increase or the number of positions per revolution will need to be reduced.

Minimize the amount of traces and board fills near the sensor. LCOM, LREF and LSENSE traces should be separated as much as possible to limit parasitic capacitances between them as shown in Figure 45. The blue traces from Reference inductor and Sense inductor are connected to LCOM, and should be routed with equivalent trace lengths and should not overlap the LSENSE and LREF traces.

To ensure matched response to the target, the geometries of the inductors need to be well matched.

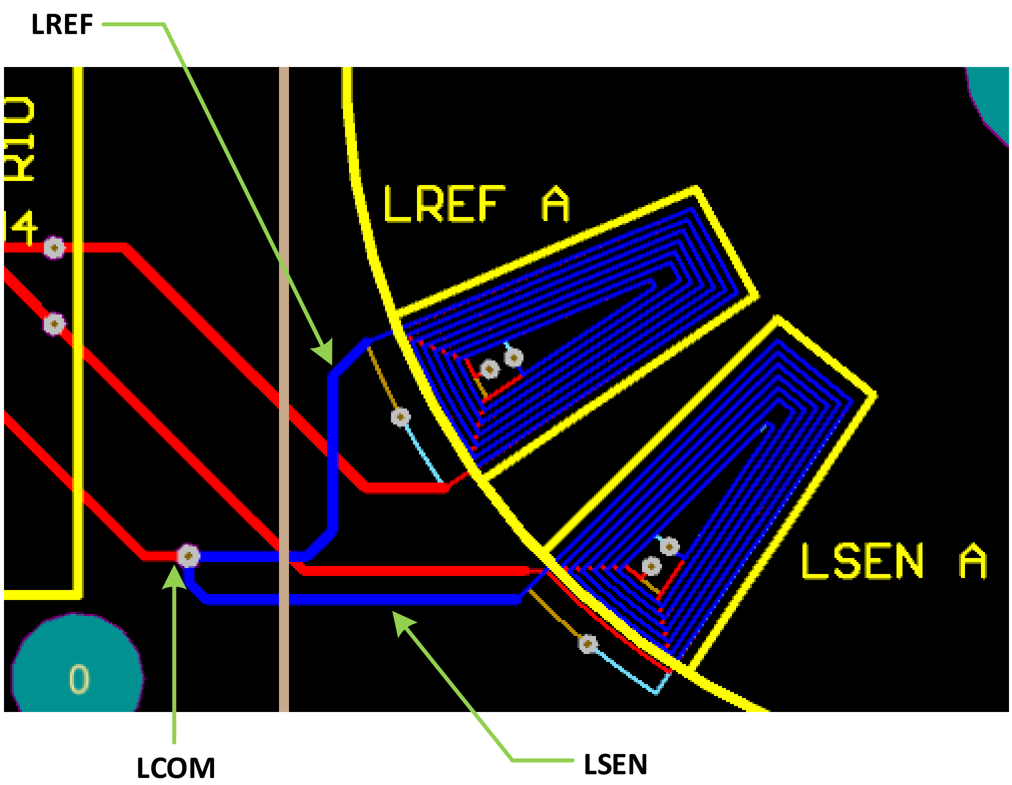

Figure 45: LSENSE, LREF and LCOM traces

8.6 Assembly Drawings

To download the Assembly Drawings, see the design files at http://www.ti.com/tool/TIDA-00828

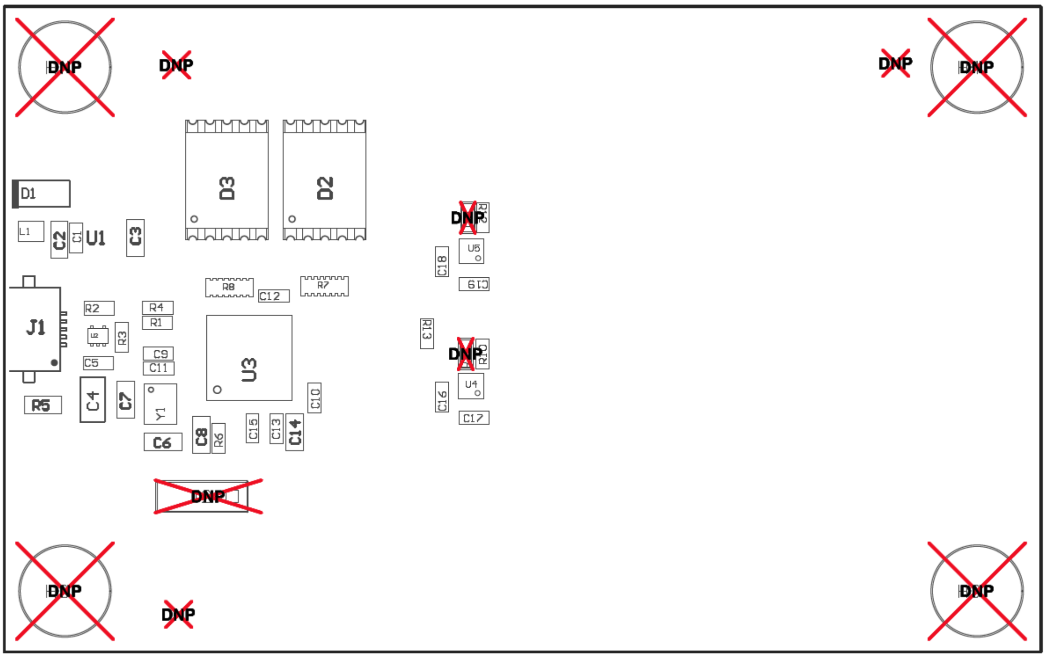

Figure 46: Sensor PCB Assembly Drawing

9 Mechanical Design Files

To download the mechanical design files, please see the link at http://www.ti.com/tool/TIDA-00828

9.1 Mechanical Components

The knob is composed of 5 pieces as shown below. All dimensions in mm.

Table 11: 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

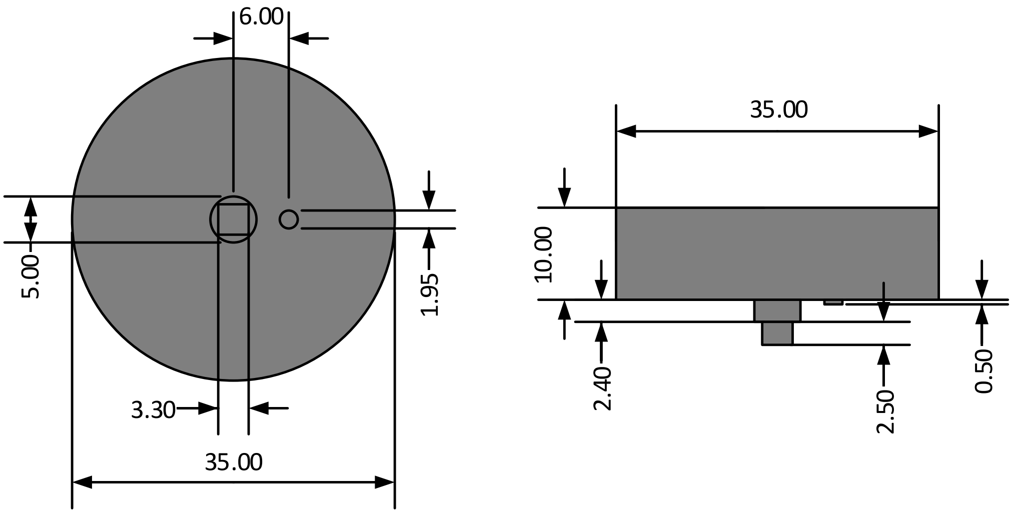

Figure 47: Knob

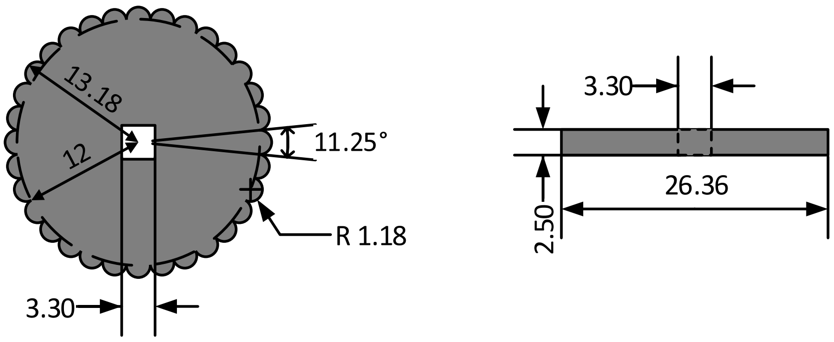

Figure 48: Index Wheel

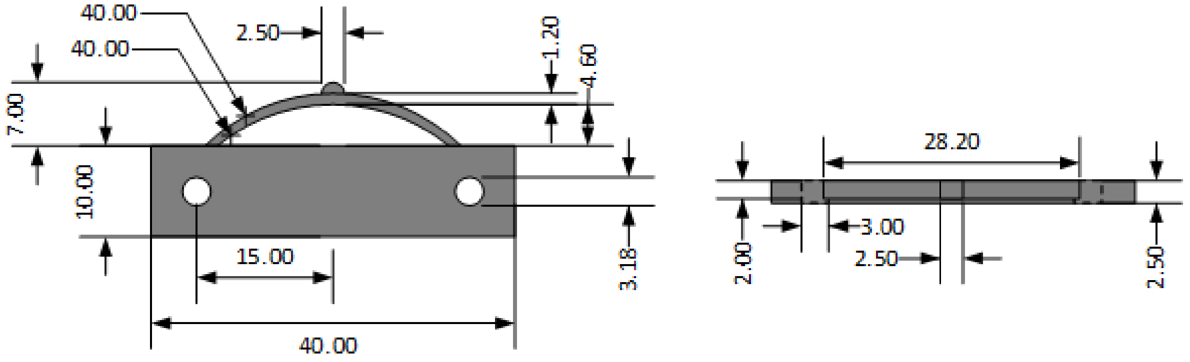

Figure 49: Indexer

9.2 Mechanical Assembly Sequence

Assembly is performed in the following sequence:

1. The Target Disk PCB is attached to the Knob using double-sided adhesive tape. Note that the Target Disk PCB and the Knob are keyed for proper alignment.
2. The Knob+Target Disk 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 attached to the bottom of the Sensor PCB using M3 bolts and nuts.

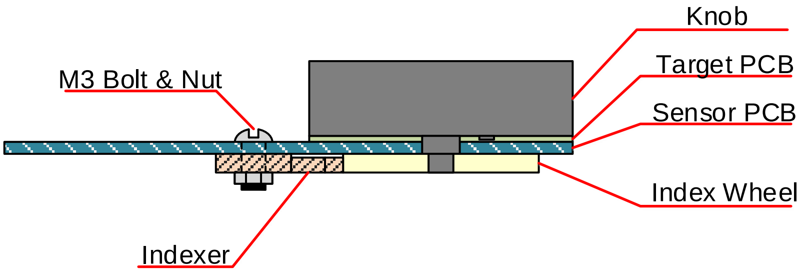

Figure 50: Mechanical Assembly

10 Software Files

To download the software files, please see the link at http://www.ti.com/tool/TIDA-00828

11 References

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12 About the Author

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