Application note

How to use a magnetometer in a position sensor application

Contents

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1. Scope

Magnetometers of Melexis measure the magnetic field in three directions (X, Y, and Z), using Hall elements, and output these measurements as a digital value relative to the magnetic field strength. Depending on the sensor used, this output can be SPI or I^2C.

This application note will discuss a few possible applications that can be made using these sensors, as well as some design constraints for the different magnetometers in Melexis' portfolio.

The applications shown in this application note are:

- A rotary knob with push/pull detection.
- A 2-DoF thumb stick.

Possible magnetometers are listed in the table below, showing the most important magnetic specifications and advantages. For a full comparison, please check our quick reference guide on the website.

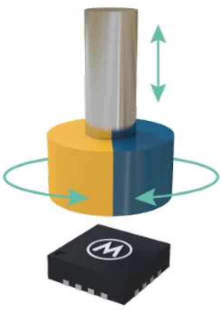
The minimum fields given are an indication only, a typically used minimum.

Magnetometer	Min field	Max field
MLX90393	5mT	$\sqrt{B_X^2 + B_Y^2} < 50mT$
MLX90395 00x	5mT (1)	$\sqrt{B_X^2 + B_Y^2} < 55mT, B_Z < 130mT$
MLX90395 10x	10mT (1)	$\sqrt{B_X^2 + B_Y^2} < 120mT, B_Z < 130mT$
MLX90392 010	0mT (2)	$\lvert B_X\rvert + \lvert B_Y\rvert + \lvert B_Z\rvert < 4912\mu T$ (at typical sensitivity of $0.15\mu T/LSB$)
MLX90392 011	5mT	$\lvert B_X\rvert + \lvert B_Y\rvert + \lvert B_Z\rvert < 49.13mT$ (at typical sensitivity of $1.5\mu T/LSB$)
MLX90394	5 mT (1)/ 0mT (2)	$\sqrt{B_X^2 + B_Y^2} < 50mT$ / $\sqrt{B_X^2 + B_Y^2} < 5mT$
MLX90397	5 mT (1)	$\lvert B_X\rvert + \lvert B_Y\rvert + \lvert B_Z\rvert < 24.56mT$ (25mT range) $\lvert B_X\rvert + \lvert B_Y\rvert + \lvert B_Z\rvert < 49.13mT$ (50mT range) For Z, up to 200mT is possible

[1] *As rule of thumb*

[2] *Or Earth Magnetic Field (EMF)*

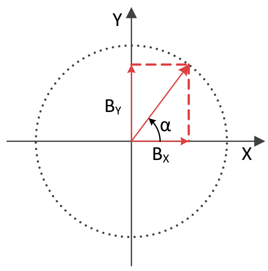
2. Rotary Position Sensor with Push/Pull detection



In this application, the goal is to measure the position of a rotary button that also allows it to be pushed. To achieve this function, only 2 components are needed. For this example, the magnet is aligned with the sensor and rotating in the XY-plane, hence the need for B_X and B_Y to be measured.

2.1. Rotary position

To get the rotational position of the magnet, the B_X and B_Y components are needed. Using an arctangent function, the angle can be retrieved:



$$\tan(\alpha) = \frac{B_Y}{B_X}$$

$$\alpha = \operatorname{atan}\left(\frac{B_Y}{B_X}\right) + \pi n\,, \text{ with } n \in \mathbb{Z}$$

Note that the range of the atan function is only $\left(-\frac{\pi}{2}, \frac{\pi}{2}\right)$, or 180°. To get the full 360° output, use the atan2 function.

$$\alpha = \operatorname{atan2}(B_Y, B_X)$$

To calculate the angle, it is not needed to convert the output value to a value in µT as the sensitivity for X- and Y-axis is equal and the conversion would simply be a scaling applied on both components which does not change the angle value itself. If this is not the case (for example MLX90393 has different sensitivity for X- and Z-axis), both components will need to be scaled to give them the same amplitude when rotating over the full 360°.

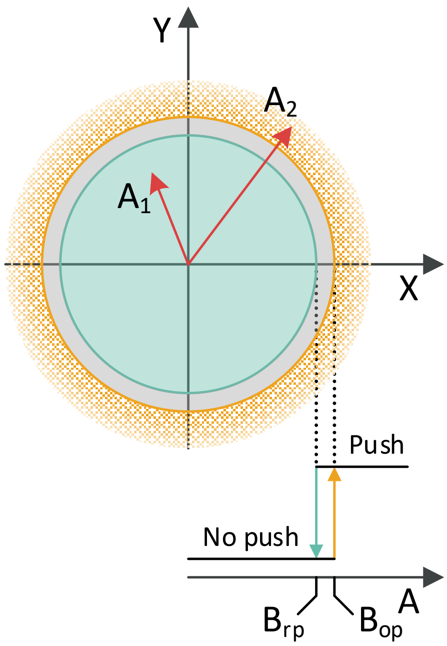
2.2. Push/Pull detection

When the button is pushed, the magnet moves closer to the IC. This leads to an increase of the total magnetic field sensed by the sensor.

The normal position and the push position will give a different amplitude. The amplitude is calculated as:

$$A = \sqrt{{B_X}^2 + {B_Y}^2}$$

A threshold can be determined by measuring the magnetic field in the normal state and in the push state. Advised is to add also a hysteresis to avoid toggling of the push state. Only if the amplitude goes above the operating threshold (B_{op}) the push state is entered. To leave the push state, the amplitude needs to drop below the return point (B_{rp}). These thresholds are stored off-chip, so in the microcontroller.



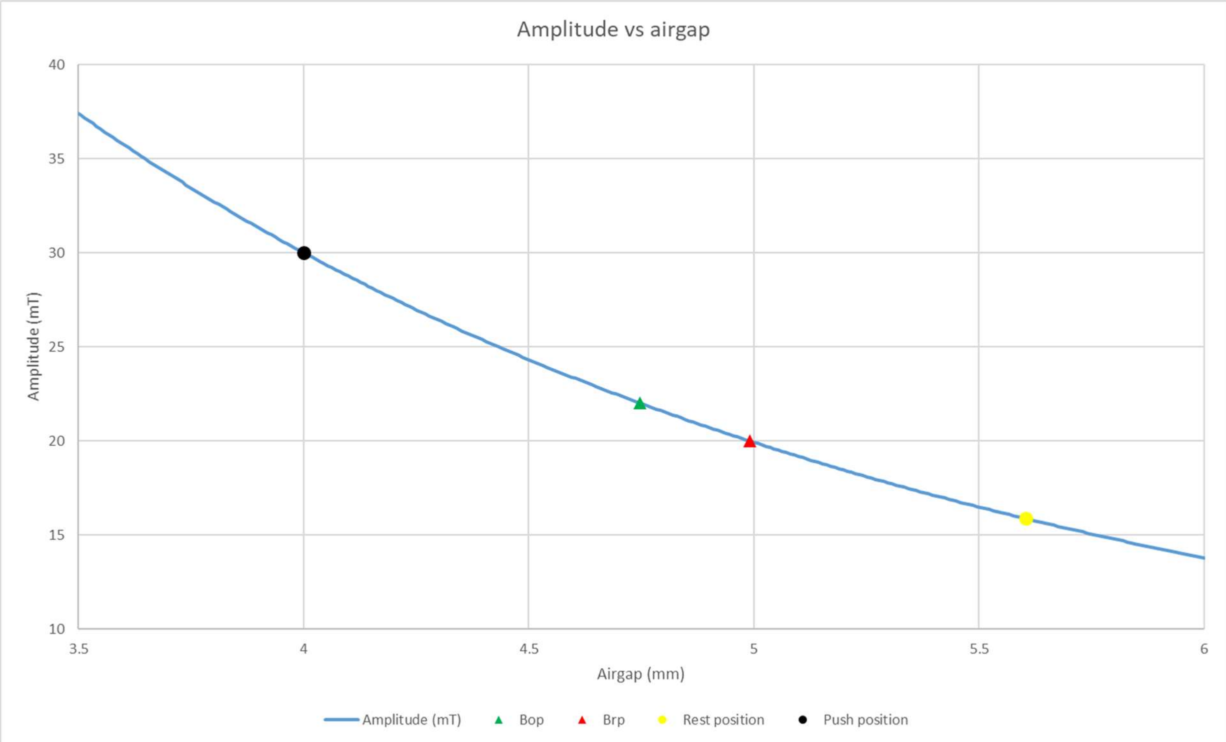
Over temperature the sensitivity of the component can change. Enable temperature compensation, or perform an off-chip temperature correction based on the temperature information that can be provided by the IC. Another option to overcome this is to compensate the Bop and Brp either based on a characterization or dynamically based on the fact that a button press is a sudden change (monitor amplitude drift in normal position).

2.3. Magnet example

As an example, a rotary/push application is simulated with the following specifications. These are very similar to the rotary/push application in the DVK kit [3]. The airgap is measured from the magnet surface to the Hall element position.

Parameter	Value
Magnet shape	Cylinder
Magnet material	SmCo
Magnet diameter	6mm
Magnet height	3mm
Magnet Br (room temperature)	1000mT
Magnetization	Diametrical
Airgap rest position	5.6mm
Airgap push position	4mm

A simulation at room temperature of the magnetic field vs airgap gives following graph:

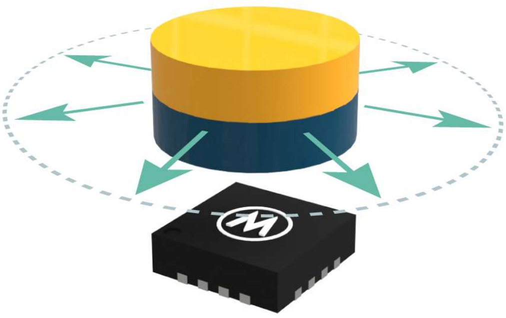


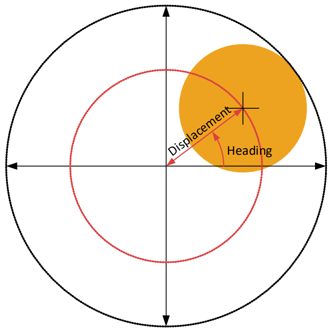
A threshold at 22mT (Bop) and 20mT (Brp) would then be an appropriate choice, as shown on the graph.

[3] https://www.melexis.com/en/product/dvkmagnetic/development-kit-magnetic-sensors

3. 2-DoF Thumb Stick

This application is basically a linear position sensor application, but the magnet moves not along one axis but can freely move in the XY-plane. As a rule of thumb, the total stroke that can be measured is roughly double the radius of the magnet. This application is Melexis proprietary technology.





3.1. Displacement information

To get the displacement information, all three magnetic components are used. The displacement is a value in mm, so a constant C is added, with unit mm/rad. k is a parameter that is used to adjust the sensitivity mismatch (different strengths measured in the XY plane than in the Z plane) which is typically present in this kind of application.

$$Displacement = C \cdot \operatorname{atan}\left(\frac{\sqrt{{B_X}^2 + {B_Y}^2}}{k \cdot B_z}\right)$$

Linearity is not given by the design, but can be achieved by replacing C with a multi-point calibration (look-up table) or function inverse to the non-linearity.

In case $B_X = B_Y = 0$, the displacement will be 0. This is important for the heading information, calculated in the next section.

3.2. Heading information

To get the heading information, the X and Y measurements are used. The heading is a value in radians. Depending on the polarity of the magnet π needs to be added.

$$Heading = \operatorname{atan}\left(\frac{B_Y}{B_X}\right) + \pi n\,,\ \text{with } n \in \mathbb{Z}$$

This formula only works if $B_X \neq 0$ and will only give a 180° range as output. For the full 360° range, the atan2 function would be needed.

$$Heading = \operatorname{atan2}(B_Y, B_X)$$

This formula will be undefined if $B_X = B_Y = 0$, which is the case exactly in the center. This is logical as the magnet did not move in any direction, and the displacement will be 0. Therefore it is not needed to calculate the heading if the displacement calculation resulted in “no displacement”.

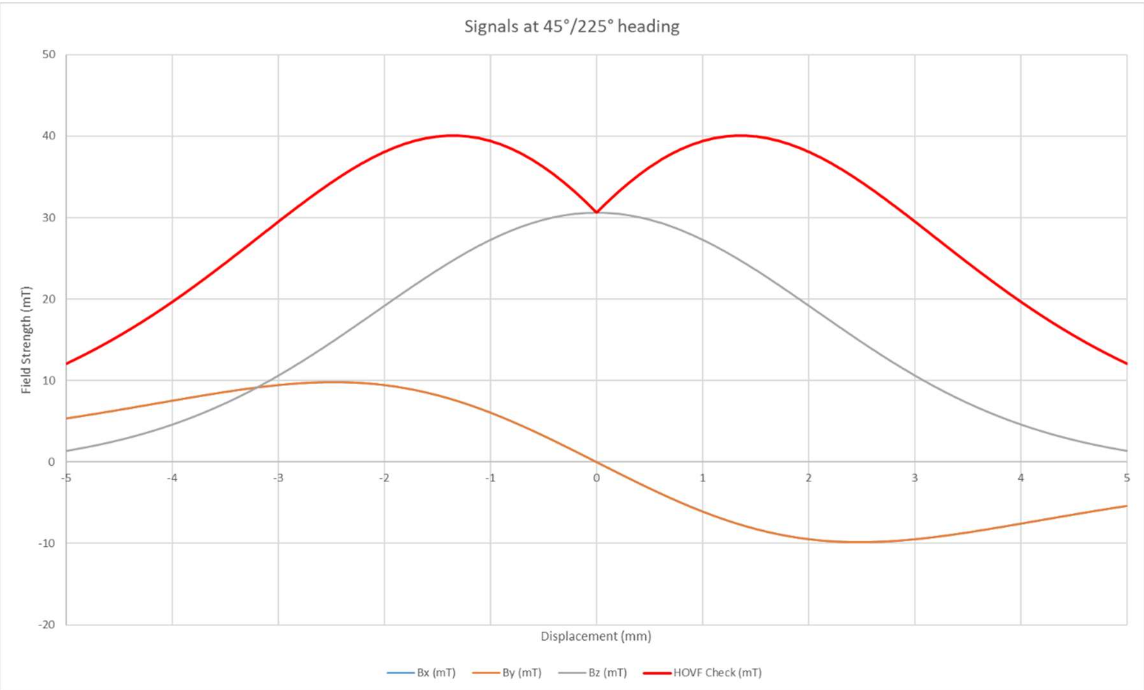
The heading can be 180° shifted vs the actual magnet position depending on the magnetization of the magnet.

3.3. Magnet example

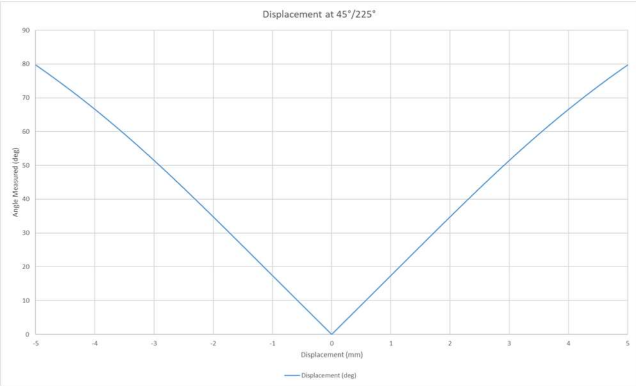
As an example, a magnet with the following properties is used. The airgap is measured from the magnet surface to the Hall element position. The sensor that is used is an MLX90392, 50mT version.

Parameter	Value
Magnet shape	Disk
Magnet material	NdFeB
Magnet diameter	4mm
Magnet height	1mm
Magnet Br	1350mT
Magnetization	Axial
Airgap in central position	3.5mm
Radius of travel	5mm

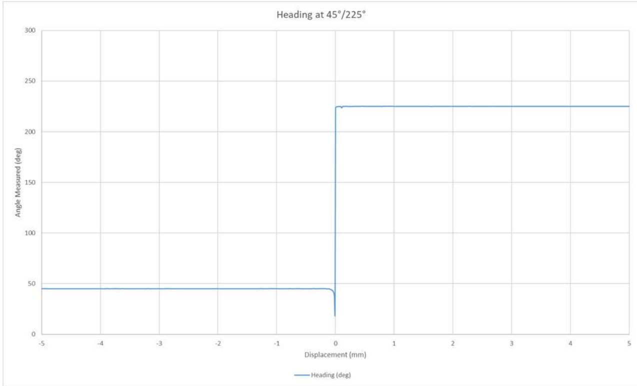
A simulation of the magnetic fields at an airgap of 3.5mm (from the face of the magnet to the Hall element) gives the following graph for a stroke of +/-5mm at a 45° stroke. The sum of the fields ($|B_X| + |B_Y| + |B_Z|$) remains for this case below 49.13mT for the HOVF not to be triggered. B_X and B_Y are the same on the 45° stroke.



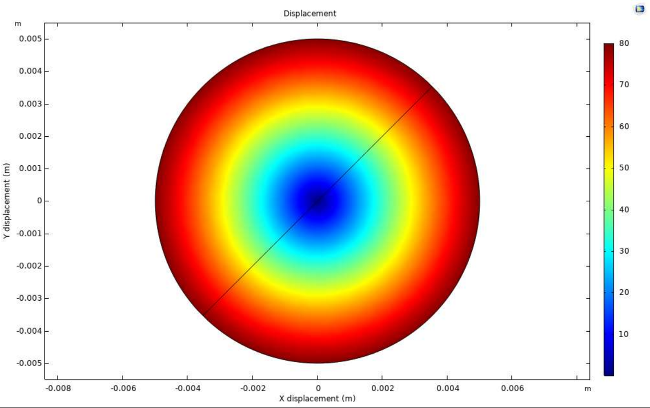
Displacement measured ($k = C = 1$)



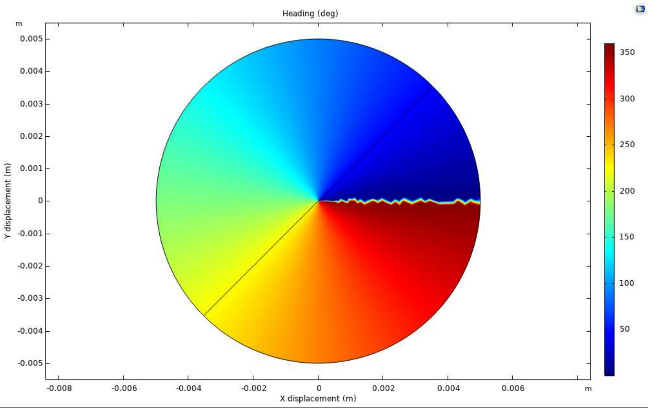
Heading measured



For full area



For full area



The displacement measurement is fairly linear, but it could be improved with a back-end calibration of choice.

4. Practical Implementation

In a typical application, requirements like update rate, current (energy) consumption and accuracy needed are given. Due to the flexibility of Melexis' magnetometers, these topics can be addressed by adjusting settings like filtering.

For this chapter, some examples using MLX90392-011 (50mT version) are shown:

- The sensor is measuring at a rate different from the offered rates in continuous mode,
- The sensor is measuring at the fastest possible update rate.

The application is the rotary position sensor with push/pull detection from section 2.

In this example, a sequence for single mode will be given, where the output update rate is 100ms (10Hz).

4.1. Filtering and conversion time

For both cases, the calculations will be given as an example, side by side. The conversion time can be calculated based on the filter parameters. It is needed to know how long a measurement takes in order not to read the data out too soon before it being ready.

Single mode	Continuous mode
OSR_HALL = 1 OSR_TEMP = 1 DIG_FILT_HALL_XY = DIG_FILT_HALL_Z = 7 DIG_FILT_TEMP = 7 50mT version, T_COMP_EN = 1 The contents of 0x14 and 0x15 then have to become respectively 0xFF and 0xB7. The conversion for one axis takes: $N_{CLOCKS} = 16 + (32 \cdot 2^{OSR}) \cdot (4 + 2^{DIGFILT+2}) = 16 + (32 \cdot 2^{1}) \cdot (4 + 2^{7+2}) = 33040$ In total (including temperature and signal processing, the conversion takes (clock @2.4MHz): $T_{CONVTOTAL}[\mu s] = 4 \cdot \frac{33040}{2.4} + \frac{926}{2.4} \cong 55453$	OSR_HALL = 0 OSR_TEMP = 0 DIG_FILT_HALL_XY = DIG_FILT_HALL_Z = 0 DIG_FILT_TEMP = 0 50mT version, T_COMP_EN = 0 The contents of 0x14 and 0x15 then have to become respectively 0x00 and 0x90. The conversion for one axis takes: $N_{CLOCKS} = 16 + (32 \cdot 2^{OSR}) \cdot (4 + 2^{DIGFILT+2}) = 16 + (32 \cdot 2^{0}) \cdot (4 + 2^{0+2}) = 272$ In total (including signal processing) the conversion takes (clock @2.4MHz): $T_{CONVTOTAL}[\mu s] = 3 \cdot \frac{272}{2.4} + \frac{573}{2.4} \cong 579$

4.2. Average current consumption

The average current consumption can be calculated once the conversion times are known. The formula is given below.

$$I_{dd_{avg}} = \frac{t_T \cdot I_{dd_T} + t_X \cdot I_{dd_X} + t_Y \cdot I_{dd_Y} + t_Z \cdot I_{dd_Z} + t_{DSP} \cdot I_{dd_{DSP}} + t_{Counting} \cdot I_{dd_{Counting}}}{t_{Total}}$$

$$t_{Total} = Period = t_T + t_X + t_Y + t_Z + t_{DSP} + t_{Counting}$$

$$I_{dd_T} = 0.73mA$$

$$I_{dd_X} = I_{dd_Y} = 1.8mA$$

$$I_{dd_Z} = 2.8mA$$

$$I_{dd_{DSP}} = 1.0mA$$

Also the tool which can be found online can be used.

Single mode

$$t_{Total} = 100ms$$

$$t_T = t_X = t_Y = t_Z = \frac{33040}{2.4} ms$$

$$t_{DSP} = \frac{926}{2.4}$$

Version	-011
T_COMP_EN	1
DIG_FILT_HALL_T	7
DIG_FILT_HALL_XY	7
DIG_FILT_HALL_Z	7
OSR_TEMP	1
OSR_HALL	1
Burst frequency (Hz)	Single
Single frequency (Hz)	10

	Number of clocks	Time (typ, ms)	Idd (typ, mA)
Temperature	33040	13.767	0.73
X	33040	13.767	1.8
Y	33040	13.767	1.8
Z	33040	13.767	2.8
DSP	926	0.386	1.0
Subtotal		55.453	
Min Counting duration		0.066	
Total Minimal		55.519	
Period		100.000	
Counting/Idle duration		44.548	0.0015

[No timing conflict?] OK/NOK:	OK
Average current consumption (mA):	0.986

Continuous mode

$$t_{Total} = 0.714ms$$

$$t_T = 0ms$$

$$t_X = t_Y = t_Z = \frac{272}{2.4} ms$$

$$t_{DSP} = \frac{573}{2.4}$$

Version	-011
T_COMP_EN	0
DIG_FILT_HALL_T	0
DIG_FILT_HALL_XY	0
DIG_FILT_HALL_Z	0
OSR_TEMP	0
OSR_HALL	0
Burst frequency (Hz)	1400
Single frequency (Hz)	1

	Number of clocks	Time (typ, ms)	Idd (typ, mA)
Temperature	0	0.000	0.73
X	272	0.113	1.8
Y	272	0.113	1.8
Z	272	0.113	2.8
DSP	573	0.239	1.0
Subtotal		0.579	
Min Counting duration		0.066	
Total Minimal		0.645	
Period		0.714	
Counting/Idle duration		0.136	0.0110

[No timing conflict?] OK/NOK:	OK
Average current consumption (mA):	1.352

4.3. Accuracy (noise excluded) and calibration

[The calculations to get the values mentioned below can be found in the **Appendix A** – Worst case calculation (MLX90392-011, XY) of this document]

The accuracy can be calculated based on the applied field strength (16mT in rest position). Before calibration, taking all the worst case values from the datasheet at room temperature, the intrinsic error can be up to 4.9° (noise excluded).

This error can be greatly reduced by performing back-end calibration. Then only thermal drift effects are to be taken into account. One can also choose to eliminate only offset and sensitivity mismatch

Offset and sensitivity mismatch are easiest to measure. Measure the X and Y signals over a full rotation, and then take the extrema to determine the offset and amplitude:

$$Offset_X = \frac{Max_X + Min_X}{2}, Amplitude_X = \frac{Max_X - Min_X}{2}$$

$$Offset_Y = \frac{Max_Y + Min_Y}{2}, Amplitude_Y = \frac{Max_Y - Min_Y}{2}$$

Then the corrections to the signals can be applied:

$$X' = X - Offset_X$$

$$Y' = (Y - Offset_Y)\frac{Amplitude_X}{Amplitude_Y}$$

The error is then reduced to roughly 1.1° at room temperature.

4.4. Measurement flow

The tables below show a typical flow in order to get the data from the sensor and calculate the rotary (+push) information based on the magnetic field measurements. The first table is for the “single mode” and the second table is for the “continuous mode”.

Step	Action (single mode)	Comment
1	Write registers Register 0x14: 0xFF Register 0x15: 0xB7	Configuration of the IC, all filters and oversampling to maximum values. Also temperature compensation enabled.
2	Read registers 0x14 and 0x15 + Verification	Verification of the configuration, to check if the write operation from the previous step was correctly executed.
3	Set Mode 1	Command the IC to perform a single measurement.
4	Wait 61ms [4]	Wait for the measurement to be fully completed before reading out.
5	Read registers 0x00 to 0x09	Readback of the measurements and the status bytes.
6	Verify STAT1 and STAT2	Verification of the validity of the data: STAT1[0] should be 1 (DRDY), STAT2[0] should be 0 (HOVF).
7	Process the data	Calculate necessary position information.
8	Wait the remaining of 100ms	To achieve the 100ms update rate, wait the remaining of the period before starting the next measurement.
9	Repeat from step 3	Since the IC is back in idle mode, a new measurement command needs to be issued.

Step	Action (continuous mode)	Comment
1	Write registers Register 0x14: 0x00 Register 0x15: 0x90	Configuration of the IC, all filters and oversampling to minimum values. Also temperature compensation disabled.
2	Read registers 0x14 and 0x15 + Verification	Verification of the configuration, to check if the write operation from the previous step was correctly executed.
3	Set Mode 13 (0xD)	Command the IC to start performing measurements at 1400Hz.
4	Wait 0.786ms [5]	Wait for the measurement to be fully completed before reading out.
5	Read registers 0x00 to 0x07	Readback of the measurements and the status bytes.

[4] *Drifts of IC taken into account,* $55.453ms \cdot 1.1 \approx 61ms.$

[5] *Drifts of IC taken into account,* $0.714ms \cdot 1.1 \approx 0.786ms.$

Step	Action (continuous mode)	Comment
6	Verify STAT1 and STAT2	Verification of the validity of the data: STAT1[0] should be 1 (DRDY), can be used to poll if the data is ready and have the fastest data out possible, STAT2[0] should be 0 (HOVF), STAT2[1] (DOR) is optional, but can be used as indication that one or more of the previous measurements was not read out. It would indicate that the current consumption could be reduced (be measuring less fast), or that the filtering can be increased to get more accurate results (comes with current consumption increase).
7	Process the data	Calculate necessary position information.
8	Repeat from step 4	Since the IC is back in continuous mode, a new measurement is automatically started.

The assumption is made that the IC is in the idle state before step 1, like after power-on reset. If this is not guaranteed, the mode should be set first to idle again (mode 0). Then also a worst case wait time has to be included (to make sure measurement is completed if exiting the continuous measurement mode) before attempting to write the configuration in the NVRAM of the IC.

5. Revision History

Revision	Changes
001, Sept. 2021	Creation + Review team
002, Feb. 2024	Correction in register 0x14 content for single mode case Added MLX90394 and MLX90397 Addition of "Melexis proprietary technology" on the 2-DoF thumb stick application Melexis logo update

For the latest revision of this document, visit www.melexis.com

For additional information, get in touch, www.melexis.com/contact

6. Disclaimer

Appendix A – Worst case calculation (MLX90392-011, XY)

To calculate the worst case error (at 35°C), the datasheet specs are used and combined such to give the max error over the full rotation. The parameters that do that are listed in the table. A simple calibration is done on the resulting measurement, to reduce the error.

Over temperature, only the offset drift is important. The sensitivity mismatch drift is negligible vs the total error. The error including the drift and with the calibration at room temperature is also shown.

Parameter	Value	Comments
B	16mT	Applied field (from application)
$SENS_{XY}$	1.67µT/LSB	Max value (in µT/LSB) gives least amount of LSB
$Offset_X$	220LSB	Offset X-axis
$Offset_Y$	-330LSB	Offset Y-axis
$SMISM_{XY}$	-5%	Sensitivity mismatch (value worse than datasheet [-3 5%])
S_{YX}	-1.7%	Cross-axis sensitivity, Y to X
S_{XY}	1.9%	Cross-axis sensitivity, X to Y
B_{hot}	14.4mT	$B \cdot \left[1 - 2000 \frac{ppm}{°C} \cdot (85°C - 35°C)\right]$ taking -2000ppm/°C as TC for the magnet
$Offset\_Drift_X$	90LSB	Thermal offset drift X-axis
$Offset\_Drift_Y$	-100LSB	Thermal offset drift Y-axis
$SMISM\_Drift_{XY}$	1.3%	$265 \frac{ppm}{°C} \cdot (85°C - 35°C) \approx 1.3\%$ (worse than datasheet)

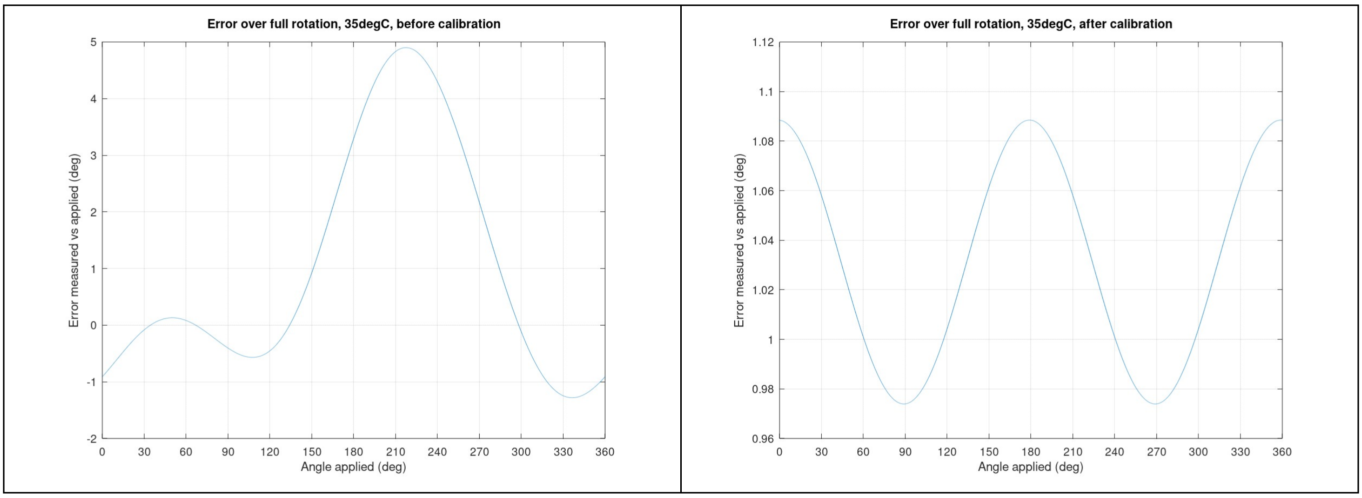
A.1 – Room temperature (35°C)

At room temperature, the worst case measured vectors over the full rotation (α is the applied angle) can be determined with the formula below.

$$\begin{bmatrix} X_M \\ Y_M \end{bmatrix} = \begin{bmatrix} 1 + SMISM_{XY} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & S_{YX} \\ S_{XY} & 1 \end{bmatrix} \begin{bmatrix} \cos(\alpha) \\ \sin(\alpha) \end{bmatrix} \cdot B \cdot \frac{1}{SENS_{XY}} + \begin{bmatrix} Offset_X \\ Offset_Y \end{bmatrix}$$

The angle is calculated and compared with the applied angle. The difference is plotted below, on the left, and reached a max value to around 4.9°.

Over a full rotation, the extrema are measured for each axis, and based on these the offset and (partially) the sensitivity mismatch can be determined. After taking these components out, the error is reduced to around 1.1°. A graph of the error is shown below, on the right.



A multipoint calibration can get rid of most intrinsic errors, as long as enough points are taken.

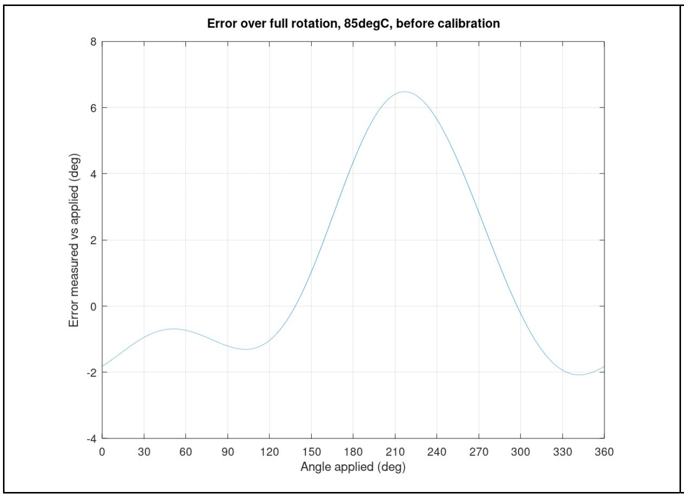
A.2 – High temperature (85°C)

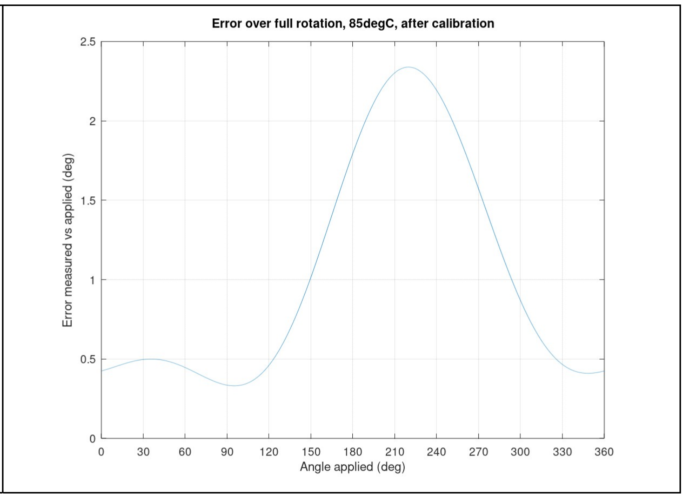
The most critical temperature of 85°C is taken, where the field strength of the magnet drops. An offset expressed in LSB will have a bigger impact with lower applied field. The calculation below is performed to estimate the worst case field vectors.

$$\begin{bmatrix} X_M \\ Y_M \end{bmatrix} = \begin{bmatrix} 1 - SMISM\_Drift_{XY} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 - SMISM_{XY} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & S_{YX} \\ S_{XY} & 1 \end{bmatrix} \begin{bmatrix} \cos(\alpha) \\ \sin(\alpha) \end{bmatrix} \cdot B_{hot} \cdot \frac{1}{SENS_{XY}} + \begin{bmatrix} Offset_X \\ Offset_Y \end{bmatrix} + \begin{bmatrix} Offset\_Drift_X \\ Offset\_Drift_Y \end{bmatrix}$$

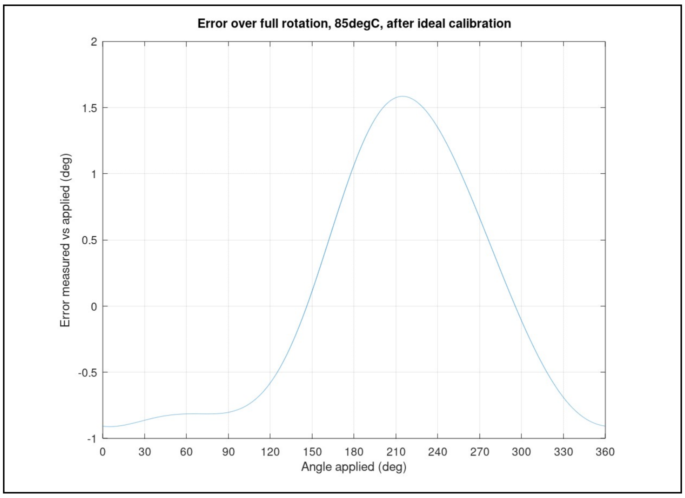
The angle is calculated and compared with the applied angle. The difference is plotted below, on the left, and reached a max value to around 6.5°.

After removing the offset and sensitivity mismatch calculated at room temperature, the error is reduced to around 2.4°. A graph of the error is shown below, on the right.





An ideal calibration, where there is no error remaining at room temperature, will give a max error at 85°C of 1.6°.



Similar calculations can be made for low field.