Out of Shaft

with magnetic 3D sensor

About this document

Scope and purpose

After reading this application note you will know how you can use a magnetic 3D sensor for an out of shaft position detection.

Note: The following information is given as a hint for the implementation of our devices only and shall not be regarded as a description or warranty of a certain functionality, condition or quality of the device.

Intended audience

This document is intended for designers to use a magnetic 3D sensor for out of shaft applications.

Advantages by using a magnetic 3D sensor

Accurate angle measurements of around ±2°…4° after calibration at room temperature[1]

- Automatic error cancellation by using auto-calibration of:
  - Sensor in-accuracies: magnetic amplitudes (=matching), offset and phase
  - System errors: Assembly tolerances, lifetime drifts
- Easy implementation
- Only easy magnetic design needed
- Very flexible configuration between sensor and magnetic encoder
- Easy calibration algorithm

[1] Further application note about typical accuracy is in preparation.

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1 Introduction

In several applications it is not possible to access the end of a shaft for an angle measurement as in **Figure 1**.

An easy-to-use approach is to use a magnetic 3D sensor by measuring the X-Y (X-Z or Y-Z) components. The sensor is located out of the shaft (see **Figure 2** and **Figure 3**).

The shaft needs to have a magnetic encoder with at least 2 poles on the shaft (see **Figure 2** and **Figure 3**).

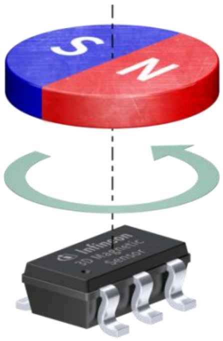


Figure 1 End of shaft principle

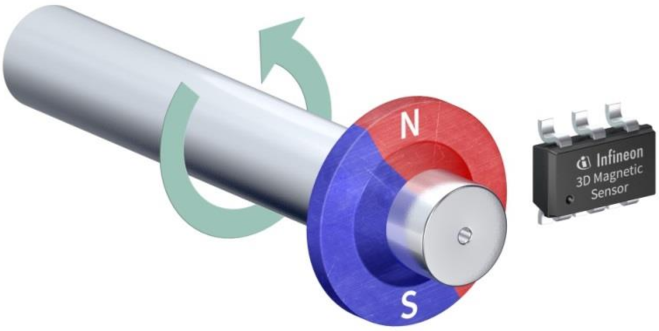


Figure 2 Example: X-Y (centered) configuration

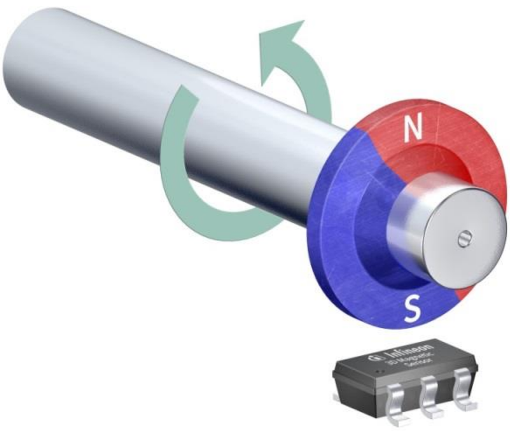


Figure 3 Example: Z-X (centered) configuration

2 Out of Shaft

2.1 Magnetic field components

The magnetic encoder provides a magnetic field. The ideal curve would be two sine shape components what show no offset and have a phase shift of 90°. But, due to the "out of shaft" approach, unfortunately, we have differences in amplitude, offset & phase. This means the components measured by the sensor have to be corrected or calibrated. As an example the magnetic components including the deviation from ideal sine shapes see **Figure 4**.

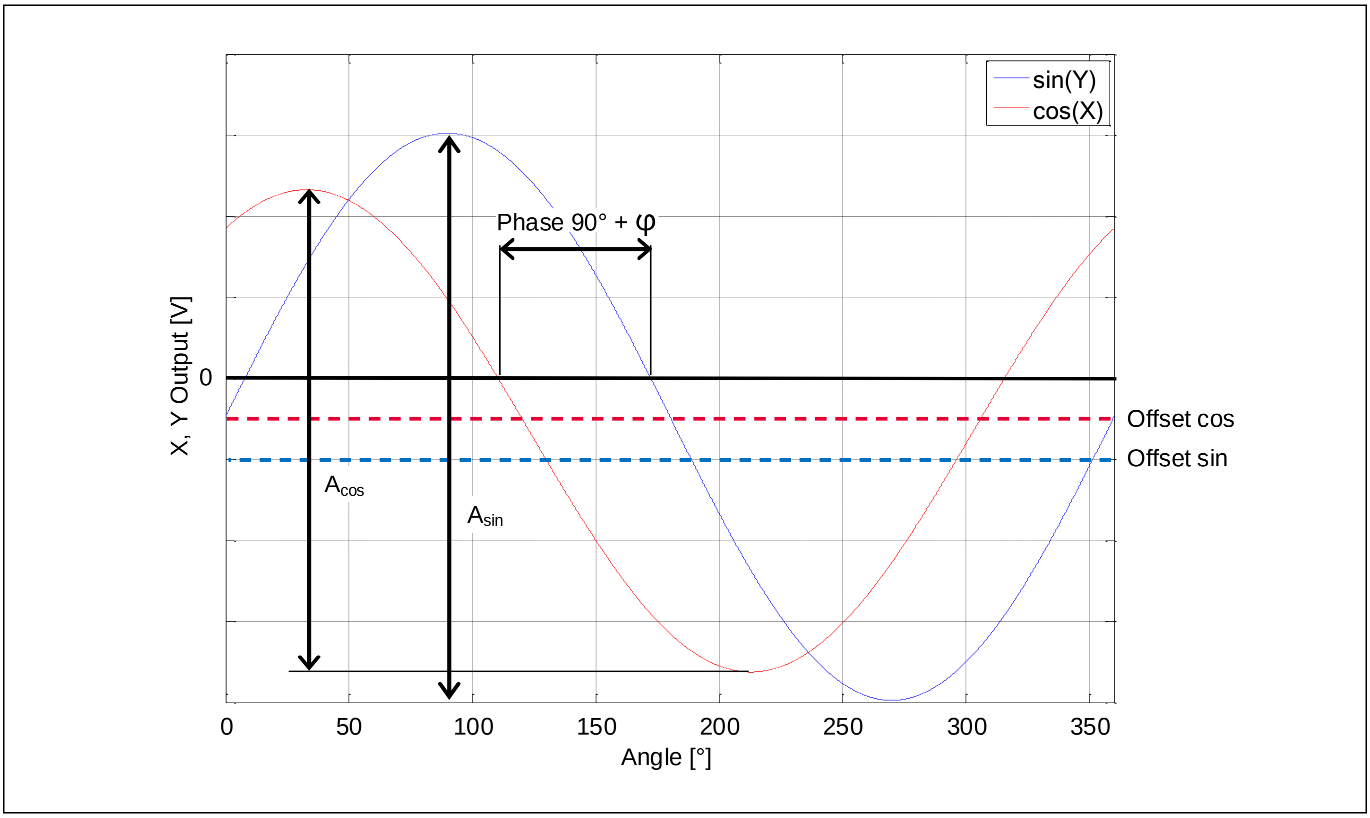


Figure 4 Errors of amplitude, offset and phase

These two components are used to calculate the angle by an arctan function. Dependent on the configuration between sensor and encoder two components have to be to chosen (see **Table 2**).

Depending on the configuration between sensor and encoder two out of three components can to be used. Please check out the table of the different placement options between sensor and encoder. These two components are used to calculate the angle by an arctan function.

2.2 Definitions

The component that is in radius is named first.

2.2.1 Axis

Definition of magnetic field

A positive field is considered as south-pole facing the corresponding hall element.

Figure 5 shows the definition of the magnetic directions X, Y, Z of the TLE493D-W2B6.

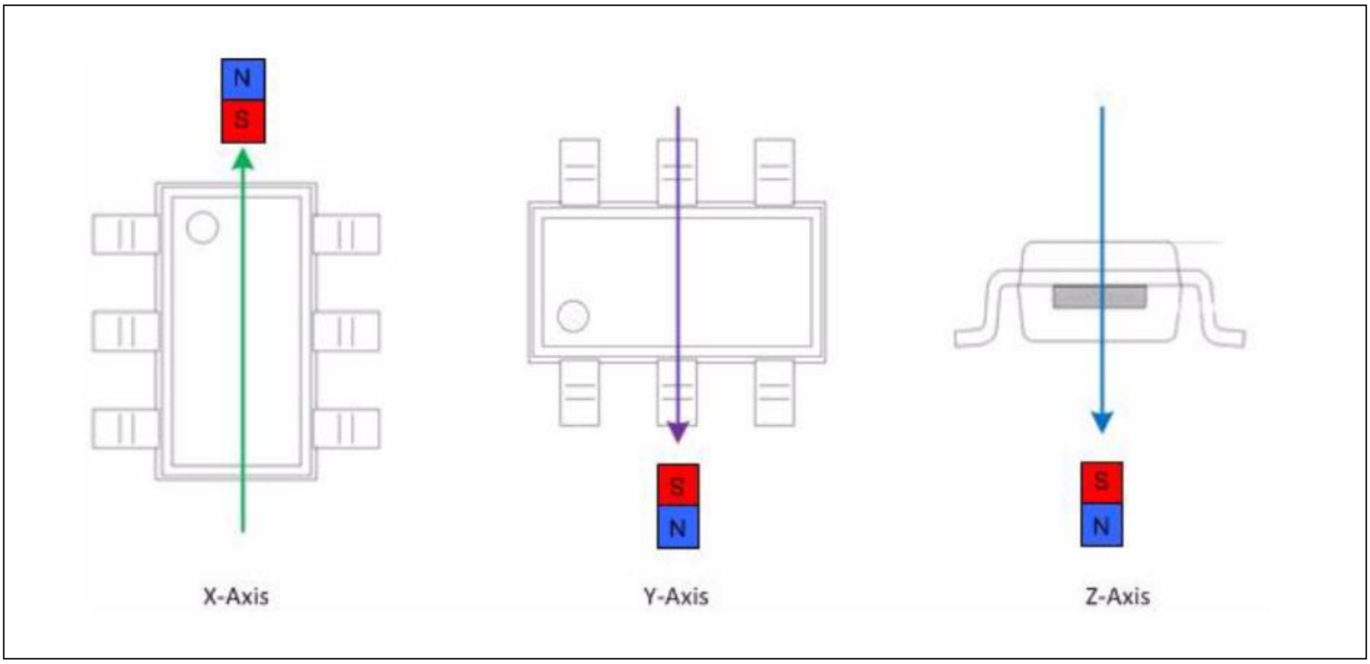
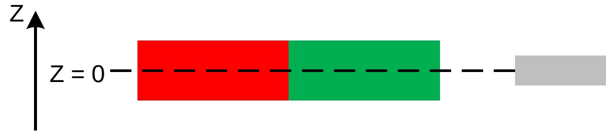
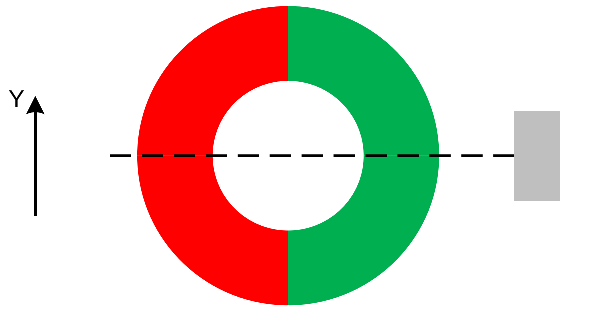
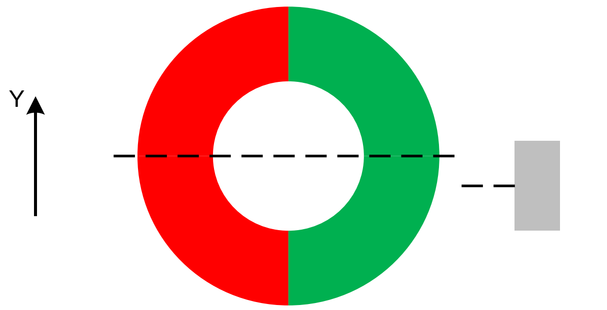
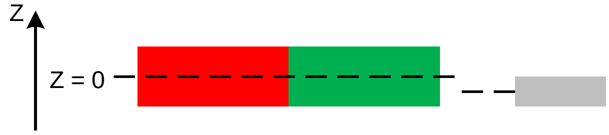


Figure 5 Definition of magnetic field direction

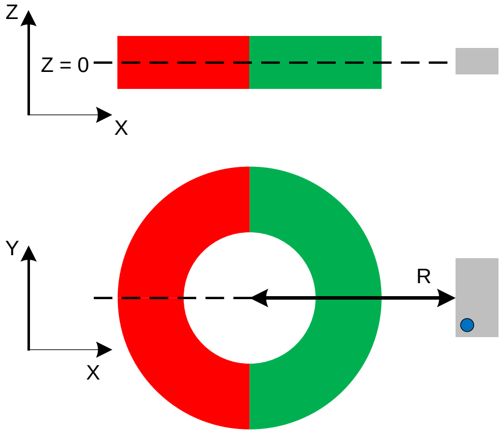
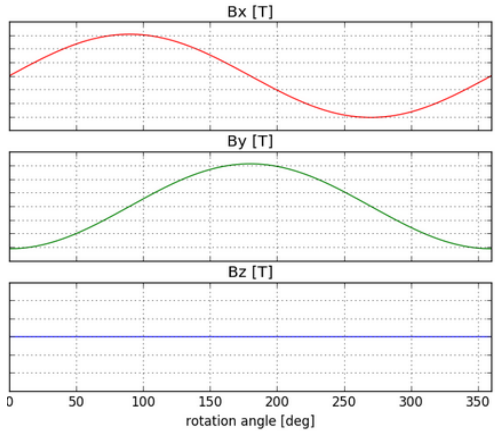
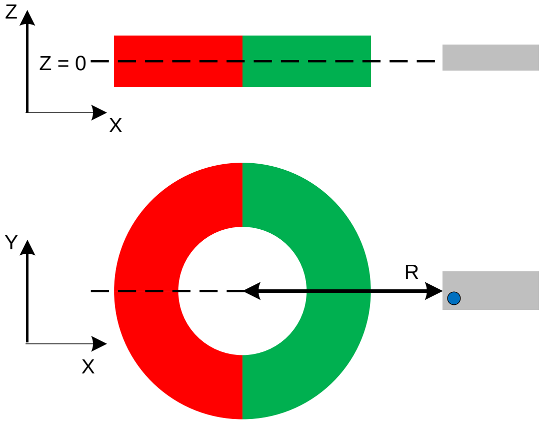
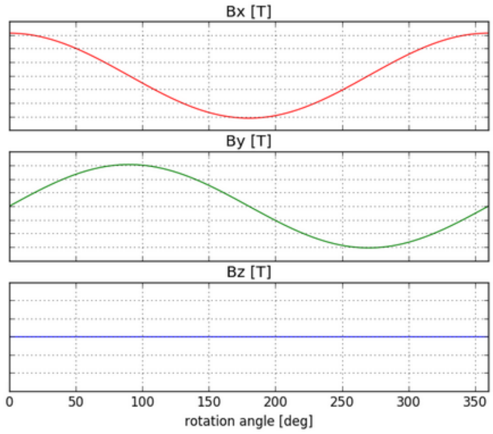
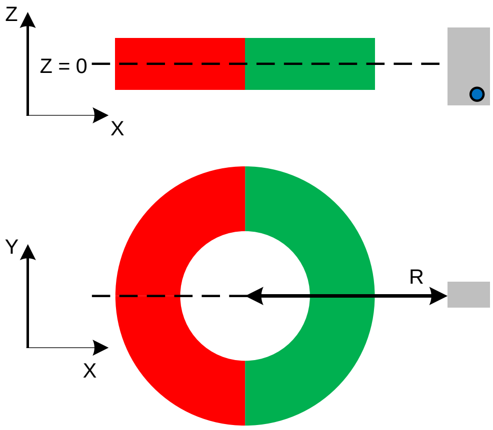
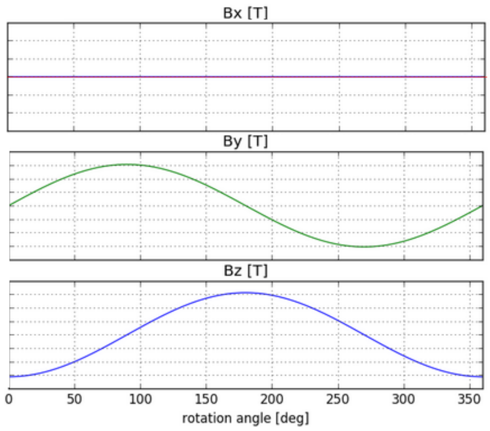
2.2.2 Naming and conventions

Table 1 Naming and conventions

Naming	Conventions
Centered	
Centered (in line with radius)	
De-centered in Y	
De-centered in Z	

3 Configuration overview

Table 2 Configurations (centered)

#	Used components	Placement	Field components
1	Y & X		
2	X & Y		
3	Y & Z[1] (X & Z)		
		All different placements are possible.	Two out of three.

[1] Preferred combination due to smaller internal signal delay between Y-Z compared to X-Z.

3.1 In-Plane (tangential) configuration (quantitative example)

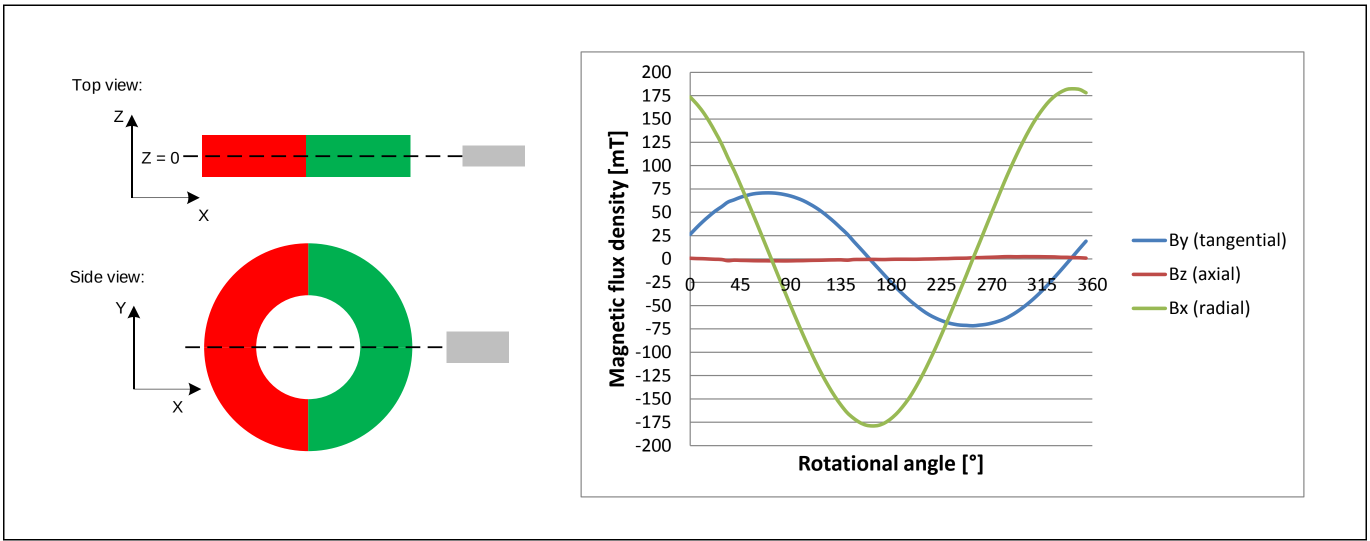


Figure 6 Magnetic components at an In-Plane configuration

By using a tangential configuration following magnetic shape is expected:

- B_x (radial) > B_y (tangential)
- B_z (axial) ~ 0

This covers #1 and #2 in **Table 2**.

4 Calibration

First, in this chapter the needed calibration values are shortly described as "Basic Calibration Parameters". Afterwards, possible ways are listed to get the needed calibration parameters (see **Chapter 5**). The different methods result in different accuracy combined with different efforts.

The least overall accuracy is reached by just a magnetic simulation. The best accuracy can be established by continuous running calibration so called "auto-calibration".

Following assumptions have been taken:

- The angle of revolution covers the needed parameters described in **Chapter 4.1**.

Note: The maximum possible update rate of the sensor limits the angle accuracy of the system. This max sampling rate is described in the according data sheet of the device.

4.1 Basic calibration parameters

In order to get proper sine and cosine functions with a phase shift of 90° a calibration of three parameters shall be executed.

Following parameters needs to be taken into consideration for calibration:

1. Amplitude[1] ratio g_x:
   a) Select maximum value of sine = A_{sin_max}
   b) Select minimum value of sine = A_{sin_min}
   c) Select maximum value of cos = A_{cos_max}
   d) Select minimum value of cos = A_{cos_min}
   ➔ Amplitude ratio g_x between sin and cos
2. Offset $_{AO\_sin}$ and A_{O_cos} of the sine and cosine signal
3. Phase shift φ between sine and cosine

A typical sensor output is shown also in **Figure 4**.

For a detailed description please refer to the "How to calculate the calibration values" (see **Chapter 5)**.

[1] The amplitdue detection is sensitive to noise. A proper mean value shall be used.

4.2 Calibration by magnetic design or magnet mapping

By using a simulation (please check also **https://design.infineon.com/3dsim**) upfront the magnetic characteristics can be seen. Out of this the ratio g, offset and phase errors can be calculated and already used for correction from the beginning.

Another possibility is to make a mapping of the magnet and get the magnetic characteristics out of this.

For low level applications this approach by a magnetic simulation can be used and correction values may be taken out and used as standard correction values.

Note: Accuracy is less compared to a continuous auto-calibration or end-of-line calibration. This approach will not cover long term drift effects of the magnet or the sensor.

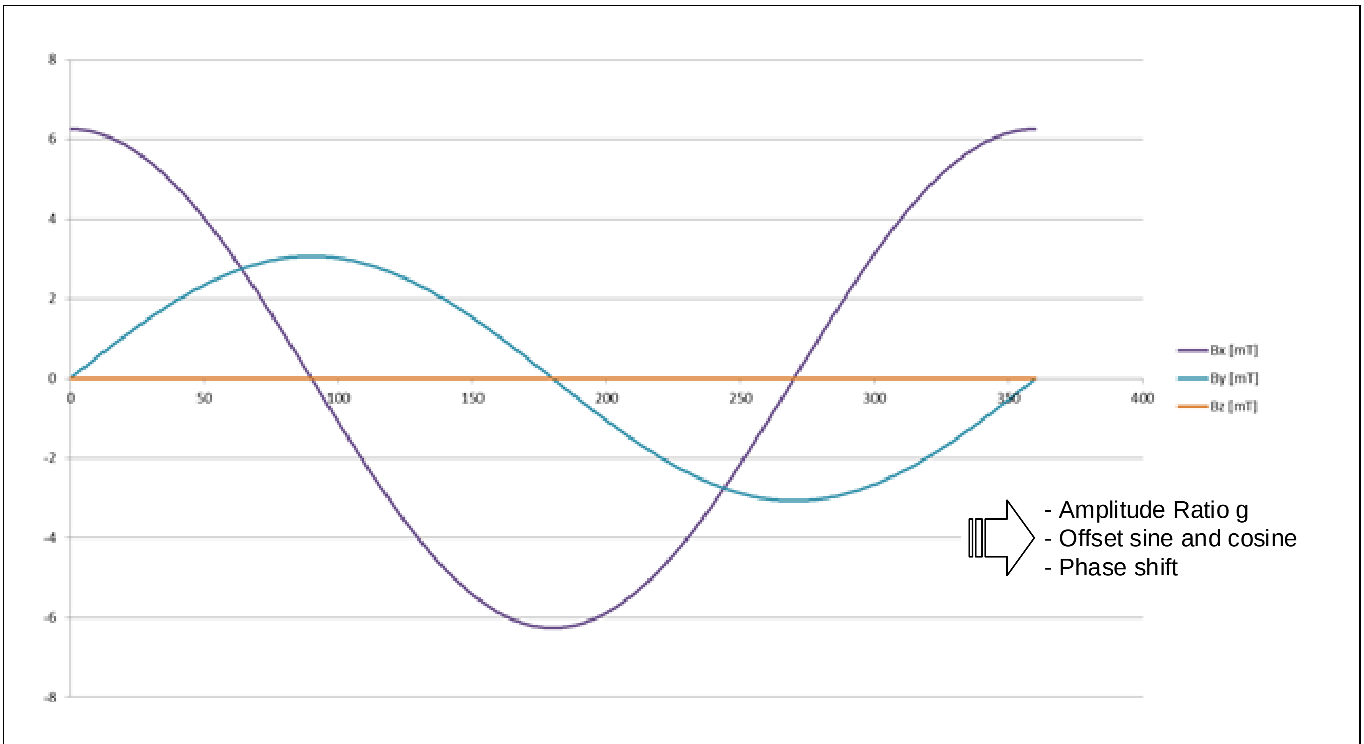


Figure 7 Determination of the calibration values by simulation

4.3 End-of-Line calibration

By using an end-of-line calibration the specific correction parameters of every sensor-magnet system can be evaluated.

Note: This approach will not cover long term drift effects of the magnet or sensor. Temperature effects will be covered in principle

4.4 Calibration with auto-calibration

The best accuracy can be achieved by using an Auto-Calibration. After detecting a full revolution the calibration parameters shall be calculated again. This means the uC always calculates and uses the correction values named in **Chapter 4.1** during operation. Sensor or magnetic drifts will be compensated in this mode all the time.

This solution offers you after one revolution for calibration around ±2°…4° accuracy at room temperature.

5 How to calculate the calibration values

This chapter explains how to determine parameters such as amplitude, offset, and the phase of two components.

The (end-of-line) calibration can be accomplished using the following sequence (see **Figure 8**).

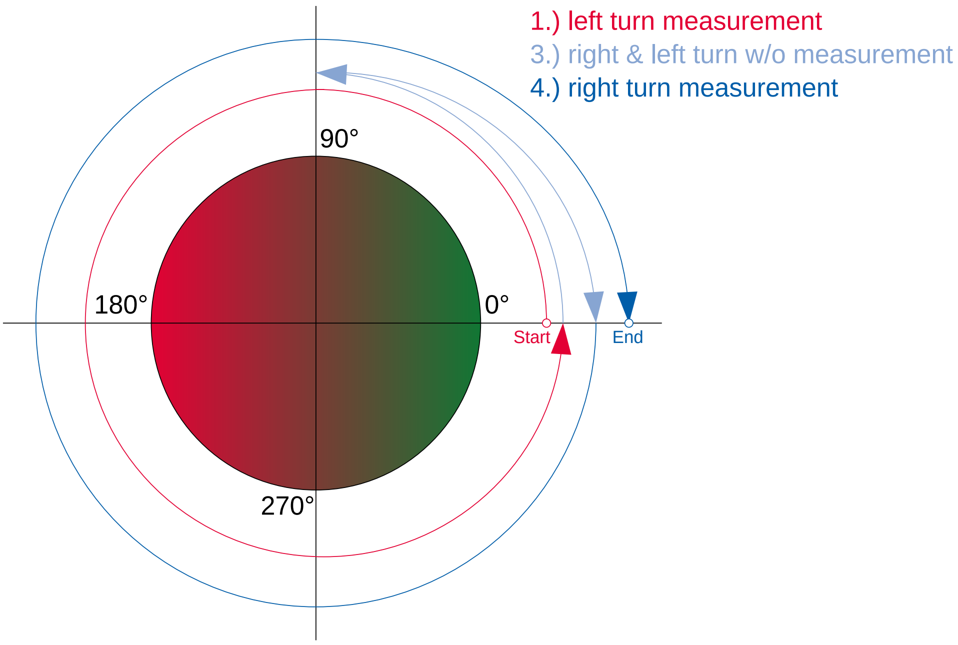


Figure 8 Calibration routine

1. Turn magnetic field 360° **left** and measure X and Y components
2. Calculate amplitude, offset, phase correction values of left turn
3. Turn further 90° left and 90° back right without measurement
4. Turn magnetic field 360° **right** and measure X and Y values
5. Calculate amplitude, offset, phase correction values of right turn
6. Calculate **mean** values of amplitude, offset, phase correction

5.1 Extraction of parameters

There are two possible methods for extracting these parameters.

5.1.1 Min-Max method

X_{max}, X_{min}, Y_{max} and Y_{min} have to be extracted out of every full-turn measurement (see **Figure 9**).

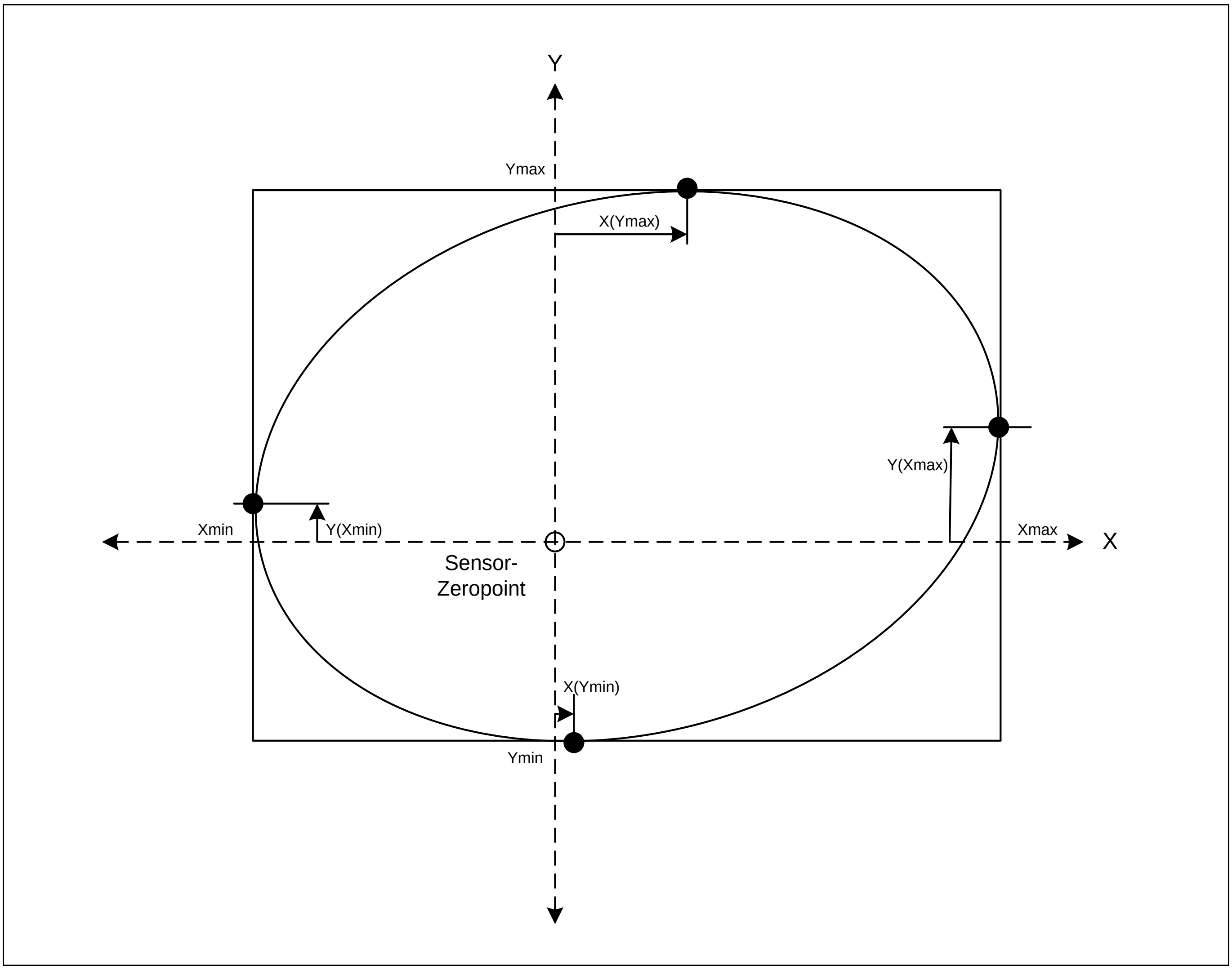


Figure 9 Min-Max method

Afterwards, amplitude [Equation 3], [Equation 4]) and offset ([Equation 5], [Equation 6]) can be calculated:

$$A_X = \frac{X_{max} - X_{min}}{2}$$ [Equation 3]

$$A_Y = \frac{Y_{max} - Y_{min}}{2}$$ [Equation 4]

$$O_X = \frac{X_{max} + X_{min}}{2}$$ [Equation 5]

$$O_Y = \frac{Y_{max} + Y_{min}}{2}$$ [Equation 6]

The corresponding maximum and zero-crossing points of the SIN and COS signals do not occur at the precise distance of 90°. The difference between X and Y phases is called the orthogonality error ([Equation 7]):

$$\varphi = \varphi_X - \varphi_Y$$ [Equation 7]

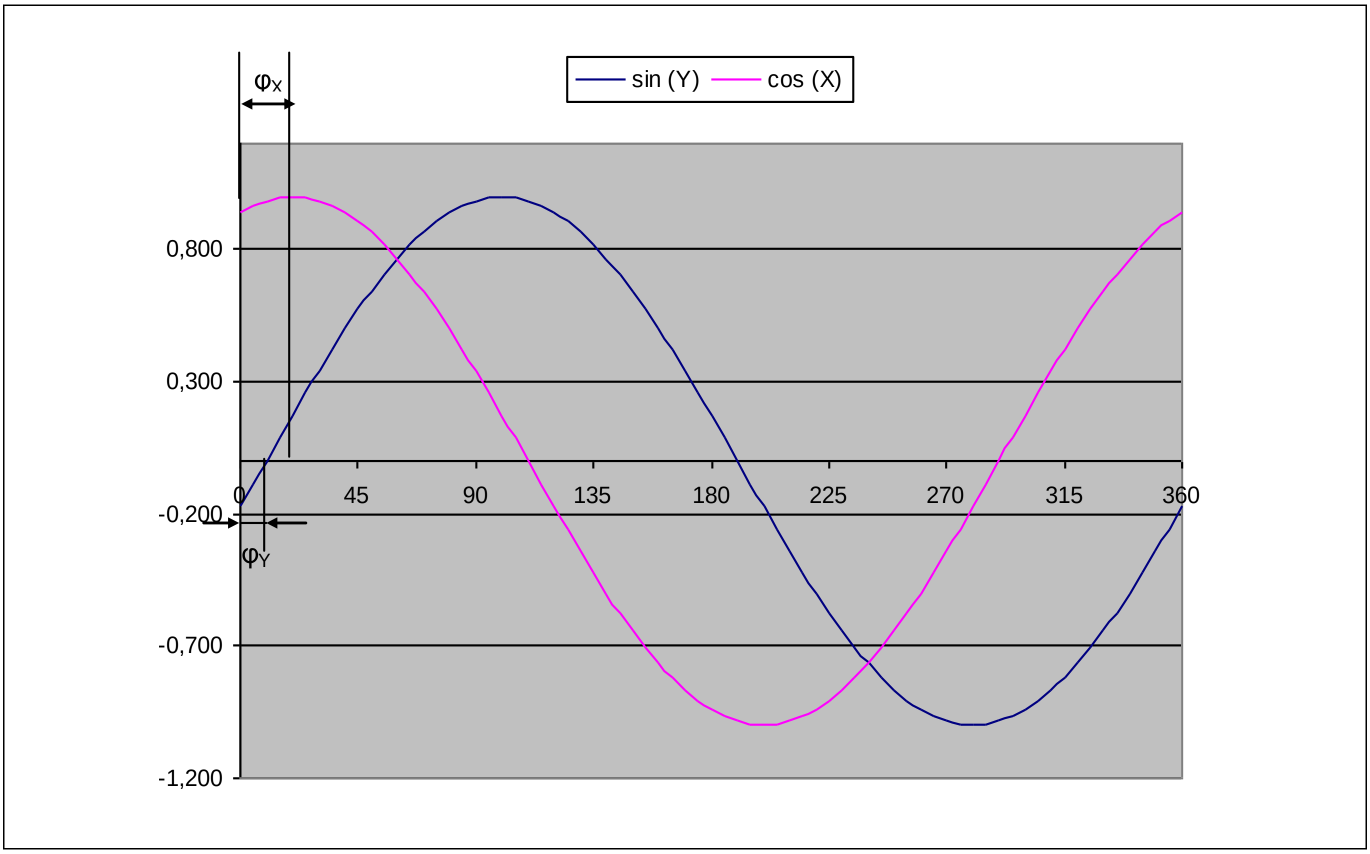


Figure 10 Orthogonality error

There is another more accurate way to determine the orthogonality error. The orthogonality can be calculated out of the magnitude of two 90° angle shifted components. Possible angle combinations are 45° and 135°, 135° and 225°, 225° and 315° or 315° and 45°.

The angle value is given by the used 3D sensor. Therefore the final parameters of amplitude and offset (**Chapter 5.2**) should be used.

At an angle output of 45° the corresponding Y(sin) and X(cos) values can be read out. This has been done also at 135° (**Figure 11**).

Next step is to calculate the length of the magnitudes ([Equation 8]):

$$M_{45} = \sqrt{X_{45}^{\ 2} + Y_{45}^{\ 2}}$$
$$M_{135} = \sqrt{X_{135}^{\ 2} + Y_{135}^{\ 2}}$$ [Equation 8]

M_{45}, M_{135} : Magnitude at 45° and 135°

X_{45}, X_{135} : Cosine values at 45° and 135°

Y_{45}, Y_{135} : Sine values at 45° and 135°

With these magnitudes the orthogonality can be calculated ([Equation 9]):

$$\varphi = 2 * \arctan(\frac{M_{135} - M_{45}}{M_{135} + M_{45}})$$ [Equation 9]

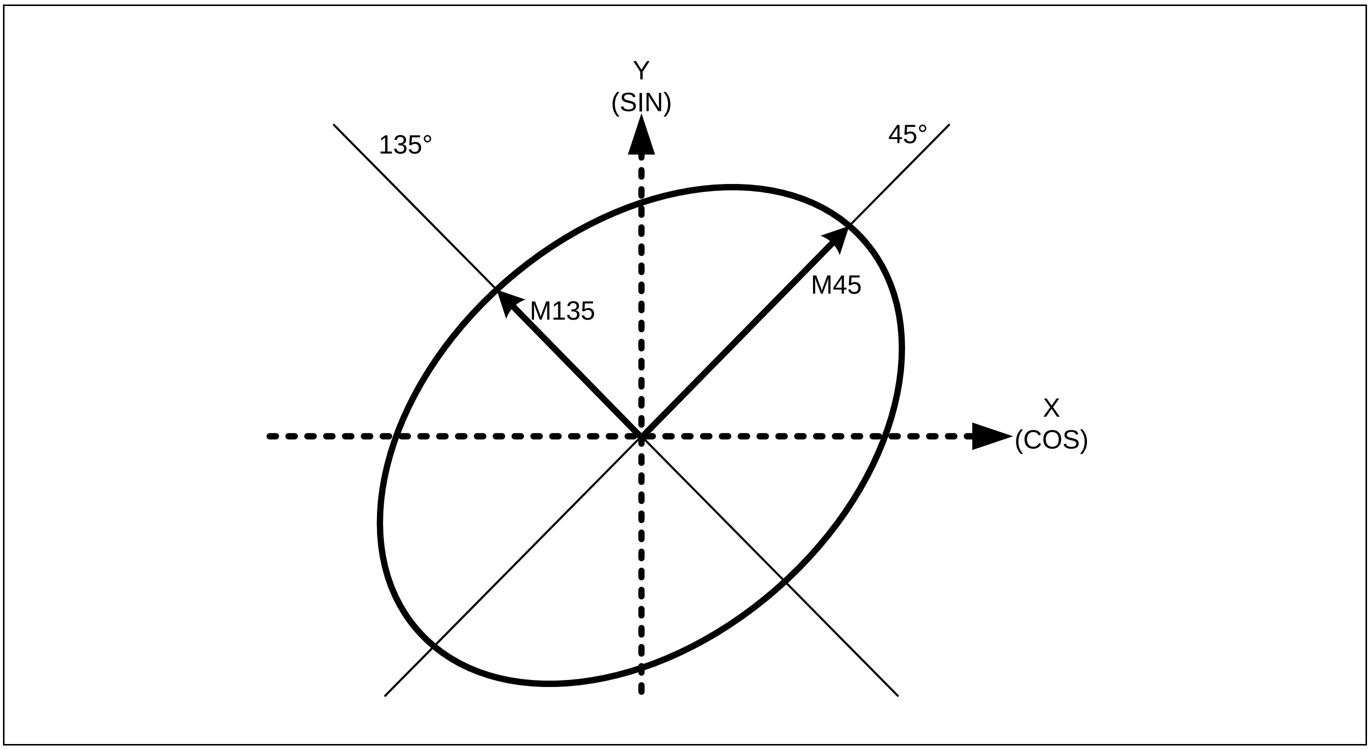


Figure 11 Correction of orthogonality error

5.1.2 Exact method

This method uses the Discrete Fourier Transform (DFT) to extract the parameters out of the measurements. Therefore an accurate reference system is necessary. This method is done using 2^m measurement points at 360° (e.g. m = 8; n = 2^m = 2^8 = 64).

DFT offset calculation:

The offset is calculated by the summation of the X- or Y- measurements divided by the number of measurement points ([Equation 10]):

$$O_x = [X(1) + X(2) + .. + X(n)] / n$$
$$O_Y = [Y(1) + Y(2) + .. + Y(n)] / n$$
[Equation 10]

X(n) : X value at measurement point n

Y(n) : Y value at measurement point n

n : Measurement points

DFT amplitude and phase calculation:

To determine the amplitude, the real and imaginary parts must be calculated. This has been done with [Equation 11] for the X values and [Equation 12] for the Y values. β describes the reference angle (e.g. n = 64; measurement every 360° / 64 = 5.625° step).

$$DFT\_X\_r = [X(1)*COS(\beta 1) + X(2)*COS(\beta 2) + .. + X(n)*COS(\beta n)]*2/n$$
$$DFT\_X\_i = [X(1)*SIN(\beta 1) + X(2)*SIN(\beta 2) + .. + X(n)*SIN(\beta n)]*2/n$$
[Equation 11]

$$DFT\_Y\_r = [Y(1)*COS(\beta 1) + Y(2)*COS(\beta 2) + .. + Y(n)*COS(\beta n)]*2/n$$
$$DFT\_Y\_i = [Y(1)*SIN(\beta 1) + Y(2)*SIN(\beta 2) + .. + Y(n)*SIN(\beta n)]*2/n$$
[Equation 12]

Now the amplitude and phase can be calculated ([Equation 13], [Equation 14]):

$$A_X = \sqrt{(DFT\_X\_r)^2 + (DFT\_X\_i)^2}$$
$$A_Y = \sqrt{(DFT\_Y\_r)^2 + (DFT\_Y\_i)^2}$$
[Equation 13]

$$\varphi_X = \arctan \frac{DFT\_X\_i}{DFT\_X\_r}$$
$$\varphi_Y = \frac{\pi}{2} - \arctan \frac{DFT\_Y\_i}{DFT\_Y\_r}$$
$$\varphi = \varphi_X - \varphi_Y$$
[Equation 14]

5.2 Final parameters

No matter what calibration method is used, you still have to calculate the symmetrical values of the parameters. This is done using the mean value of the clock-wise (cw) rotation parameters and counterclock-wise (ccw) rotation parameters. This calculation has to be done with X and Y parameters. These parameters have to be used for the signal correction.

$$A_M = \frac{A_{cw} + A_{ccw}}{2}$$
$$O_M = \frac{O_{cw} + O_{ccw}}{2}$$
$$\varphi_M = \frac{\varphi_{cw} + \varphi_{ccw}}{2}$$
[Equation 15]

$(A,O,\varphi)_M$: Mean parameters

$(A,O,\varphi)_{cw}$: Parameters of clock-wise rotation

$(A,O,\varphi)_{ccw}$: Parameters of counterclock-wise rotation

The device has a temperature dependent offset behavior. It is possible to do a temperature offset compensation to achieve more accurate angle values over the whole temperature range.

The temperature coefficient can be calculated out of two measurements at two different temperatures (e.g. T25 and HT).

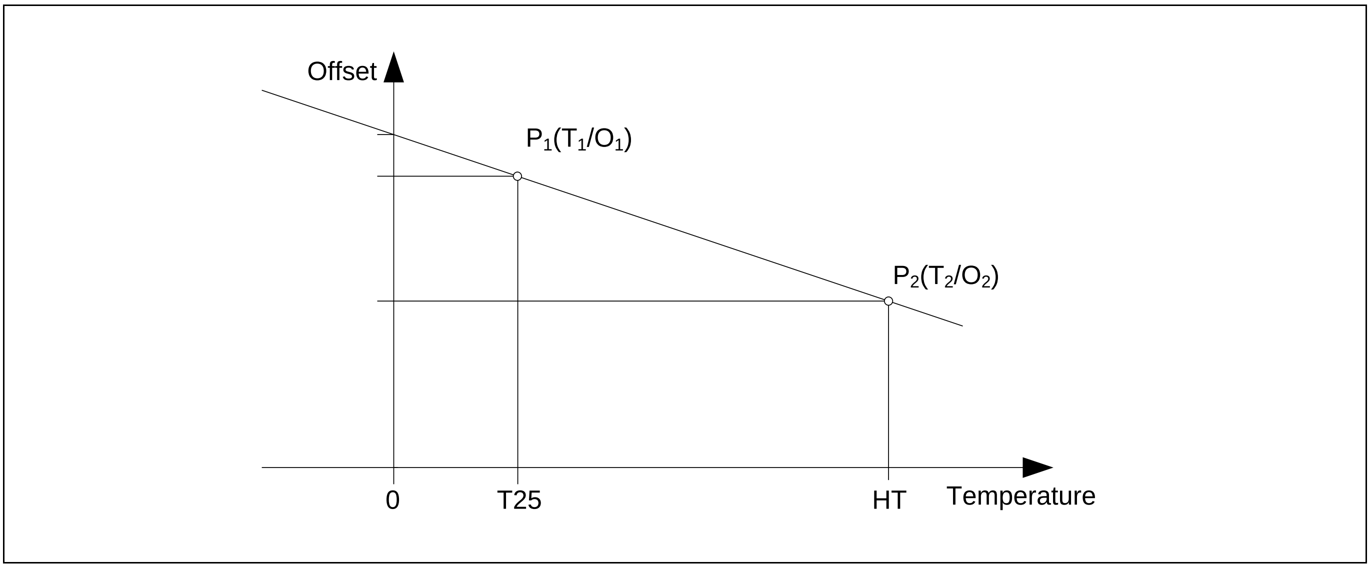


Figure 12 Temperature coefficient

The offset of X and Y components at two temperatures have to be known before the coefficient can be calculated with [Equation 16]:

$$KT_O = \frac{O_2 - O_1}{T_2 - T_1}$$ [Equation 16]

O_1,O_2 : Offset

T_1,T_2 : Temperature

5.3 Angle calculation

To get highly accurate angle values, the following angle calculation must be performed. **Figure 13** shows the implementation within a microcontroller.

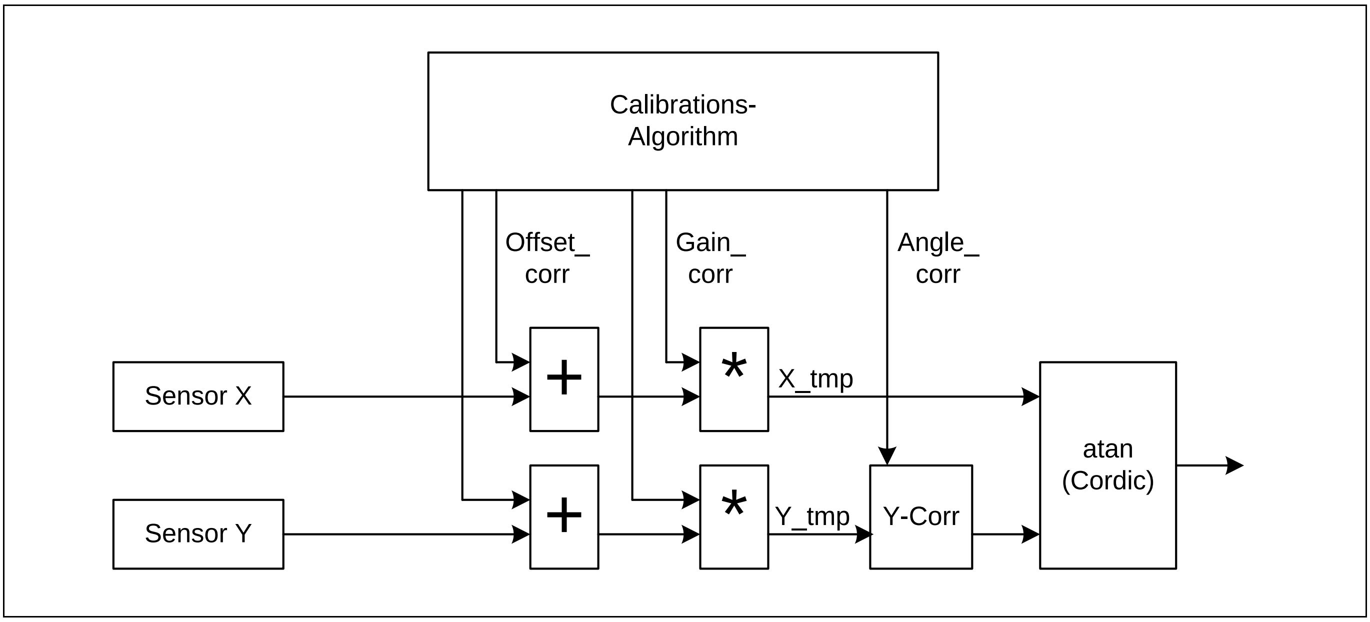


Figure 13 Implementation of angle calculation

Offset Correction (Offset_corr)

To increase the accuracy, the temperature-dependent offset drift can be compensated for. The temperature of the chip has to be read out. The offset values O_X and O_Y can be described by the following equations:

$$O_x = O_{X25} + KT_{OX} * (T - T_{25})$$
$$O_Y = O_{Y25} + KT_{OY} * (T - T_{25})$$ [Equation 17]

O_{X25} : Offset of X(COS) signal at room temperature

O_{Y25} : Offset of Y(SIN) signal at room temperature

KT_{OX} : X-Offset coefficient

KT_{OY} : Y-Offset coefficient

T : Temperature (in digits)

T_{25} : Temperature at room temperature

After the X and Y values are read out, the temperature-corrected offset value must be subtracted ([Equation 18]):

$$X_1 = X - O_X$$
$$Y_1 = Y - O_Y$$

[Equation 18]

Amplitude Normalization (Gain_corr)

The next step is to normalize the X and Y values by using the mean values determined in the calibration.

$$X_2 = \frac{X_1}{A_{XM}}$$
$$Y_2 = \frac{Y_1}{A_{YM}}$$

[Equation 19]

Non-Orthogonality Correction (Angle_corr)

The influence of the non-orthogonality can be compensated for by using [Equation 20], in which only the Y channel must be corrected.

$$Y_3 = \frac{Y_2 - X_2 * \sin(-\varphi)}{\cos(-\varphi)}$$

[Equation 20]

Resulting Angle

After correction of all errors, the resulting angle can be calculated using the arctan function[1].

$$\alpha = \arctan(\frac{Y_3}{X_2}) - \varphi_X$$

[Equation 21]

[1] Microcontroller library function arctan2(Y_3,X_2) works better to resolve 360°.

Revision history

Document version	Date of release	Description of changes
1.0	2018-07-31	Initial creation.

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