Design Guide: TIDA-060045

Accurate Low Latency Linear Position Sense Reference Design With Quad 3D Hall-Sensors

Description

This reference design demonstrates precision, low latency linear position sensing of a N45 magnet target using single or multiple equidistant placed 3D Hall-effect sensors TMAG5170 with high-speed 10MHz SPI, where the Z-axis and X-axis magnetic field strength as well as CRC data are transmitted in a single 32-bit frame for low latency and enhanced data integrity. The digital interface with 3.3V I/O is compatible to the C2000™ MCU LaunchPad and enables evaluation of our 3D Hall-effect sensing technology with a C2000™, Sitara or other MCUs.

Resources

TIDA-060045	Design Folder
TMAG5170	Product Folder
TMAG5170-CODE-EXAMPLE	Tool Folder
TI-MAGNETIC-SENSE-SIMULATOR	Tool Folder
LAUNCHXL-F280049C	Tool Folder

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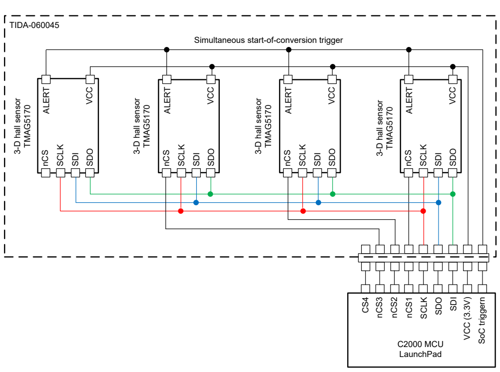
Features

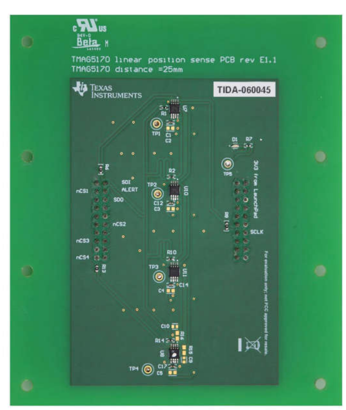
- Single-chip 3D Hall-effect sensor with integrated ADC and SPI interface reduce BOM and PCB size.
- Linear position accuracy typically ±0.15mm over 100mm range help achieve more precise linear motor transport systems.
- 3D Hall-effect sensors with configurable sensitivity ±25mT to ±100mT and ±75mT to ±300mT to help optimize measurement range and accuracy.
- Sample rates up to 8 kHz at low latency of 57.5us and 10MHz SPI enable higher speed position control.
- Dedicated ALERT pin enables simultaneous start-of-conversion of X,Y,Z axis across multiple 3D Hall-effect sensors.
- 3D Hall-effect sensors diagnostics features help detect and report both system and device-level failures.

Applications

- Linear Motor Position Sensor
- Servo Drive Position Sensor
- Position Sensor
- Proximity Switch

Design Images





1 System Description

Linear position sensing using Hall-effect sensors is used in many applications such linear servo drives, proximity switches in factory automation and linear motor transport systems. Depending on the application, either the sensor head with a Hall-effect sensor is moving over a static magnetic stripe with multiple poles, or a magnetic target is moving over a static Hall-effect sensor or an array of Hall-effect sensors.

Linear motor transport systems allow multiple magnetic movers traveling in one or even two dimensions with speeds up to 10m/s and a linear position accuracy and repeatability as low as 0.01mm. The magnetic field range present at the magnetic sensor depends on the mover's sense magnet and the distance between the mover magnet to the static multi-position sensor printed-circuit board (PCB).

Figure 1-1 shows the sensing principle of the linear position sensing using equally spaced high-precision linear 3D Hall-effect sensors. The distance between each 3D Hall-effect sensor is system specific and depends on the magnetic strength of the mover, the magnet diameter, the airgap and the desired position accuracy. Typical distances between adjacent 3D Hall-effect sensors are system specific and can be in the range of 10mm to 50mm.

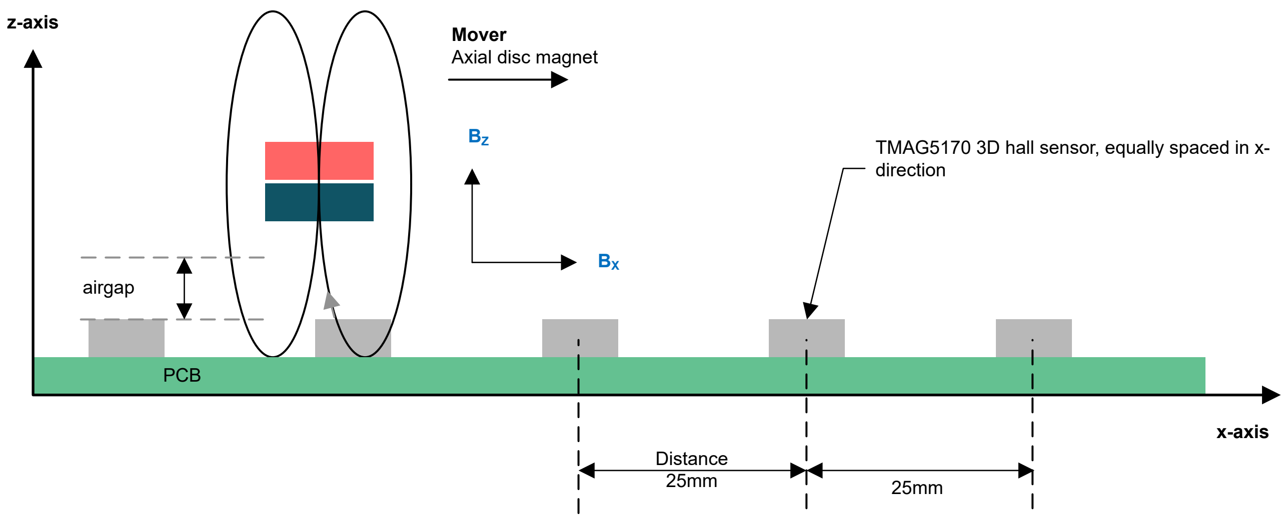


Figure 1-1. Cross PCB Section With Multiple 3D Hall-Effect Sensors

This reference design demonstrates precision, low latency linear position sensing of a N45 magnet target using four 3D Hall-effect sensors TMAG5170 with a 25mm displacement. A common start-of-conversion signal enables simultaneous measurement of the four 3D Hall-effect sensors. The Z-axis, X-axis, and CRC data measured with the TMAG5170 are transmitted in a single 32-bit frame over 10MHz SPI for low latency and enhanced data integrity. The data can be read out through SPI either sequentially using the chip-select of the corresponding 3D Hall-effect sensors or all four sensors in parallel through an MCU. The digital interface with 3.3V I/O is compatible to the C2000™ MCU LaunchPad and enables evaluation of our 3D Hall-effect sensing technology with a C2000™, Sitara or other MCUs.

1.1 Key System Specifications

The key specifications of this reference design are provided in Table 1-1. The reference design can be directly connected to a C2000 MCU LaunchPad.

Table 1-1. Key Design Specifications

PARAMETER	VALUE (TYPICAL)	COMMENT
Maximum sensing range	100mm	
Position accuracy	±0.15mm (±0.15%)	Measured at 25°C
3D Hall-effect sensor	TMAG5170A1	±100mT (MAX) for A1, drop-in version A2 supports ±300mT(MAX)
Sensor full-scale range	±50mT (Z-Axis), ±25mT (X-Axis)	Programmable ±25mT, ±50mT, ±100 mT
Number of sensors	4	Scalable
Sensor distance (x-axis)	25mm	Selected for 25mm magnetic
Sensor distance to magnet (y-axis)	1.52mm	adjustable
Moving magnet	N45-1350	NdFeB axial disc magnet: , 1350mT, 25mm diameter, 3mm height
Sensor sample rate	4kHz	8kHz possible
Simultaneous sensing	Yes	All four TMAG5170 are triggered at the same time
SPI to host MCU	up to 10MHz	
Latency	57.5us	Time from effective sampling point to ADC results ready to read through SPI
Interface to host MCU (1)	3.3V I/O	Compatible to C2000 LaunchPad interface, refer to table 4-1 and 4-2 pin assignment
Supply voltage	3.3V	

2 System Overview

2.1 Block Diagram

The block diagram of this reference design is shown in Figure 2-1. A dedicated start of conversion pin (ALERT), enables simultaneous sampling of all 3D Hall-effect sensors by the host MCU and enables low jitter synchronization of the position sampling time with respect to the power stage and segment control algorithms.

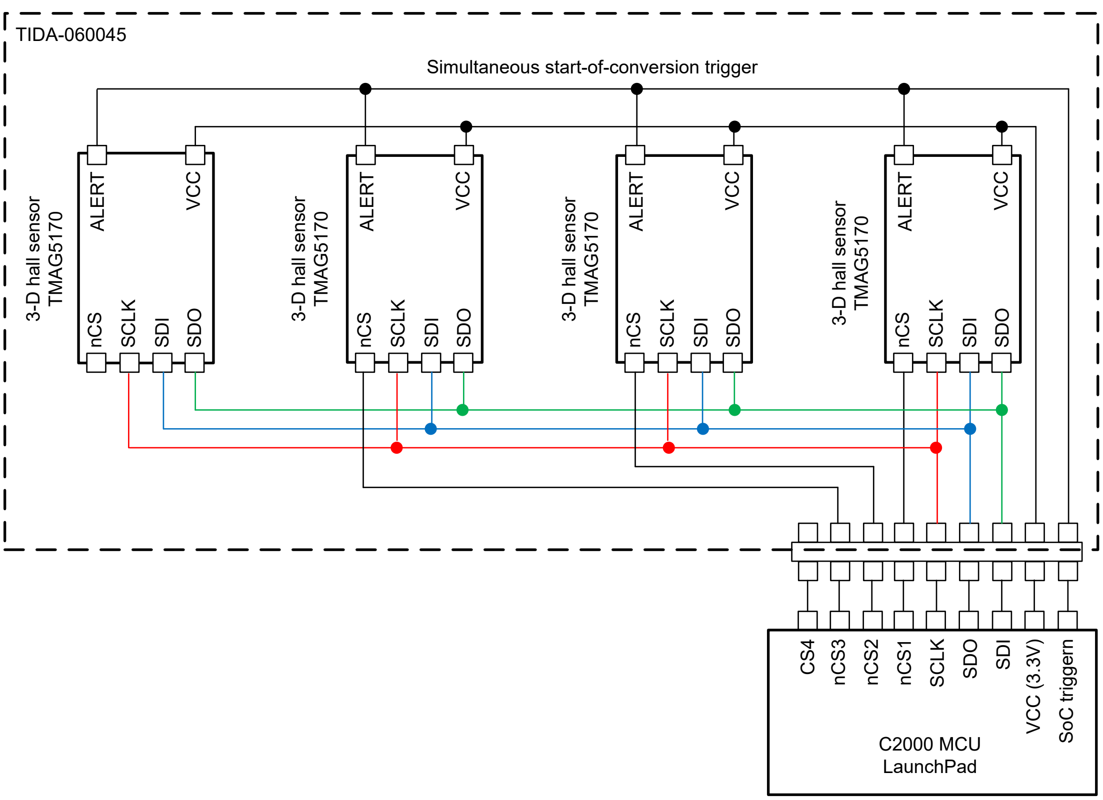


Figure 2-1. System Block Diagram

2.2 Design Considerations

Linear motor transport systems enable multiple magnetic movers travelling in one or even two dimensions with speeds up to 10m/s and a linear position accuracy and repeatability as low as 0.01mm. The magnetic field range present at the magnetic sensor depends on the mover's sense magnet and the distance between the mover magnet to the static multi-position sensor printed-circuit board (PCB). Typically, the magnetic field ranges from 50mT to 300mT. Due to space requirements, small packages with highly integrated 3D Hall-effect sensor system-on-chip (SoC) are an advantage. An ambient operating temperature of the sensor beyond 85C, such as 125C, ambient enable higher power densities, while still capturing accurate sensor data under these extreme conditions. Since the position of multiple movers within one segment need to be detected at the same time, simultaneous sampling and low latency position measurement are important. 3D Hall-effect sensors with low latency digital interface offer an advantage over analog output SoC due to higher robustness against noise. A further advantage of an SoC with digital interface is the option to integrate diagnostics and monitoring of the SoC, for example die temperature, Hall-effect element or supply voltage diagnostics to increase system reliability.

Since the maximum field strength in Z-axis and X-axis can possibly not be identical, a 3D Hall-effect sensor which allows for individual range programming and optimization of each magnetic field axis helps support a higher position resolution and accuracy. Example system requirements of linear motor transport systems and the impact on the 3D Hall-effect sensor specifications are show in Table 2-1.

Table 2-1. Example Requirements for Magnetic Sensors for Linear Motor Transport Systems

PARAMETER	EXAMPLE VALUE	IMPACT TO POSITION SENSOR SoC
Mover speed	up to 10m/s	Impacts sensor sampling rate, closed loop position control frequency can be 4kHz or higher.
Mover position accuracy/repeatability	as low as 0.01mm	Impacts sensor resolution, accuracy and minimum displacement between adjacent sensors.
Sensor technology	3D/2D Hall-effect sensor	3D Hall-effect sensors enable two-dimensional position sensing.
Sensor magnetic field range	50mT … 300mT	Full-scale magnetic field strength linear input range
Sensor resolution	Typical 12-bit resolution	SoC with programmable magnetic field range adjustment allow adjust input range for each axis and help increase resolution and accuracy.
Sensor interface	Analog or serial digital	Interface to MCU
Sensor latency	as low as 100us	Higher speed SPI, for example... 10MHz SPI help reduce system latency.
Simultaneous sampling of multiple movers position	Sensor with low-jitter start-of-conversion capability.	Sensor with hardware pin or SPI command-based start-of conversion signal input.
Sensor solution PCB area	As small as possible.	Integrated 3D Hall-effect SoC with digital interface enable smaller system footprint.
Operating temperature range	Small form-factor and high-power density lead to higher temperature inside a segment.	3D Hall-effect SoC with greater 85C ambient temperature operating range.
EMC immunity	SPI interface with CRC	A digital interface with CRC offers higher robustness against impulse noise.
System reliability, predictive maintenance and fault detection	3D Hall-effect sensor, supply voltage, die temperature monitoring	Enable through for example sensor with SPI and integrated diagnostics.

2.3 Highlighted Products

The TMAG5170 is a high-precision linear 3D Hall-effect sensor designed for a wide range of industrial and personal electronics applications. The high level of integration offers flexibility and accuracy in a variety of position sensing systems. This device features 3 independent Hall-effect sensors at X, Y, and Z axes. A precision signal-chain along with an integrated 12-bit ADC enables high accuracy and low drift magnetic field measurements while supporting a sampling of up to 20ksps. On-chip temperature sensor data is available for system-level drift compensation. Among the many features of TMAG5170 are:

- Independently selectable X, Y, and Z magnetic ranges:
  - TMAG5170A1: ±25, ±50, ±100 mT
  - TMAG5170A2: ±75, ±150, ±300 mT
- Dedicated ALERT pin enables simultaneous start-of-conversion of X,Y,Z axis across multiple 3D Hall-effect sensors.
- Pseudo-simultaneous sampling mode
- 10MHz serial peripheral interface (SPI) with cyclic redundancy check (CRC)
- 2.3V to 5.5V supply voltage range
- Operating temperature range: –40°C to +150°C
- Oversampling which reduces output noise by averaging 2,4,8,16, or 32 conversions

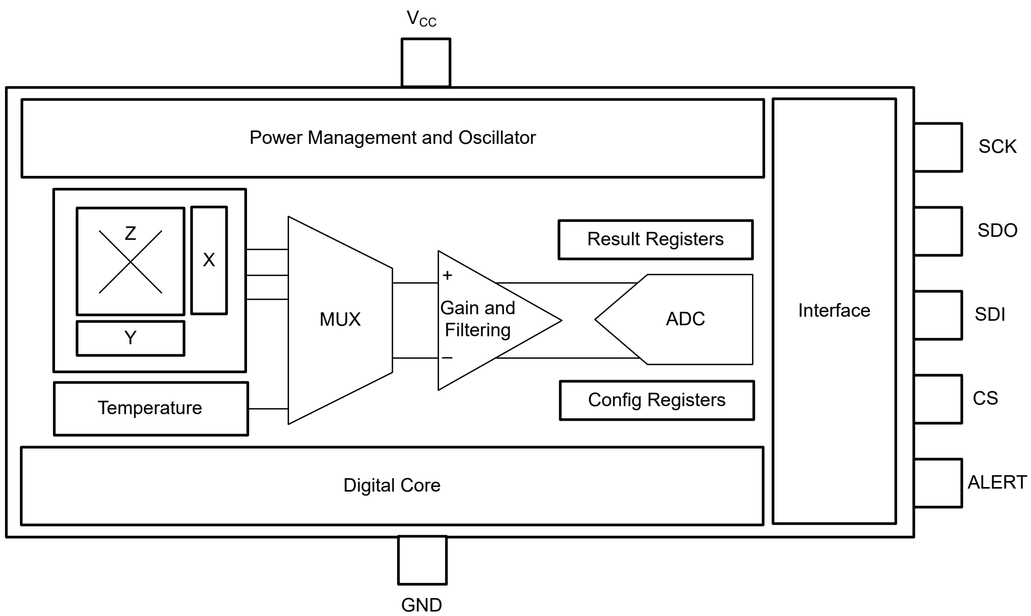


Figure 2-2. TMAG5170 Functional Block Diagram

3 System Design Theory

3.1 Hardware Design

Due to the high integration with the TMAG5170 3D Hall-effect sensor, the schematic is rather simple. The schematic is shown with Figure 3-1.

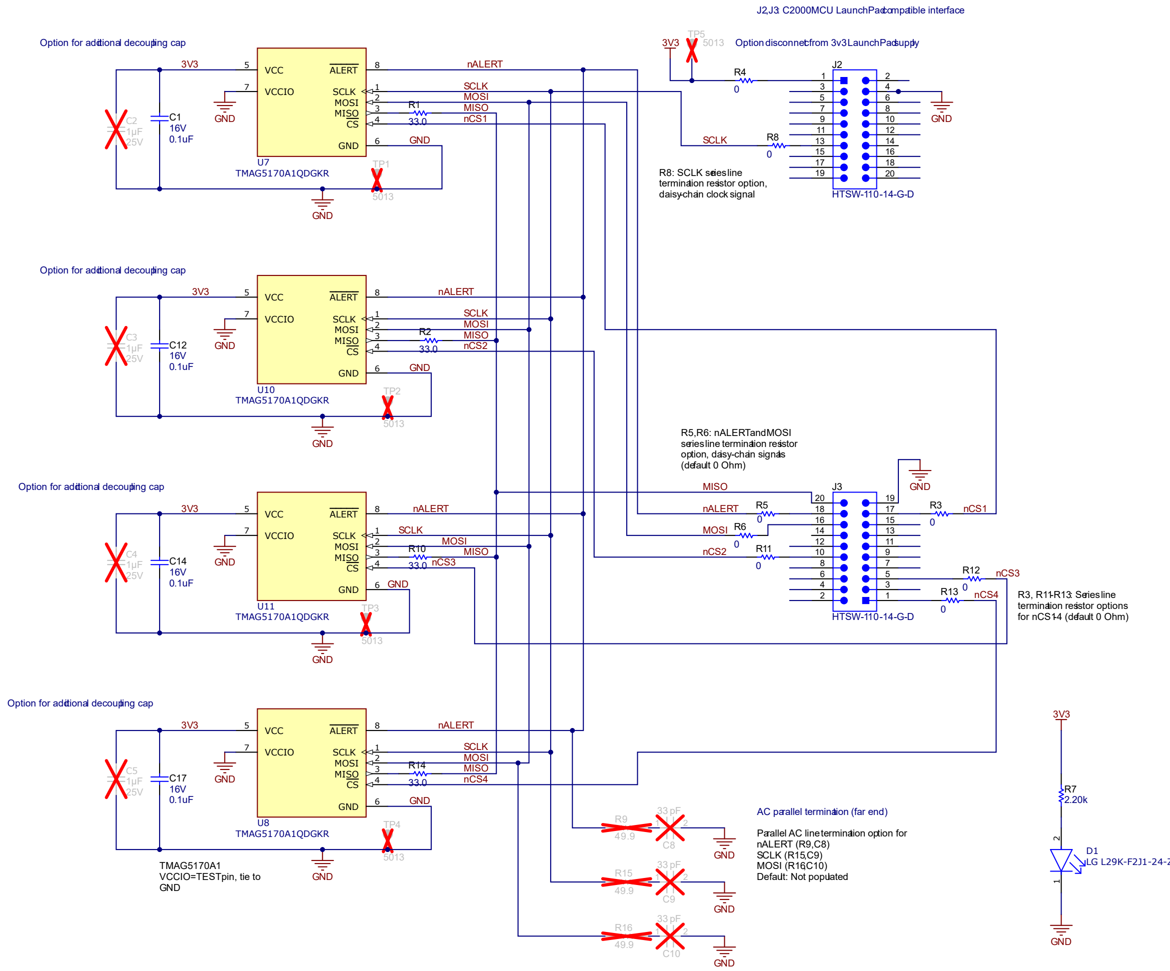


Figure 3-1. Quad TMAG5170 Schematic

The following description takes the U7 TMAG5170 as an example and applies to the remaining three TMAG5170 if not noted otherwise.

A 100nF decoupling capacitor C1 is added closed to the VCC and GND pin. An optional additional 1uF capacitor C2 is added in case of a more noise 3.3V supply, but was not populated in this design.

The TMAG5170 TEST pin, in the Altium schematic symbol named VCCIO, need to be tied to GND. The TMAG5170 nALERT pin is an input and is used to simultaneously trigger the start of the A/D converters with all four TMAG5170. The nALERT pin is routed from the connector J3-18 as daisy-chain from the first TMAG5170 (U7), through U10 and U11 to the last TMAG5170 (U8) for better signal integrity. A series line termination resistor option R5 at connector J3-18 was added as well as a far end parallel AC termination option with R9 and C8 (not populated by default) at U8 for test and validation. The SPI signals SCLK and SDO (MOSI) were routed as daisy-chain too, with a series line termination resistor and a far end parallel AC termination. For the SPI signal SDI (MISO), each SDO (MISO) output of the four TMAG5170 have a 33Ω termination, such as R1 with U7. The signals are routed in star topology and length matched from each TMAG5170 to a junction point where the signals are combined and routed to the connector J3-1. The SPI chip-select signals nC1, nC2, nC3, nC4 of each TMAG5170 where routed from the corresponding header J3 and each has a series line termination resistor option, such as R3 for U7.For SPI signal integrity tests, a GND test point TP1 through TP4 was added.

For SPI signal layout guidelines refer to chapter 5.

The test points TP1 through TP5 were not assembled on the final PCB to not disturb the TMAG5170 magnetic field measurement. A green LED D1 was added to indicate that the 3.3V supply is present.

The 3.3V input supply (+/10% tolerance) at the connecter J2-1 is routed to all four TMAG5170. A 0Ω resistor R4 is added for additional test and validation options. Either replace R4 with a ferrite bead for better RF noise rejection, if needed, or remove R4 to disconnect the 3.3V supply from the C2000 MCU Launch and use a separate 3.3V supply from a bench supply through test point TP5. In this reference design the 3.3V supply was used from the C2000 MCU LaunchPad.

3.2 Software Design

To validate this reference design a TI internal test software has been developed with the TMS320F280049C LaunchPad using the TMAG5170 header files, TMAG5170-CODE-EXAMPLE, and the C2000WARE software development kit for C2000 MCUs.

3.2.1 TMAG5170 SPI Frame

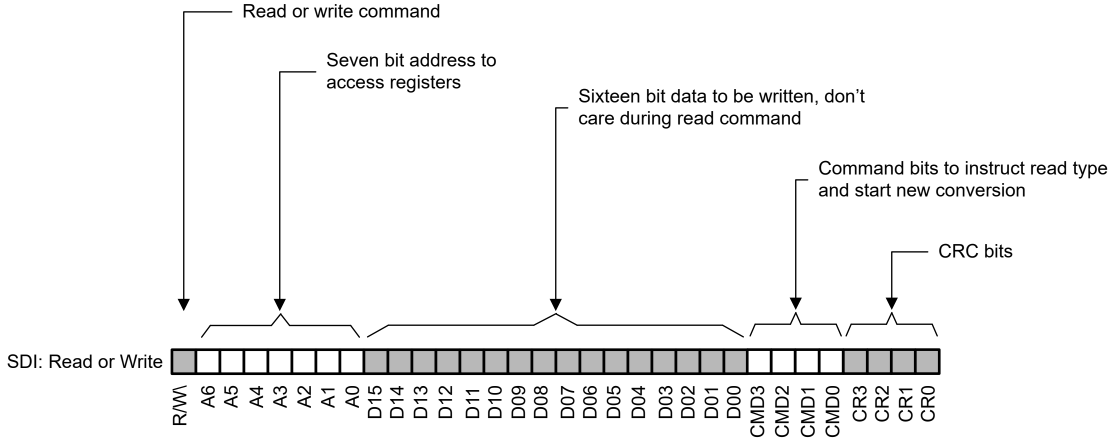
The TMAG5170 supports a 4-wire SPI. The primary communication between the device and the external microcontroller is through the SPI bus that provides full-duplex communication. The external microcontroller works as the SPI controller that sends command requests on the SDI pin and receives device responses on the SDO pin. The TMAG5170 device works as the SPI peripheral device that receives command requests and sends responses (such as status and measured values) to the external microcontroller over the SDO line. The TMAG5170 supports a fixed 32-bit frame size to communicate with a controller device. The 32-bit frame can be configured through DATA_TYPE register bits to support a regular single register read or write data packet, or a special packet to read two-channel data simultaneously.

The serial clock SCLK represents the host controller clock signal. This clock determines the speed of data transfer and all receiving and sending are done synchronously to this clock. The output data on the SDO pin transitions on the falling edge of the SCK and input data on the SDI pin is latched on the rising edge of the SCLK.

The nCS activates the SPI. As long as the nCS signal is high, the TMAG5170 does not accept the SCLK signal or the serial-data-in (SDI), and the serial-data-out (SDO) is in high impedance. The nCS needs to be held low for the duration of a communication frame without toggling to maintain proper communication. The SPI is disabled each time nCS is brought from low to high.

3.2.1.1 Serial Data In 32-Bit Frame

The serial-data-in (SDI) line is used by the host controller to configure the TMAG5170 registers, start a new conversion, or send a read command. The SDI bits are latched with each SCLK rising edge when the nCS pin is low. Figure 3-2 explain the SDI frame. There are 4 command bits in the SDI line to select the status bit for the next frame or start a new conversion.



CMD0	CMD0 = 0	No conversion start through command bits
	CMD0 = 1	Start of conversion at the CS going high
CMD1	CMD1 = 0	Display SET_COUNT [2:0] in STAT [2:0] bits at SDO next frame
	CMD1 = 1	Display DATA_TYPE [2:0] in STAT [2:0] bits at SDO next frame

* CMD2 & CMD3 are reserved bits
** SET_COUNT register bits indicate the rolling count of the conversion data set. The counter is reset after 111b.
*** DATA_TYPE register bits indicate the type of data being read through the SDO line

Figure 3-2. TMAG5170 32-Bit SDI Frame

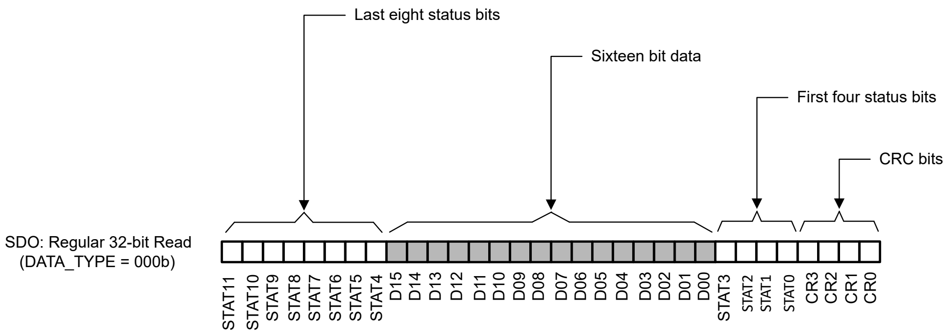
3.2.1.2 Serial Data Out 32-Bit Frame

The Serial-data-out (SDO) line is used by the controller to read the data from the TMAG5170. The TMAG5170 shifts out command responses and ADC conversion data serially with each rising SCK edge when the CS pin is low. This pin assumes a high-impedance state when CS is high. Based off the DATA_TYPE bit setting, the TMAG5170 supports two different SDO frames:

- Regular 32-Bit SDO Read frame
- Special 32-Bit SDO Read

The Regular 32-Bit SDO Read frame is used for TMAG5170 configuration in this reference design. The Special 32-Bit SDO Read frame is used in this design to read the read the Z-axis and X-axis magnetic field strength in a single frame for lowest latency.

With DATA_TYPE = 000b, the TMAG5170 supports a regular 16-bit register read during the 32-bit SDO frame as explained in Figure 3-3. In this read mode, 12-bit status bits are displayed. All the status bits except for the ERROR_STAT bit are directly read from the status registers. The ERROR_STAT bit indicates if any error bit set in the device.

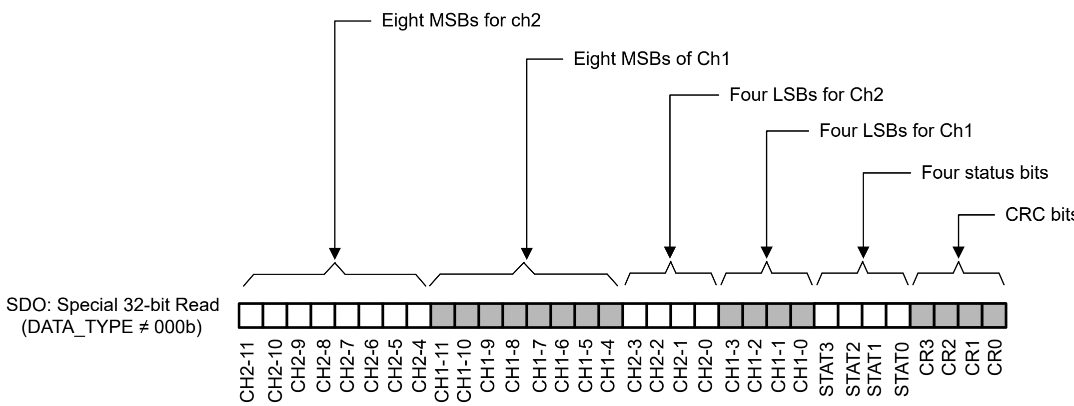


STAT11	STAT10	STAT9	STAT8	STAT7	STAT6	STAT5	STAT4	STAT3	STAT2	STAT1	STAT0
PREV_CRC_STAT	CFG_RESET	ALRT_STATUS1	ALRT_STATUS0	X	Y	Z	T	ERROR_STAT	Follows CMD1 instruction from previous frame		

* PREV_CRC_STAT indicates if there is any CRC error in the immediate past frame
** ERROR_STAT indicates if there is any error bit flipped in the part
*** STAT10 to STAT4 indicate select status bits from the CONV_STATUS and AFE_STATUS registers

Figure 3-3. TMAG5170 Regular 32-Bit SDO Frame

With DATA_TYPE > 000b, the TMAG5170 supports a special 32-bit SDO frame for two-channel simultaneous data read. Each channel data is limited to 12 bits. This feature is useful for systems requiring faster data throughput while performing multi-axis measurements. Figure 3-4 explains the detail construction of the special 32-bit SDO frame. When the device is set to special 32-bit read, the device continues to deliver the 2-channel data set through the SDO line during consecutive read or write cycles. DATA_TYPE bits must be reset to get back to a regular read cycle. Only four status bits are transmitted in this mode. All the status bits except for the ERROR_STAT bit are directly read from the status registers. The ERROR_STAT bit indicates if any error bit set in the device. The status bits, STAT[2:0] can be changed based off CMD1 value in the previous frame.



STAT3	STAT2	STAT1	STAT0
ERROR_STAT	Follows CMD1 instruction from previous fram		

* ERROR_STAT indicates if there is any error bit set in the device

Figure 3-4. TMAG5170 Special 32-Bit SDO Frame

For more information on the TMAG5170 SPI such as CRC refer to the *TMAG5170 data sheet*.

3.2.2 TMAG5170 Register Configuration

The SPI on the TMS320F280049C MCU was setup as host with 10MHz SPI clock and two consecutive 16-bit SPI data transfers to support 32-bit frames. The serial clock was configured to low level before and after the SPI transfer. The SPI receive data (MISO) is latched on the rising SPI clock edge (SCLK) and the transmit data (MOSI) is transmitted on the falling clock edge.

After start-up the TMAG5170 registers were configured using the regular 32-Bit SDO read frame. Table 3-1 shows the default configuration with the N45 magnet used in this reference design.

Table 3-1. TMAG5170 Register Configuration

REGISTER OFFSET [HEX]	VALUE [HEX]	COMMENT
0h	0130h	No averaging, sense magnetic temp coefficient 0.12%/deg C (NdBFe), active trigger mode
1h	0345h	XZX channel enabled (pseudo-simultaneous sampling),Z range ±50mT, X range ±50mT
2h	0400h	Conversion start at nALERT pulse (falling edge)
3h	0000h	Default
4h	7D83h	Default
5h	7D83h	Default
6h	7D83h	Default
7h	6732h	Default
8h	0040h	Read only
9h	0058h	Read only
Ah	0000h	Read only
Bh	7FD0h	Read only
Ch	4500h	Read only
Dh	0000h	Read only
Eh	0300h	Read only
Fh	0040h	CRC enabled in SPI communication (default)
10h	0000h	Reset OSC counter (default)
11h	0000h	Default
12h	0000h	Default
13h	0000h	Read only
14h	0000h	Read only

After the TMAG5170 register configuration was completed, a write command to each TMAG5170 to set the special 32-bit SDO frame. In this mode the field strength of the Z and X axis and CRC are transmitted a single 32-bit frame to reduce the overall latency.

Table 3-2. TMAG5170 Register Setting for Special 32-Bit SDO Frame

REGISTER OFFEST [HEX]	VALUE [HEX]	COMMENT
2h	0480h	Conversion start at nALERT pulse (falling edge). Enable special 32-bit SDO frame (set bit 8)

For the absolute angle measurement using CORDIC, sensor data from the Z-axis and the X-axis are required to calculate an accurate angle. The magnetic field data collected at different times through the same signal chain with a single A/D converter introduces an error in the angle calculation. The TMAG5170 offers pseudo-simultaneous sampling data collection modes to eliminate this error. Figure 3-5 shows the example for the XZX channel mode (pseudo-simultaneous sampling mode) to collect XZX data and calculate the average X data from the dual X samples. Then the time stamps for the average X and Z sensor data are the same, assuming the X-axis signal frequency is significantly lower than the ADC sample rate.

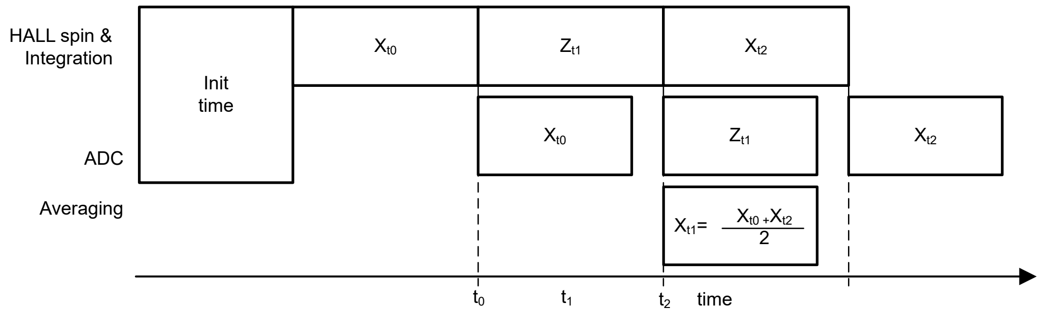


Figure 3-5. TMAG5170 Pseudo-Simultaneous Sample Mode

3.2.3 SPI and Start-of-Conversion Timing

The SPI and nALERT signal timing to trigger a simultaneous conversion of the Z-axis and X-axis and read the data of all four 3D Hall-effect sensors at a 4kHz sample rate are shown in Figure 3-6.

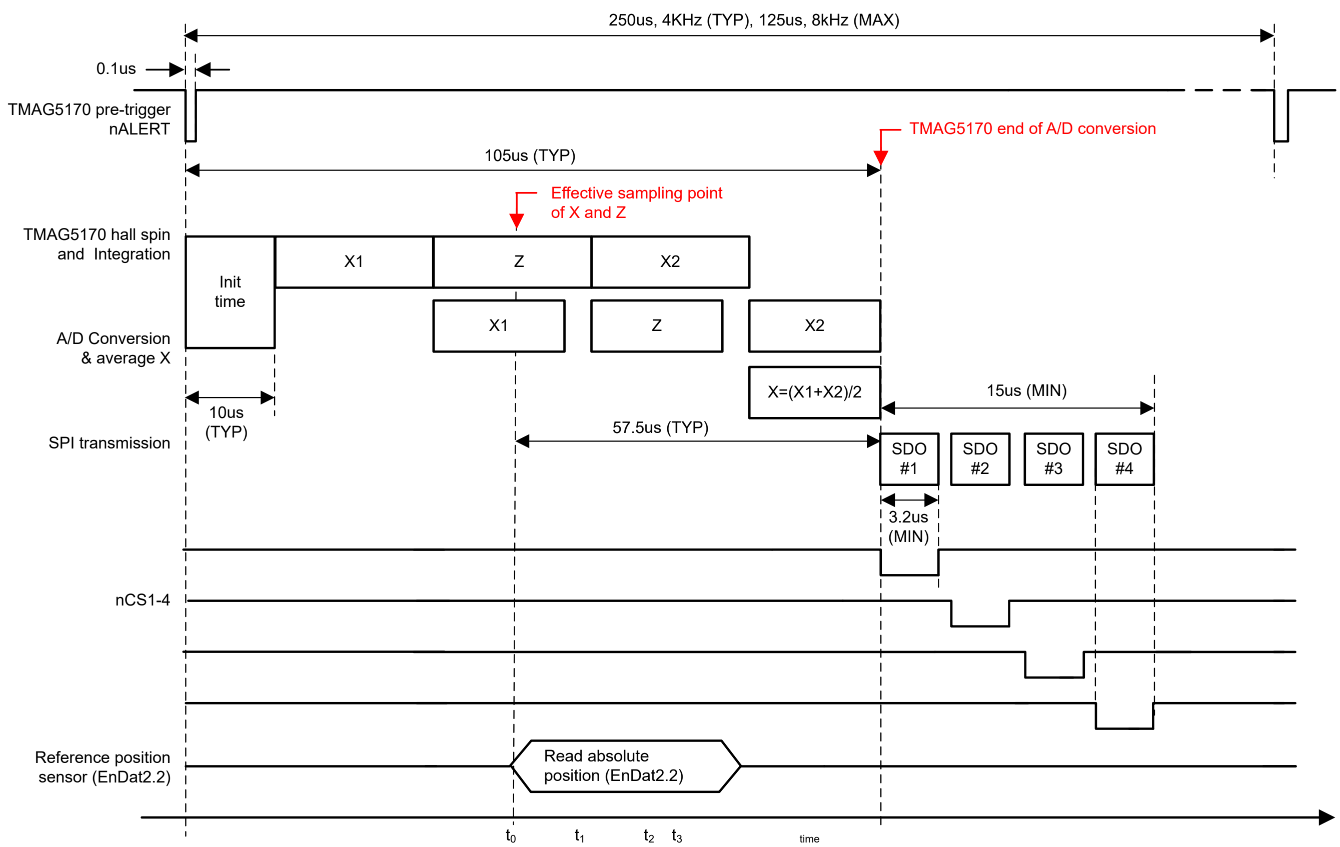


Figure 3-6. TMAG5170 Simultaneous Sampling and SPI Timing

The host MCU such as the C2000 MCU generates an active low nALERT trigger pulse with 100ns width at a 4 kHz sample rate. Each of the four TMAG5170 initiates a Hall-effect sensor spin and integration. The TMAG5170 samples and converts the sequence XZX and the calculate the average X value. After the A/D conversion is complete, the C2000 MCU reads out each of the four TMAG5170 sequentially using an individual active low chip select signal. The effective sampling of the average X and Z axis data occurs approximately 47.5μs after the active low ALERT trigger pulse. The latency from the effective sample point until SPI transfer starts is around 57.5μs, the sequential SPI transfer of the 4 channels is completed after 15μs. Hence the total signal latency including SPI transfer is around 72.5μs.

A Heidenhain LC415 EnDat2.2 linear position encoder with 10um resolution was used as reference. The C2000 MCU reads the position of the LC415 EnDat2.2 encoder at the same time than sampling the Z and X axis of the four TMAG5170.

3.2.4 Linear Position Calculation

The linear position over the four equidistant spaced TMAG5170 is calculated in every interrupt service routine at a 4kHz rate sample rate per below flow-chart in Figure 3-7.

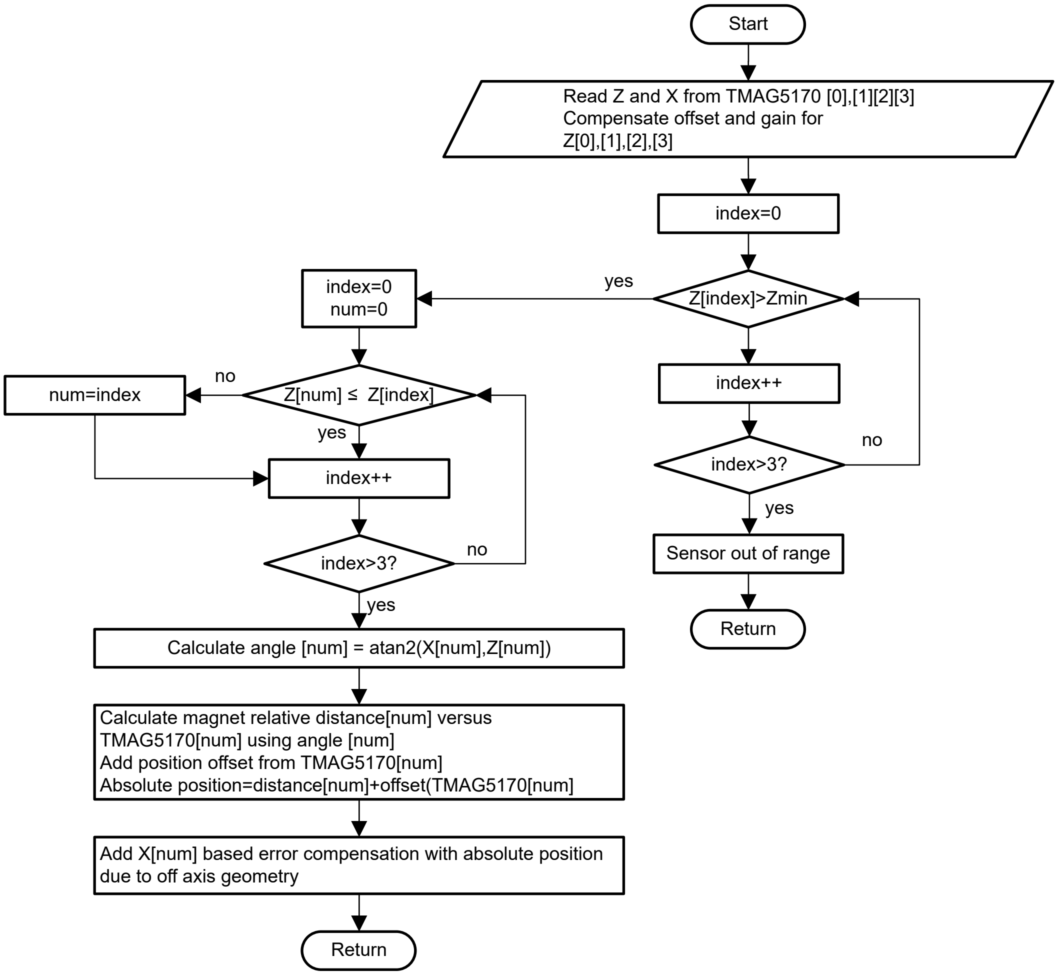


Figure 3-7. Simplified Position Calculation Flowchart

The Z-axis and X-axis data of the four TMAG5170 are read. If none of the Z-axis magnitude exceeds a minimum field strength, the moving magnet is out of range. If not, the TMAG5170 with the highest magnitude in the Z-axis is identified. A hysteresis can be used to avoid switching between two adjacent TMAG5170. This happens when the sense magnet position is in the center between two adjacent TMAG5170, hence both TMAG5170 measure similar Z-axis magnetic field strengths.

The angle calculation is only continued for the TMAG5170 with the highest magnetic field strength in the Z-axis.

In the first step the offset and gain of the Z-axis are corrected as identified during the system calibration. Then the angle with respect to the X position of the Hall-effect element with the corresponding TMAG5170 is calculated using the atan2 function of the calibrated Z-axis and X-axis, as per Equation 1.

$$Angle_{deg}[num] = \frac{180°}{\pi} \cdot atan(Z[num], X[num]) \quad (1)$$

In the second step, the linear position is calculated per Equation 2. Depending on the TMAG5170 number, the corresponding linear position offset is added too.

$$LinPos_{cm}[num] = \frac{Angle_{deg}[num]}{90°} \cdot 1.25cm + num \cdot 2.5cm + RefOffset_{cm} \quad (2)$$

In the third step, the error due to the off-axis measurement is compensated using the absolute magnitude of the X-axis with a compensation factor identified during system calibration as per Equation 3.

$$LinPos_{cm}[num] = LinPos_{cm}[num] + abs(X[num] \cdot CompFactor) \cdot \frac{cm}{mT} \quad (3)$$

The source code, which was used for calculating the linear position with the reference design is shown below.

```
//-------------------------------------------------------
// Angle calculation
//-------------------------------------------------------
// z_max_num
// 0: Out of range (Z-field too small)
// 3: TMAG5170[0] has highest Z-field
// 5: TMAG5170[1] has highest Z-field
// 7: TMAG5170[2] has highest Z-field
// 9: TMAG5170[3] has highest Z-field
//-------------------------------------------------------
void calcLinPos(int16_t zmax_num_index)
{
    float       tnom;
    float       tdenom;

    PositionRead.LinPosRef_cm = LC415LinPos_cm;             // Absolute linear position reference
    if (zmax_num_index==0)                                  // Magnet is out of range
    {
        PositionRead.LinPos_cm = 0;                         // Measured absolute linear position
        PositionRead.LinPosError_cm = 0;                    // Measured position error
    }
    else
    {
        // Gain and offset compensated Z-axis
        tnom = TMAGS_ARRAY[(zmax_num_index-3)/2].Z_mT-
PositionCalc.OffsetZ_mT[(zmax_num_index-3)/2];
        tnom =
tnom*PositionCalc.GainComp[(zmax_num_index-3)/2];

        tdenom = TMAGS_ARRAY[(zmax_num_index-3)/2].X_mT;     // X-axis
        PositionRead.Angle_deg = (180/3.1415)*atan2f(tdenom,tnom);
        PositionRead.LinPos_cm = PositionRead.Angle_deg/90*PositionCalc.DistanceTMAG5170_cm/2;
        PositionRead.LinPos_cm += PositionCalc.DistanceTMAG5170_cm * ((zmax_num_index-3)/2);
        PositionRead.LinPos_cm += -PositionCalc.RefOffset_cm;

        // Nonlinear position error compensation using X-field
        PositionRead.LinPos_cm += PositionCalc.PosXfieldComp * abs(TMAGS_ARRAY[(zmax_num_index-3)/
2].X_mT);
        // calculate position error versus reference
        PositionRead.LinPosError_cm = PositionRead.LinPos_cm - PositionRead.LinPosRef_cm;
    }
}
```

For more information on angle and linear position calculation algorithms refer to the application reports *Achieving Highest System Angle Sensing Accuracy* and *Magnet Selection for Linear Position Applications (Rev. A)*.

4 Hardware, Software, Testing Requirements, and Test Results

4.1 Hardware

4.1.1 PCB Overview

The PCB top and bottom view is shown below.

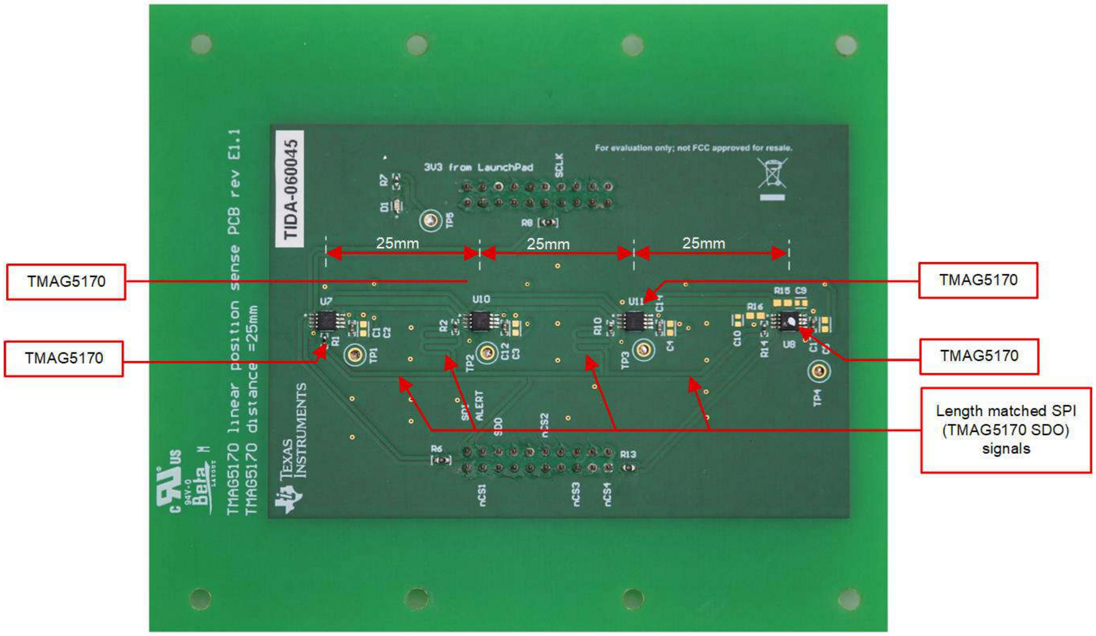


Figure 4-1. PCB Top View

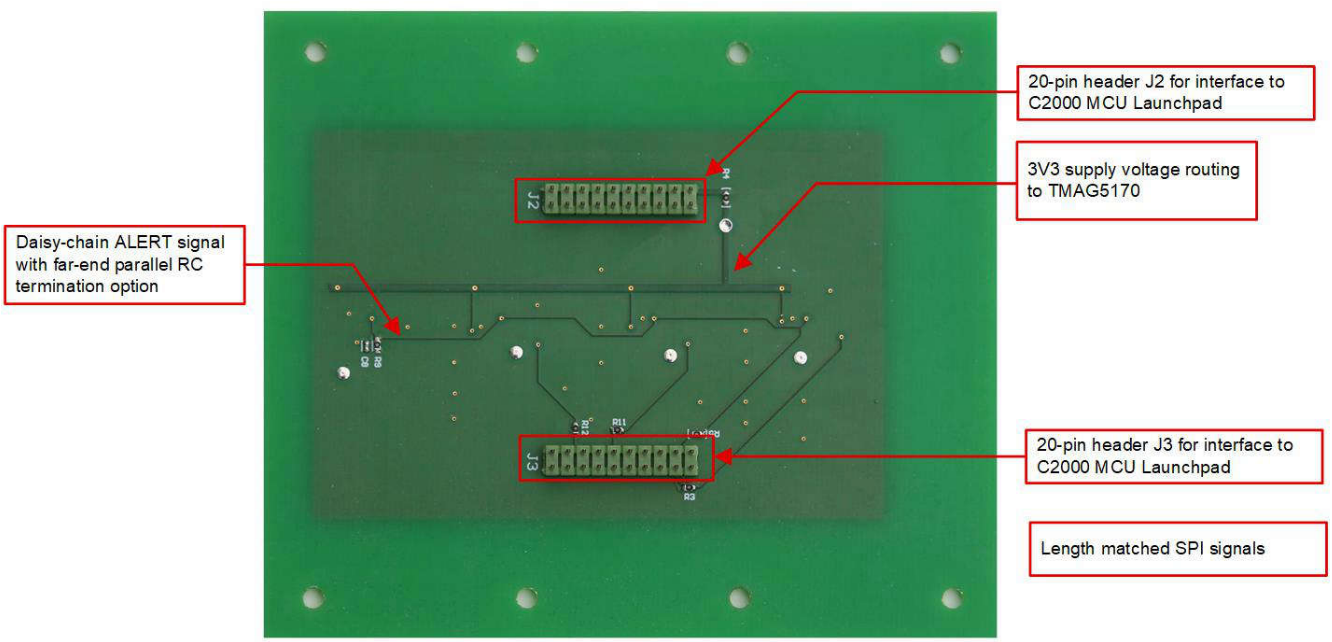


Figure 4-2. PCB Bottom View

4.1.2 MCU Interface Connector

The TIDA-060045 interface specification is compliant to the TI BoosterPack plug-in module standard. The pin assignment is shown in Table 4-1 and Table 4-2.

Table 4-1. Header J2 Pin Assignment

PIN	SIGNAL	I/O	PIN	SIGNAL	I/O
J2-1	3.3V supply	Input	J2-2	NC	
J2-3	NC		J2-4	GND	GND
J2-5	NC		J2-6	NC	
J2-7	NC		J2-8	NC	
J2-9	NC		J2-10	NC	
J2-11	NC		J2-12	NC	
J2-13	SCLK	Input	J2-14	NC	
J2-15	NC		J2-16	NC	
J2-17	NC		J2-18	NC	
J2-19	NC		J2-20	NC	

Table 4-2. Header J3 Pin Assignment

PIN	SIGNAL	I/O	PIN	SIGNAL	I/O
J3-1	nCS4	Input	J3-2	NC	
J3-3	NC		J3-4	NC	
J3-5	nCS3	Input	J3-6	NC	
J3-7	NC		J3-8	NC	
J3-9	NC		J3-10	nCS2	Input
J3-11	NC		J3-12	NC	
J3-13	NC		J3-14	NC	
J3-15	NC		J3-16	SDO (MOSI)	Input
J3-17	nCS1	Input	J3-18	nALERT	Input
J3-19	GND	GND	J3-20	SDI (MISO)	Output

4.2 Test Setup

The following hardware equipment was used to evaluate this reference design.

Table 4-3. Prerequisites

EQUIPMENT	COMMENT
TIDA-060045	This reference design
LAUNCHXL-F280049C	F280049C LaunchPad™ development kit C2000™ Piccolo™ MCU
N45-1350	Cylindrical disc magnet, 1350mT, 25mm diameter, 3mm height
LAUNCHXL-F28379D	F28379D LaunchPad™ development kit for C2000™ Delfino™ MCU
TIDA-010026	Robust interface reference design for EnDat2.2 absolute encoders
Heidenhain LC 415	EnDat2.2 absolute linear position encoder, accurate grade ± 5µm, 0.010µm resolution

The test setup is shown in Figure 4-3 and Figure 4-4.

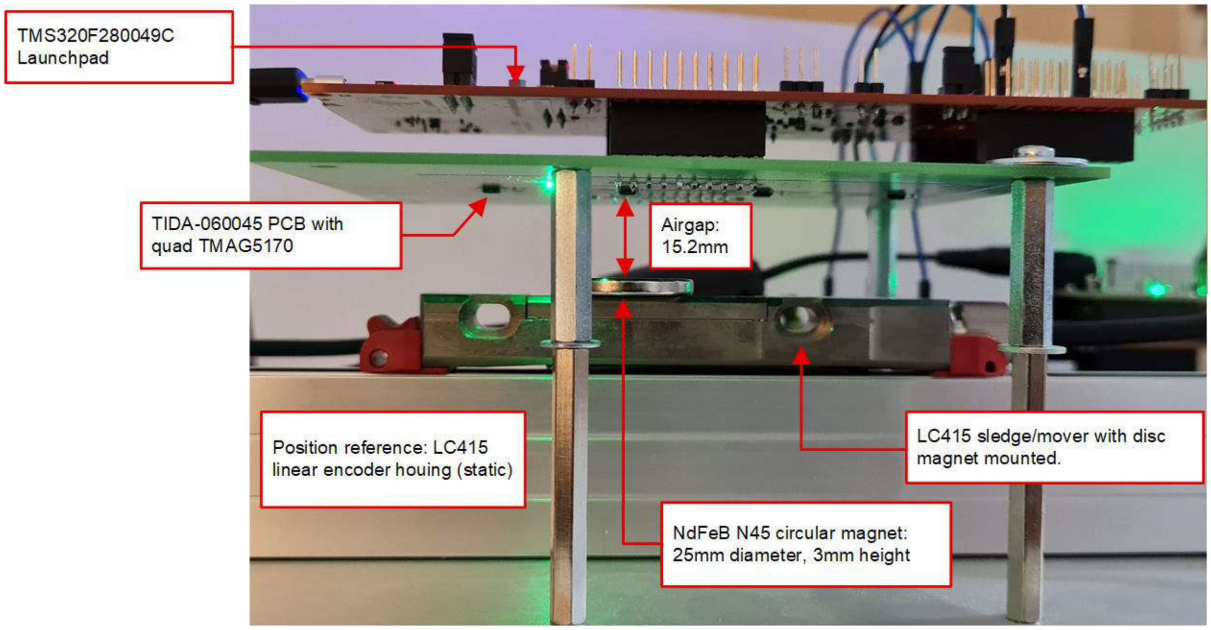


Figure 4-3. Test Setup Side View

The above Figure 4-3 shows the side view of the test setup. A Heidenhain absolute linear encoder with EnDat2.2 and 320mm length is used as position reference and mounted on a fixed plate. The circular sense magnet is mounted on top of the moving sledge of the LC415 linear encoder. The sledge is connected to the EnDat2.2 interface cable and pulling the cable allows moving the position of the magnet. The TIDA-060045 PCB is mounted to the fixed plate on top of the LC415 linear encoder with the four TMAG5170 3D Hall-effect sensors facing downward. The center of each 3D Hall-effect sensor inside the TMAG5170 (y axis) is adjusted to the center of the moving magnet. The airgap (z-axis) between the top of the magnet and the Hall-effect sensor inside TMAG5170 is 15.2mm. The TMS320F280049C LaunchPad connects to the TIDA-060045 PCB through the headers J1, J3 and J2, J4. In this test setup, the TMS320F280049C LaunchPad provides the 3.3V supply to the TIDA-060045 too.

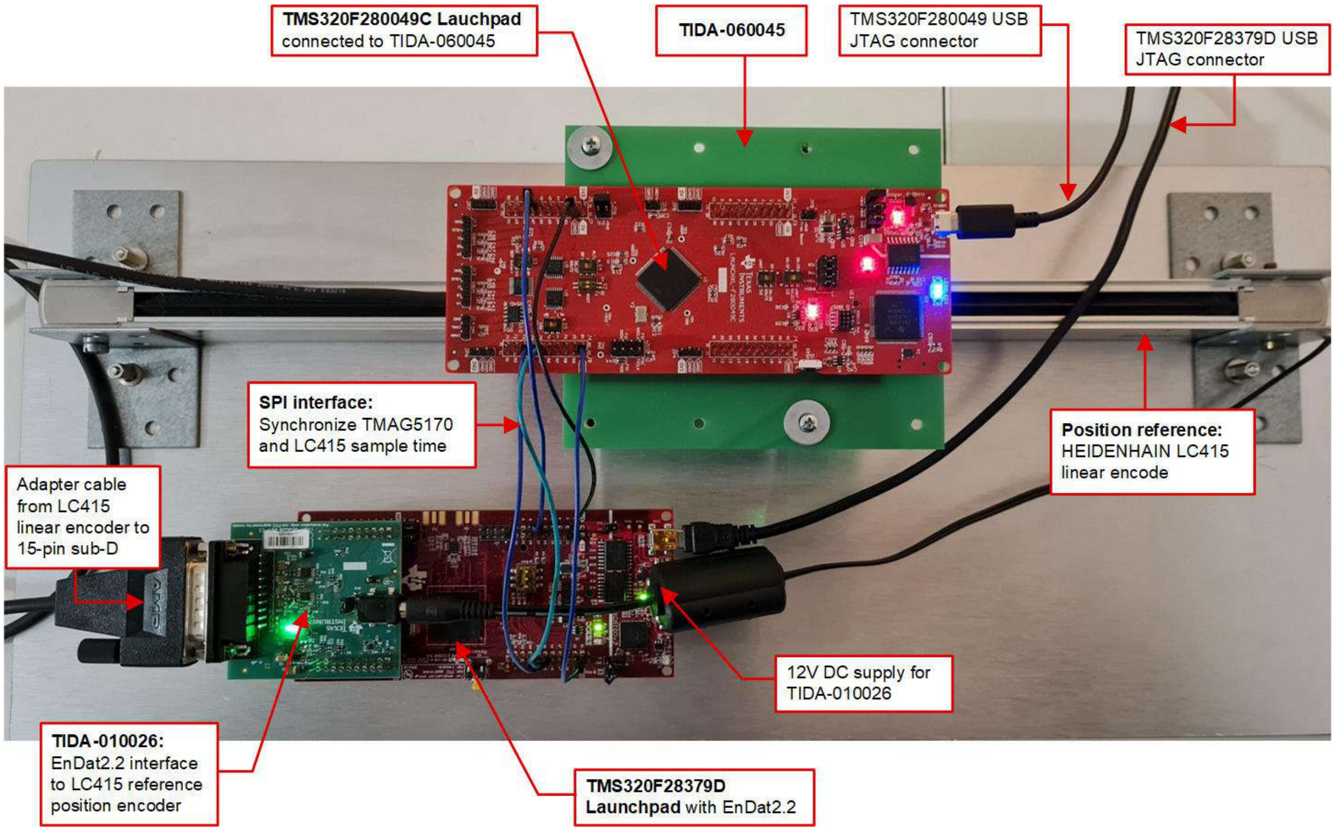


Figure 4-4. Test Setup Top View

Figure 4-4 shows the top view of the test setup with the TIDA-060045 and the TMS320F280049C LaunchPad mounted on top of the LC415 linear position reference encoder as described before. The LC415 linear encoder connects to the TIDA-010026 EnDat2.2 reference design. The TIDA-010026 is powered from 12V and connected to a TMS320F28379D LaunchPad, which runs the EnDat2.2 software. Both LaunchPads are connected through SPI to synchronize the sampling time of the four TMAG5170 and the LC415 linear encoder and send the corresponding LC415 reference position at a sample rate up to 4kHz to the TMS320F280049C LaunchPad.

To validate this reference design a TI internal test software has been developed with the TMS320F280049C LaunchPad using the TMAG5170 header files TMAG5170-CODE-EXAMPLEand the C2000WARE software development kit for C2000 MCUs. For question on C2000WARE refer to the E2E™ design support for the C2000 microcontroller forum. For questions on the TMAG5170-CODE-EXAMPLE refer to thesensors forum.

The TI internal test software running on the TMS320F280049C has two operating modes. The real-time mode continuously measures the absolute linear position (x-axis) of the magnet mounted to the LC415 sledge at a 4kHz rate and calculates the corresponding position error. The trigger mode starts sampling a sequence of 200 positions after the magnet reaches a predefined absolute start position read from the LC415 reference encoder. Refer to the test results section for more details. This absolute start position is 12cm absolute and the 10 cm measurement range of the quad TMAG5170 begins at 13.2cm to 23.2cm absolute reference position. This is used for dynamic accuracy measurements, where the LC415 shuttle with the sensor magnet is moved accordingly and all the data is stored in memory. The data is read out through Code Composer Studio and validated with tools such as Excel and MATLAB®.

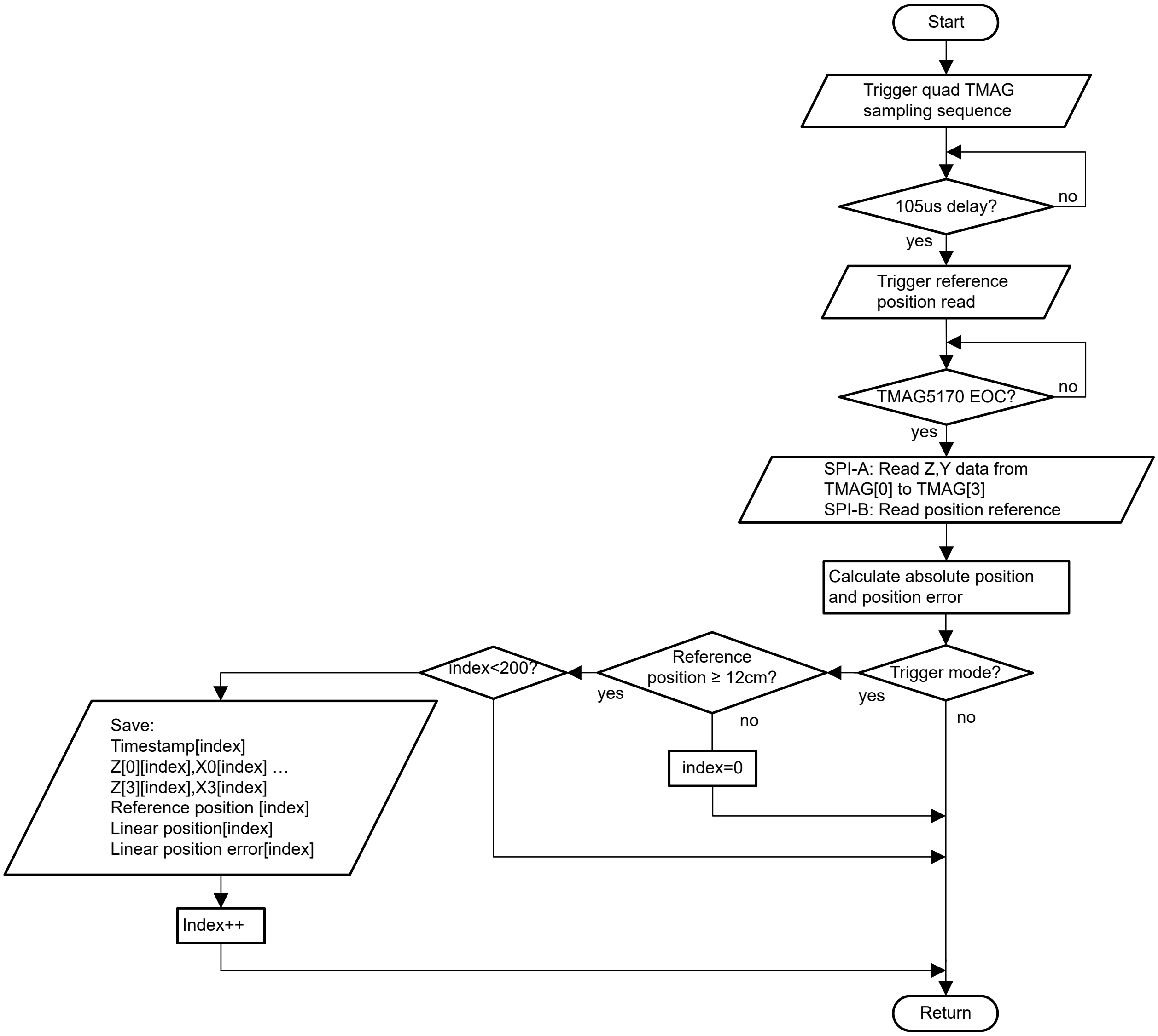


Figure 4-5. Flowchart Linear Position Test Software

4.3 Test Results

4.3.1 Magnetic Z and X Field Measurement

The 2D magnetic field strength in x- and z-direction was measured at a 4kHz sample rate with the trigger mode enabled to dump 200 consecutive samples. Figure 4-6 shows the measured x- and z-axis data over the absolute linear position measured with the reference position encoder.

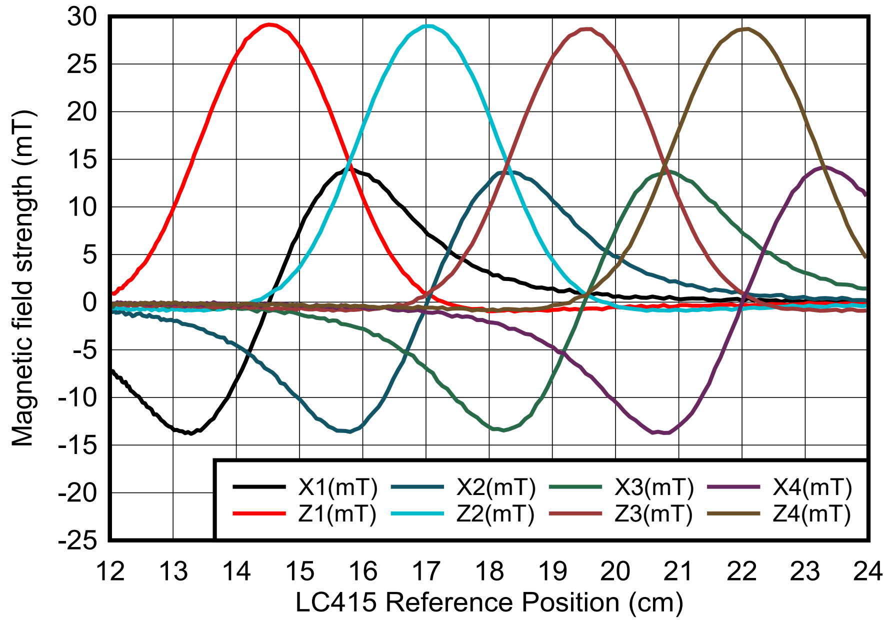


Figure 4-6. Z and X Magnetic Field of the Four TMAG5170 Versus Reference Position

When analyzing the captured data, we see that the X and Z component data observed by each TMAG5170 sensor overlapped. The z-axis has unipolar range and can be approximated within ±90 degree to a cosine signal with an offset equal to the amplitude. The X-axis has a bipolar amplitude, and can be approximated within ±90 degree to a sine signal. Due to that, the full-scale magnetic range for each TMAG5170 is set to ±50mT for the Z-axis and ±25mT for the x-axis.

The reason for the declining Z field amplitude from the first to the last TMAG5170 is since the TIDA-060045 PCB was not exactly mounted parallel to the mounting plate and the airgap slightly increased from the first TMAG7170 to the last. This mechanical calibration was not done.

Figure 4-7 and Figure 4-8 show the time domain plot of 1000 consecutive samples of the X-field and Z-field measured with the first TMAG5170 at a 4kHz sample rate. For this test the absolute position of the sense magnet was 14.19cm.

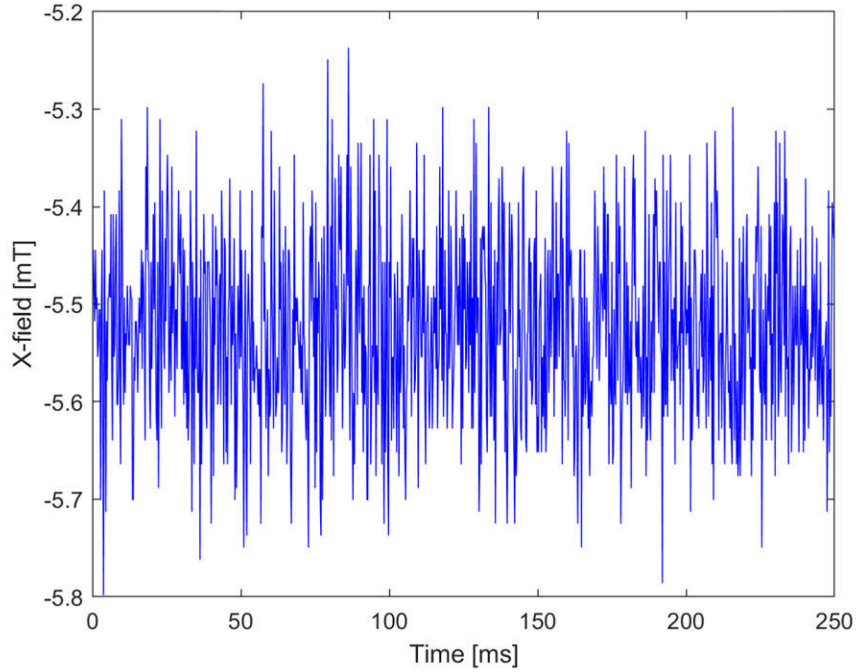


Figure 4-7. X-Field of First TMAG5170 at Magnet Position 14.19cm

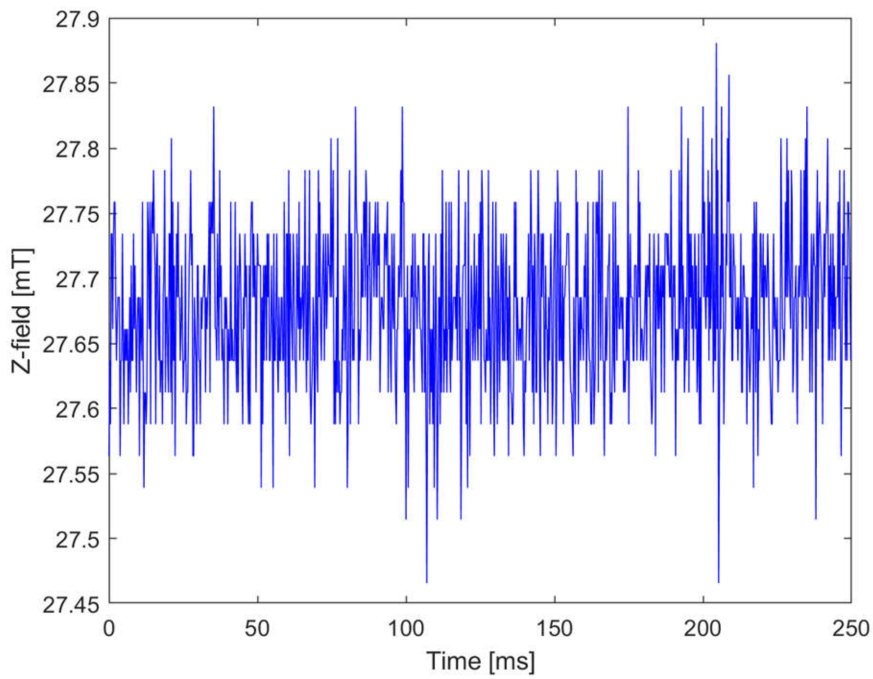


Figure 4-8. Z-Field of First TMAG5170 at Magnet Position 14.19cm

Figure 4-9 and Figure 4-10 show the corresponding histogram of the X-field and Z-field data.

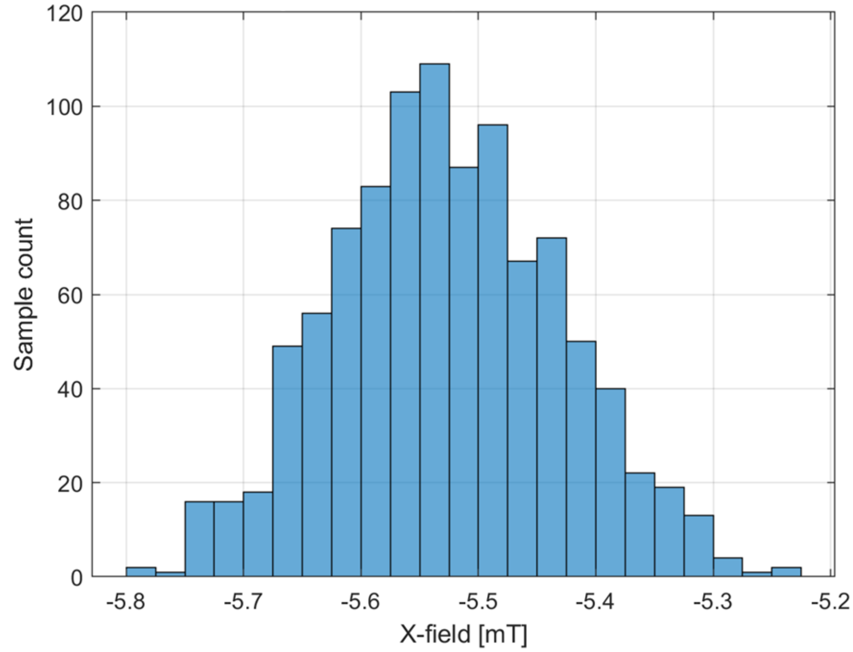


Figure 4-9. Histogram of X-Field of First TMAG5170 at Magnet Position 14.19cm

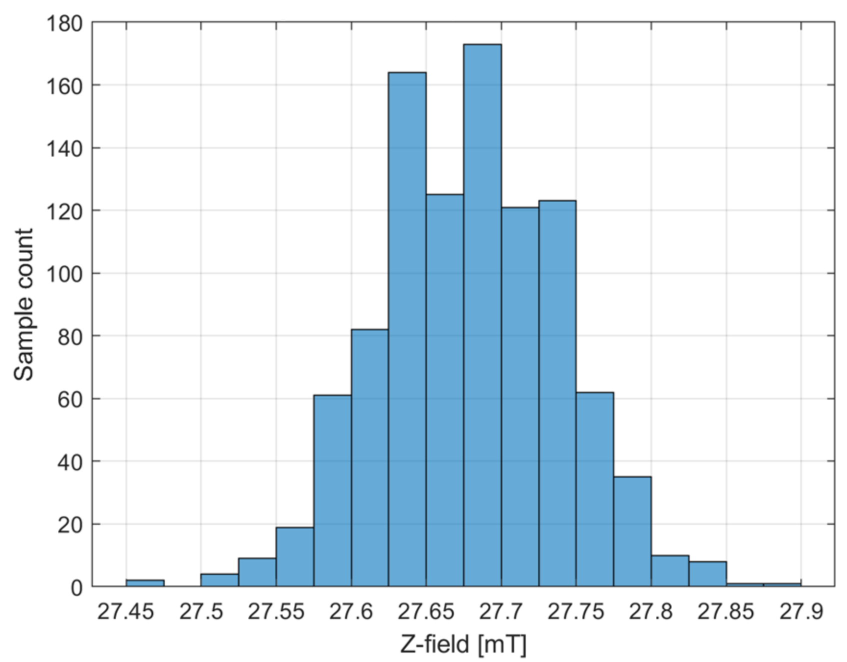


Figure 4-10. Histogram of Z-Field of First TMAG5170 at Magnet Position 14.19cm

The standard deviation, signal-to-noise ratio (SNR) and effective number of bits (ENOB) versus full-scale range are shown in Table 4-4. The noise in the X-axis dominates due to the higher gain setting with the TMAG5170 X-axis.

Table 4-4. Standard Deviation, SNR and ENOB versus TMAG5170 Full Scale Range

TMAG5170	Z-AXIS	X-AXIS	COMMENT
Standard deviation [mTrms]	0.059	0.094	rms
Full-scale range ± [mT]	50	25	peak
SNR [dB]	55.55	45.48	dB
ENOB [bit]	8.94	7.26	Bit

4.3.2 Linear Position Measurement

As described in Section 3.2.4, the moving magnet position is calculated from the sensor with the highest Z-field magnitude using the Z- and X-field components. To adjust for the off-axis measurement the measured Z field was calibrated for gain and offset. In addition, a compensation factor multiplied by the absolute magnitude of the X field was used to compensate a nonlinearity with the position calculation. In addition, the displacement between each TMAG5170 on the PCB was corrected. For simplicity, the same value was used as distance between each TMAG5170.

Table 4-5. Calibration Factors

TMAG5170	1	2	3	4
Z offset	14.6mT	14.3mT	14mT	13.8mT
Z gain	0.94	0.93	0.94	0.94
Displacement	24.97mm	24.97mm	24.97mm	24.97mm
X axis compensation factor	0.001538	0.001538	0.001538	0.001538

The position was measured at a linear speed of around 0.4m/s at 22°C room temperature. The peaks observed at either end of the data capture are the result of the magnet leaving the sensing range of the quad sensor PCB.

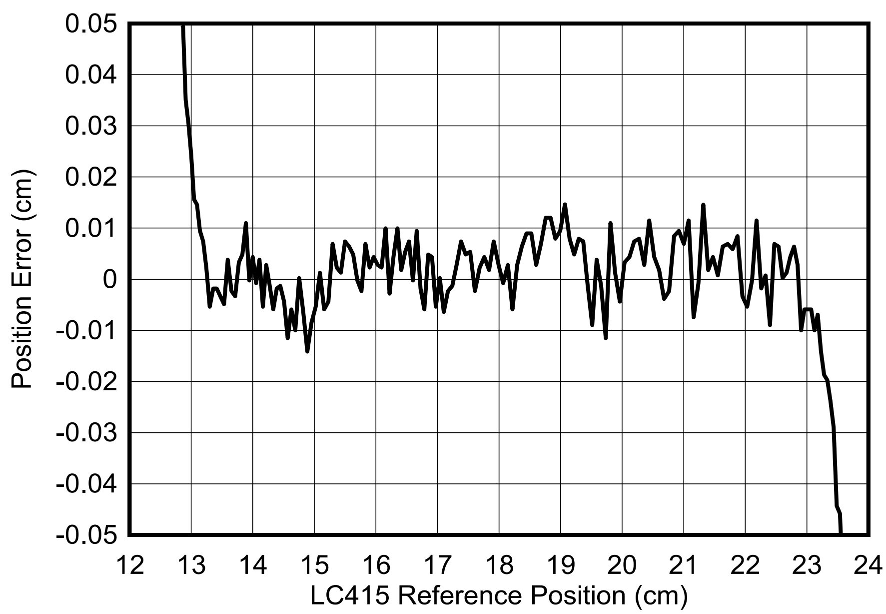


Figure 4-11. Linear Position Error Over Quad TMAG5170 at Room Temperature

To measure the impact of the Z field and X field noise floor, the static position error at 14.19cm was measured at over 1000 samples at 4kHz, as shown in Figure 4-11. The corresponding histogram is shown in Figure 4-12. Measurements are at 22°C room temperature.

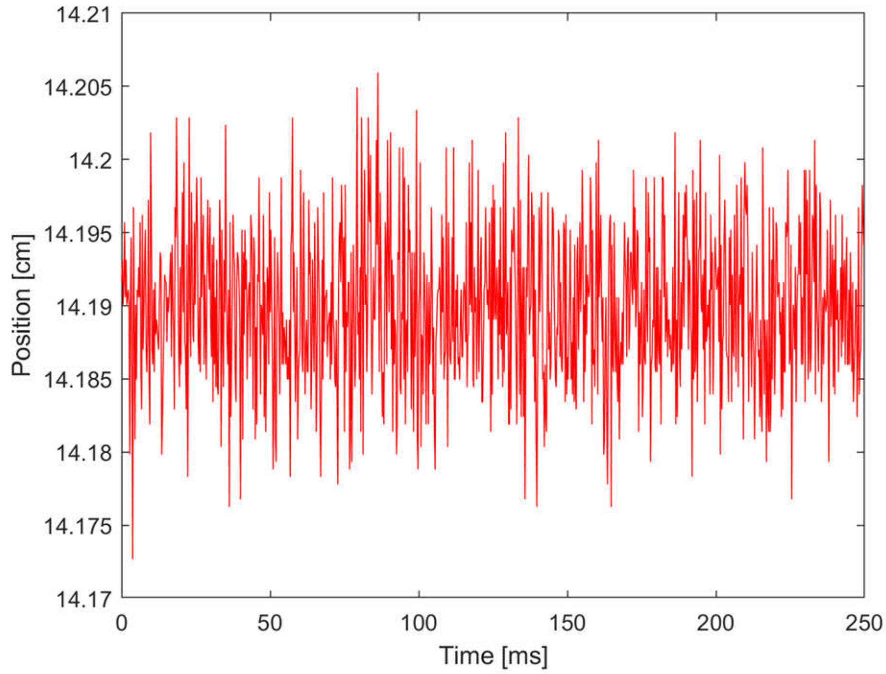


Figure 4-12. Static Position Over 1000 Samples at 4kHz Sample Rate

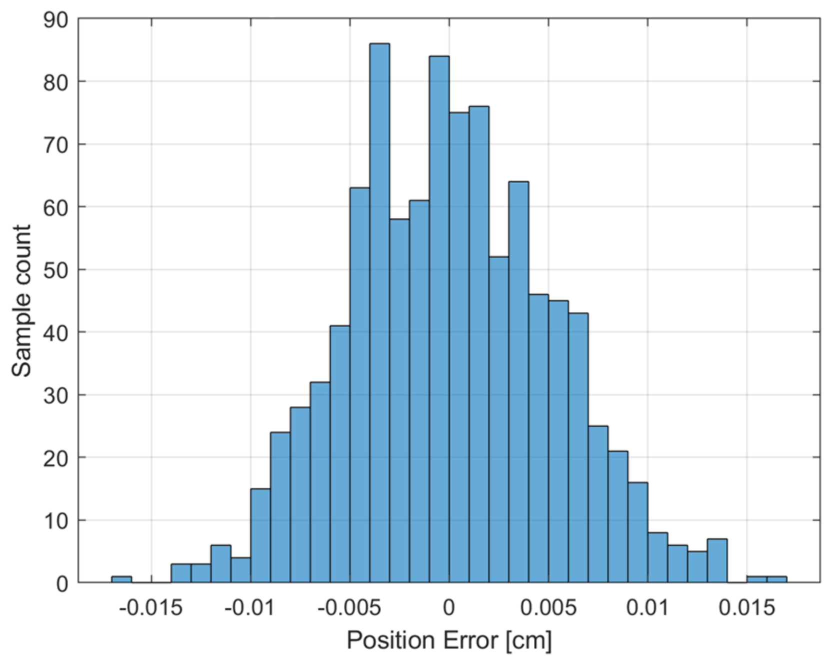


Figure 4-13. Histogram of Position Error at Magnet Position 14.19cm

The corresponding standard deviation and ENOB versus full-scale position measurement range are shown in Table 4-6.

Table 4-6. Standard Deviation, SNR and ENOB at Static Position 14.19cm for quad TMAG5170

QUAD TMAG5170	POSITION ERROR	COMMENT
Standard deviation [cm]	0.0053	
Full-scale range [cm]	10	quad 3D sensors
ENOB [bit]	10.6	

Each individual TMAG5170 provides an ENOB of 8.6-bit over the 2.5cm measurement range. Due to the quad TMAG5170 array with the 10cm range, the overall ENOB increase by 2-bit to the 10.6-bit shown in the table above.

Following that test, the position measurement was repeated 5 times at a linear speed of around 0.4m/s to outline the impact of the Z field and X field noise to the absolute accuracy. The test result is shown Figure 4-14.

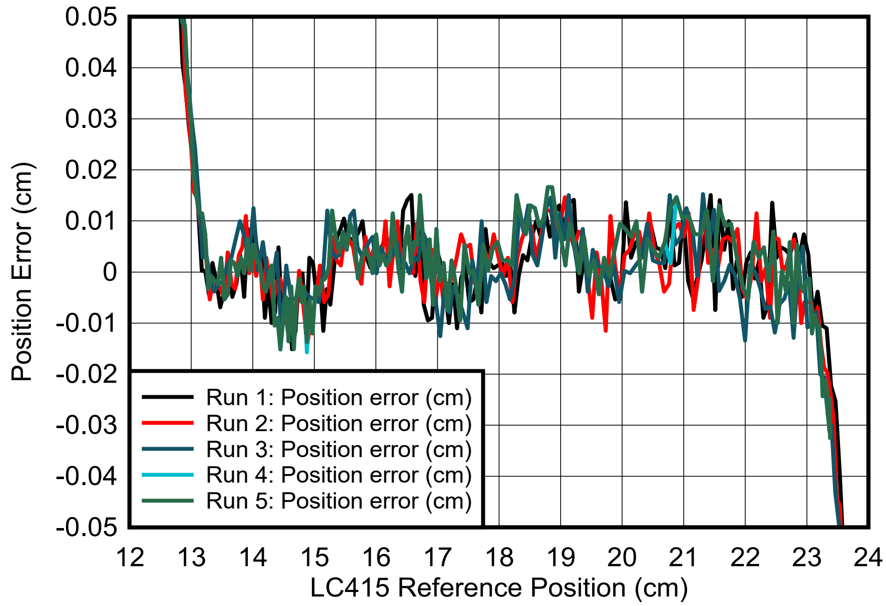


Figure 4-14. Linear Position Error Over 5 Test Runs

Further optimization is possible by more advanced compensation algorithms, see also. Magnets with higher field strength allow increase of the magnetic field strength to 100mT for the Z-axis and 50mT for the X-axis and help increase the signal to ratio by a factor of 2, respectively. Refer to *Magnet Selection for Linear Position Applications (Rev. A)*.

A video demonstration of TIDA-060045 can be viewed at *Designing with 3D Hall-effect sensors: Linear position encoding*. For help simulating magnetic systems, the TI Magnetic Sense Simulator (TIMSS) tool can accelerate design and evaluation of magnetics systems.

4.3.3 SPI Signal Measurement

Figure 4-14 shows the 32-bit SPI timing frame with nCS1 measured at the first TMAG5170 (U7) in the daisy-chain. The red signal is the SDI write frame (read command) and the corresponding special 32-bit SDO read frame with the two 12-bit X and Z field data, the status bits and the CRC. The transfer takes 3.4us.

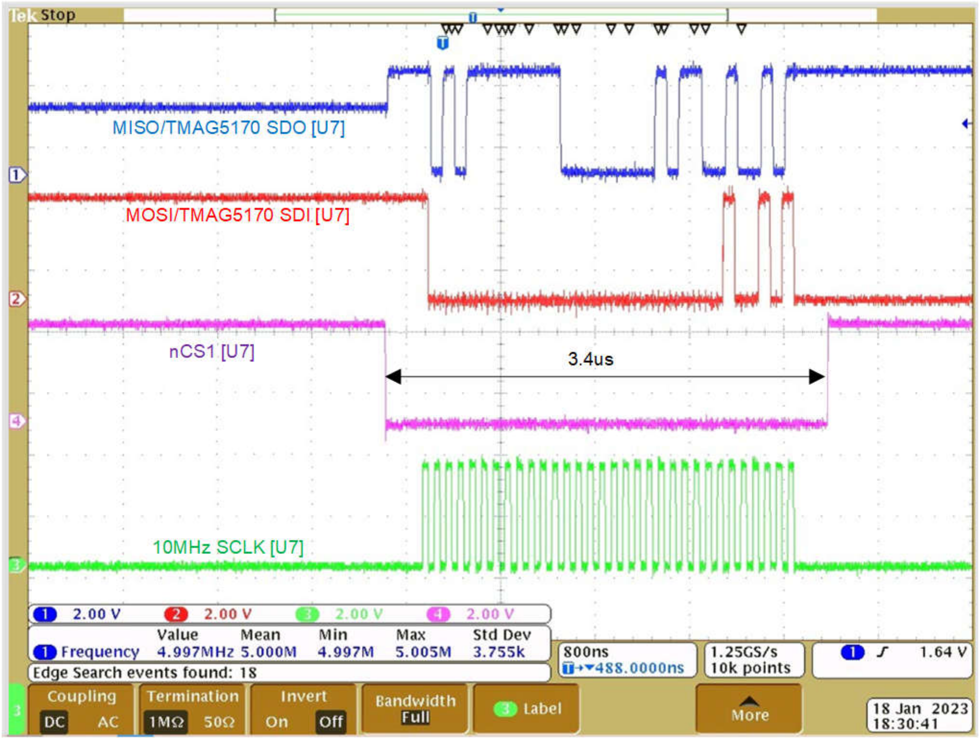


Figure 4-15. SPI 32-bit Frame Timing

Figure 4-15shows the timing of TMAG5170 (U7) SDO output versus the SPI clock SCLK input. The delay time of the SDO signal versus the falling clock edge is 20ns. The SDO rise time is 7ns, the fall time 3ns.

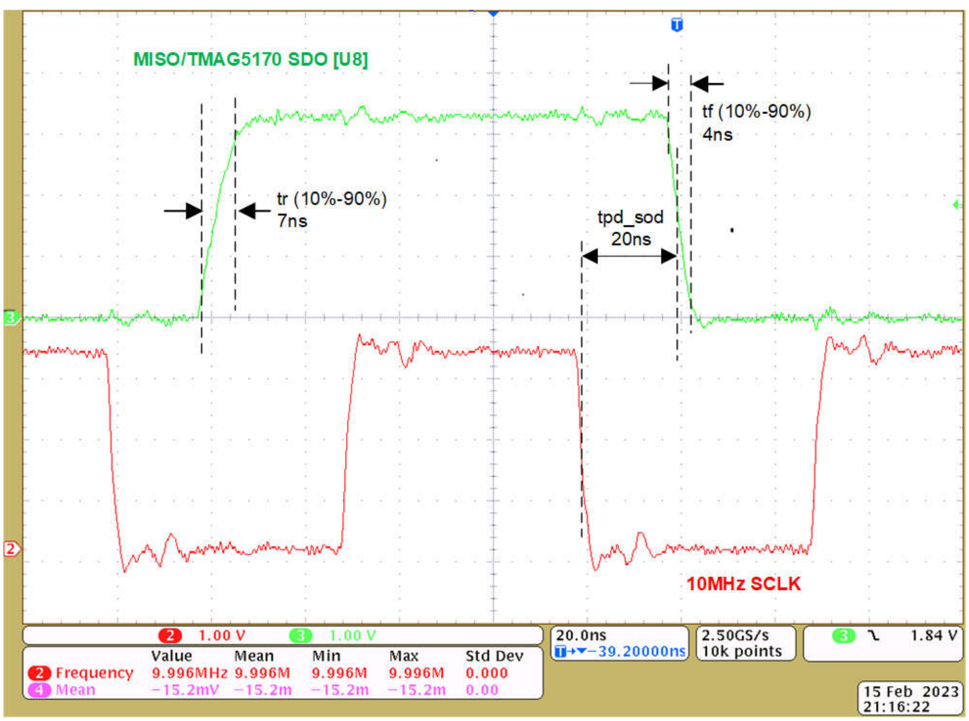


Figure 4-16. TMAG5170 U8 SDO (MISO) and SCLK

Figure 4-16 shows the timing of SDO output versus the SPI clock SCLK input at the TIDA-060045 MCU headers J3-20 and J2-13. The setup time t**su** is 22ns, the hold time t**h** is 66ns versus the rising clock edge.

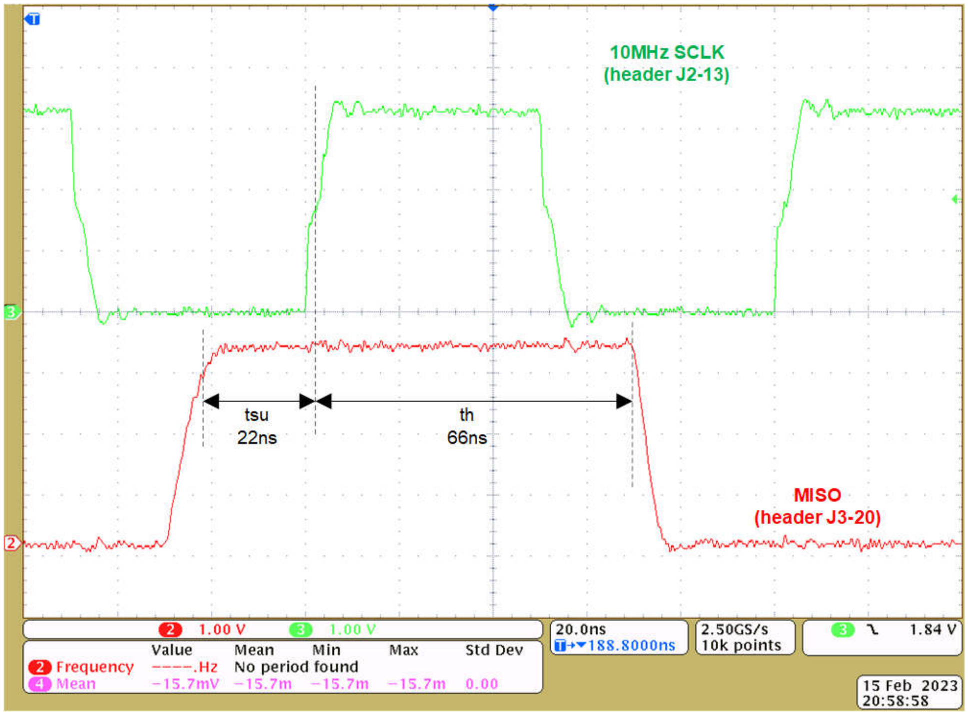


Figure 4-17. MISO and SCLK at MCU Headers J2 and J3

Figure 4-17 shows the timing of TMAG5170 SDI input (MOSI) versus the 10MHz SPI clock (SCLK). Both the setup time (t_{su_si}=47ns) and hold time (t_{h_si}=48ns) meet the 25ns (MIN) TMAG5170 requirement.

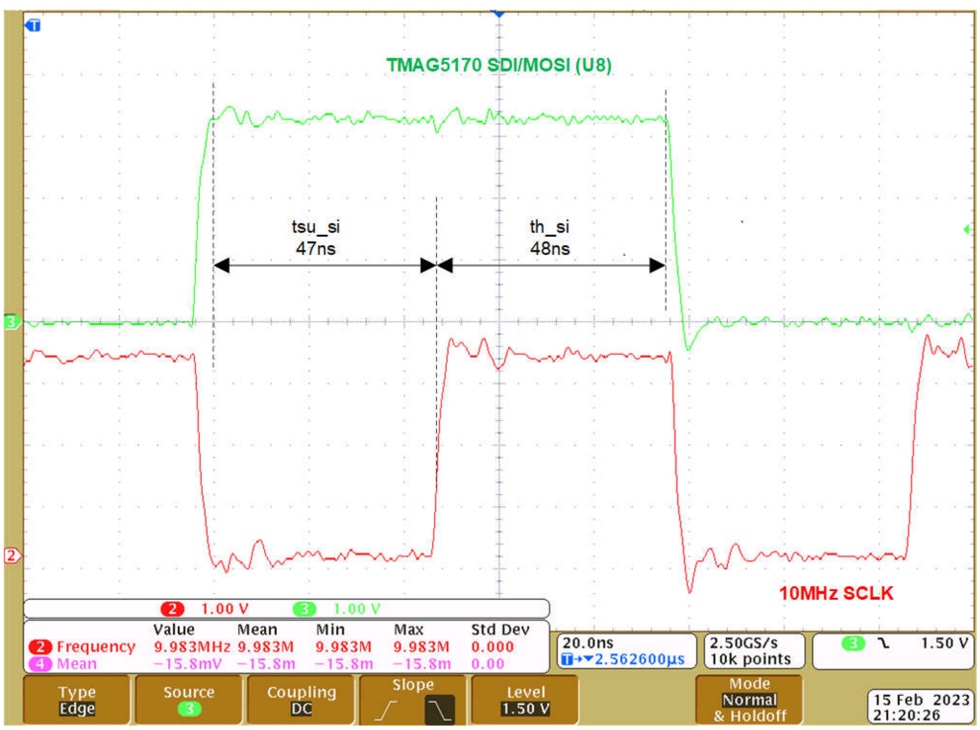


Figure 4-18. TMAG5170 U8 SDI (MOSI) and SCLK

The following figures show a comparison of the SPI clock (SCLK) signal measured at the first TMAG5170 MCU (U7) and the last TMAG5170 (U8) in the SCLK daisy-chain with and without AC parallel termination.

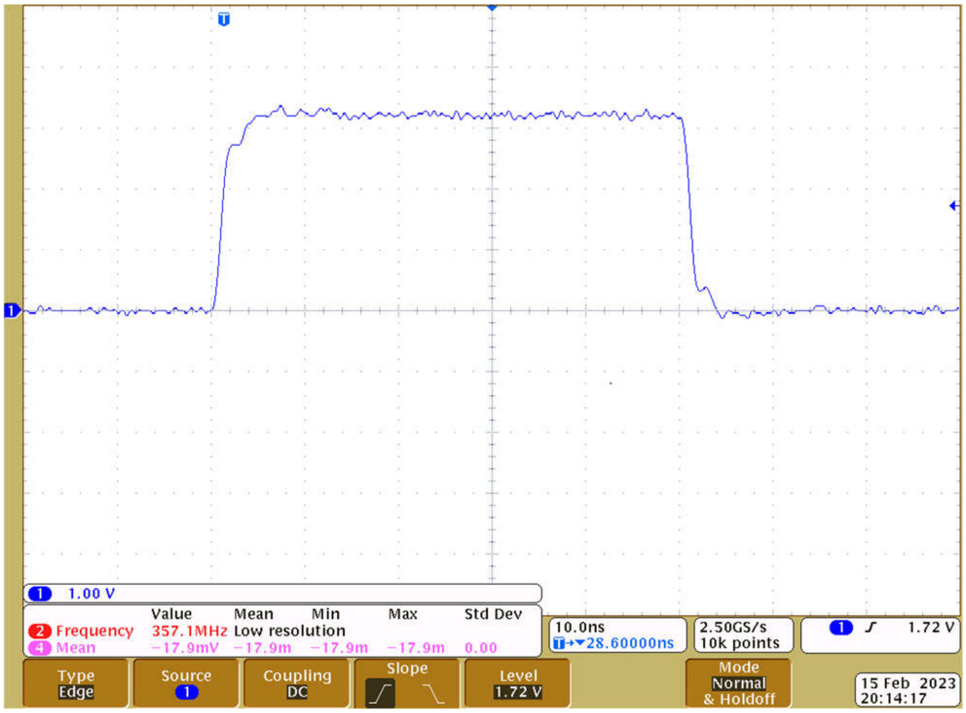


Figure 4-19. SCLK at U7 With AC Parallel Termination at U8

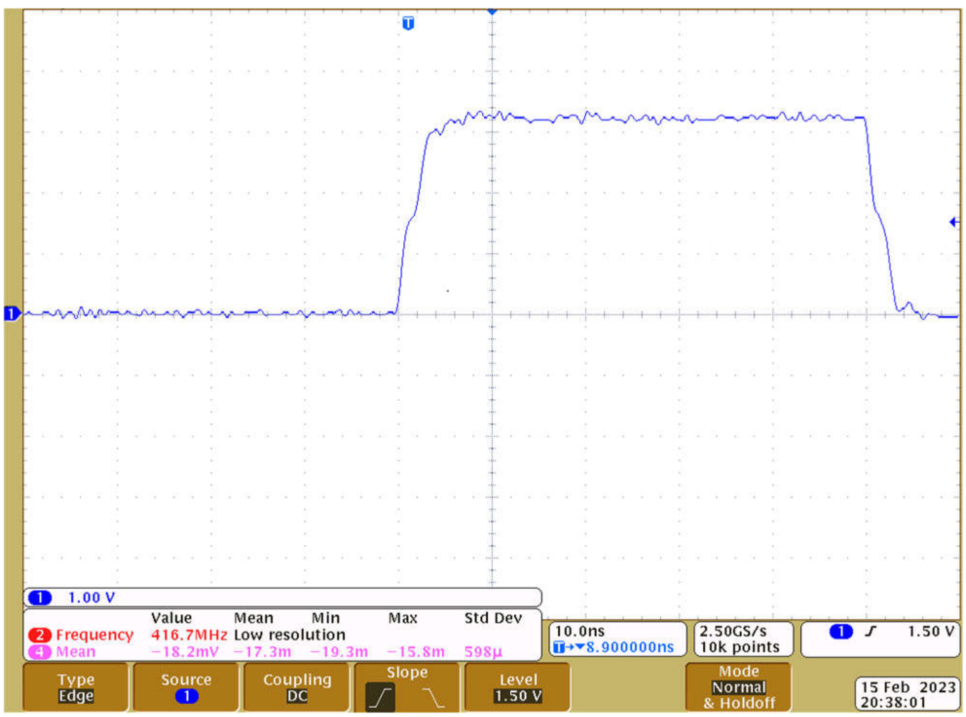


Figure 4-20. SCLK at U7 Without Parallel AC Termination at U8

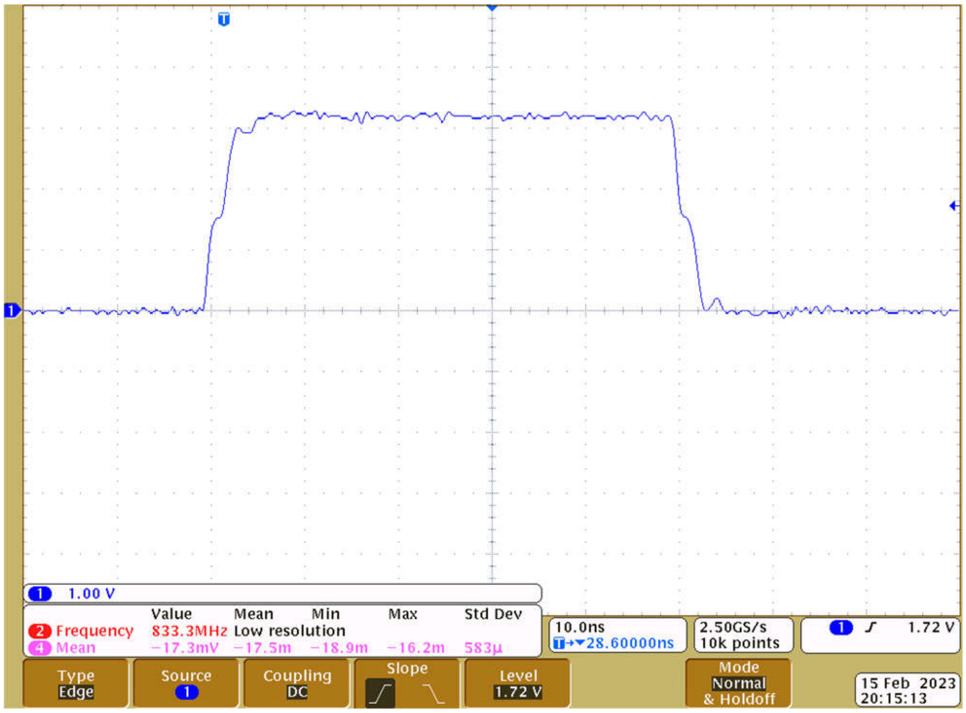


Figure 4-21. SCLK at U8 With AC Parallel Termination at U8

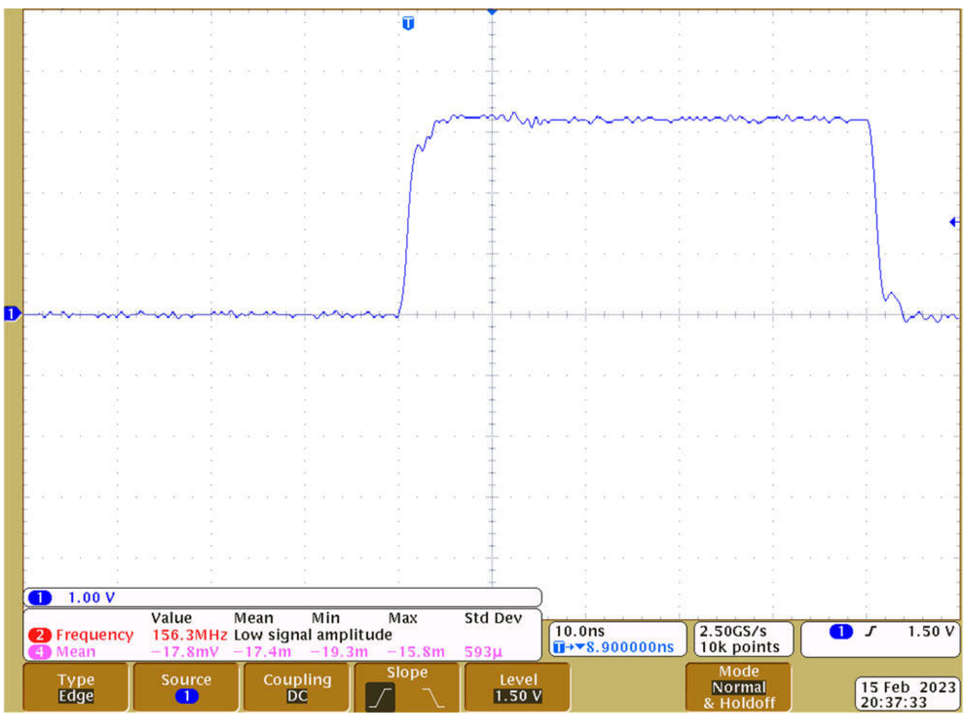


Figure 4-22. SCLK at U8 Without Parallel AC Termination at U8

The series line termination resistors for the MCU output signals nALERT, MOSI, SCLK and nCS1 to nCS4 have a 0Ω series line termination resistor close to the MCH header. The reason that these resistors are 0Ω by default is that the corresponding traces on the TMS320F280049C LaunchPad are similar length that on the TIDA-060045.

The SPI traces on the TIDA-060045 are less than 20cm (8 inch). The corresponding propagation delay of around 1.3ns is rather small versus the rise and fall-time. There was no significant impact of the AC parallel termination, when the F280049C LaunchPad was connected.

For custom designs, the series line termination resistors should be placed directly at the MCU's output, which was not possible when using the TMS320F280049C LaunchPad. Depending on the SPI trace length AC parallel termination may be considered or not.

5 Design and Documentation Support

5.1 Design Files

5.1.1 Schematics

To download the schematics, see the design files at TIDA-060045.

5.1.2 BOM

To download the bill of materials (BOM), see the design files at TIDA-060045.

5.1.3 PCB Layout

5.1.3.1 Layout Prints

To download the layout prints, see the design files at TIDA-060045.

5.1.3.2 Layout Guidelines

The layout of the SPI clock signal SCLK is shown in Figure 5-1. The SCLK is routed on the top layer in daisy chain from the first TMAG5170 (U7) to the last TMAG5170 (U8) with a serial line termination resistor and an optional far end AC parallel termination. The nALERT and the MOSI (TMAG5170 SDI) signals are routed the same way. A solid GND plane on the mid 1 layer below acts as a return GND.

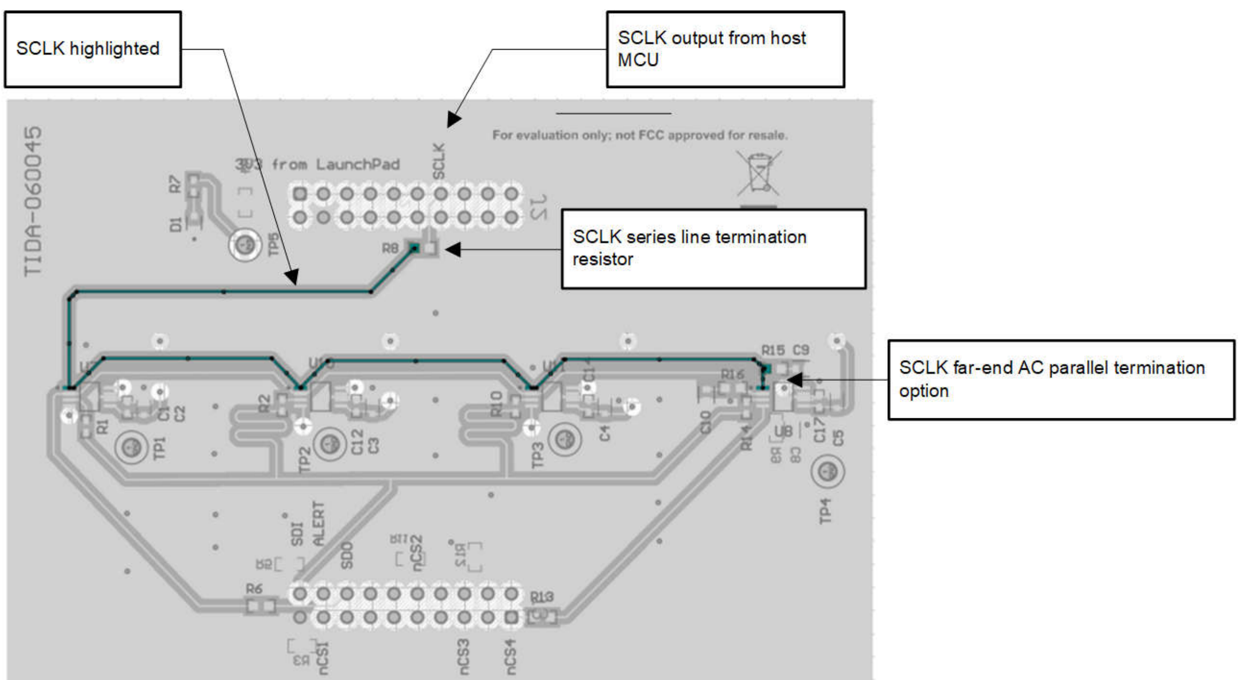


Figure 5-1. SPI Clock (SCLK) Trace Routing

The individual SDO output (SPI MISO) of each TMAG5170 has a serial line termination resistor. The four SDO traces from each TMAG5170 are star routed with similar length before being merged into a single trace to connect to the host processor MISO input pin.

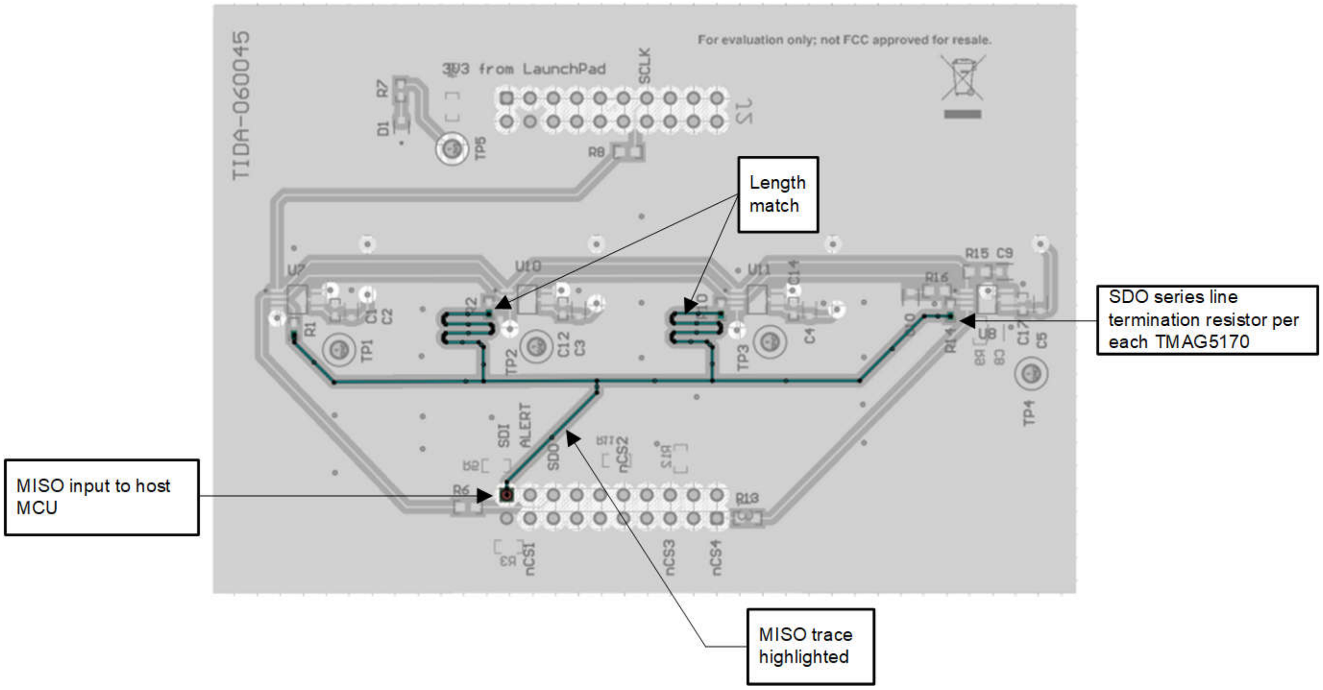


Figure 5-2. MISO Length Matched Star Topology

5.2 Tools and Software

Tools

TI-MAGNETIC-SENSE-SIMULATOR	Magnetic simulation software that includes mechanical motion and sensor output.
LAUNCHXL-F280049C	F280049C LaunchPad™ development kit C2000™ Piccolo™ MCU.

Software

TMAG5170-CODE-EXAMPLE	TMAG5170 and TMAG5170-Q1 C code example.
C2000WARE	C2000Ware is a cohesive set of software and documentation created to minimize development time. It includes device-specific drivers, libraries, and peripheral examples.

5.3 Documentation Support

1. Texas Instruments, *Multi-mover Position Sensing with Linear Motor Transport Systems*, Application Brief
2. Texas Instruments, *Designing with 3D Hall-effect sensors: Linear position encoding*, Video
3. Texas Instruments, *Magnet Selection for Linear Position Applications (Rev. A)* , Application Report
4. Texas Instruments, *Achieving Highest System Angle Sensing Accuracy*, Application Report
5. Texas Instruments, *Introduction to TI Magnetic Sense Simulator Features*, Application Brief
6. Texas Instruments, Robust interface reference design for EnDat2.2 absolute encoders

5.4 Support Resources

TI E2E™ support forums are an engineer's go-to source for fast, verified answers and design help — straight from the experts. Search existing answers or ask your own question to get the quick design help you need.

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6 About the Author

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