Online Digital Compensation Method for AMR Sensors

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***Abstract*—Anisotropic Magnetoresistance (AMR) sensors are magnetic sensors often used for angle measurements. The sensor outputs should be two perfect sinusoidal signals that depend on the angle to be measured. However due to non-ideal properties of the sensor, the actual outputs include undesired parameters as offset voltage, amplitude imbalance and harmonics. All of them generate errors in the angle calculation. Offset voltage and amplitude imbalance are the first and second largest sources of angle errors for which until now are the mainly compensated. The required compensation factors are usually estimated at the start of the sensor life and not updated during its lifetime.**
Although the sources of angle errors show variations due to wearing and aging effects, so far it is considered that these variations are not significant to affect the sensor accuracy. However, this will change in the future, especially in safety-critical applications that will demand higher accuracy. Then it will be necessary to update the compensation factors during the sensor lifetime. This paper proposes an online compensation method to reduce the offset voltage, the amplitude imbalance and hence the angle error in AMR sensors. It was verified using simulated data as well as real measurements, showing a good performance in all the cases. Unlike most of the compensation methods proposed until now, our method is suitable to be used during the sensor lifetime.

***Index Terms*—AMR sensors; angle error; online compensation**

I. INTRODUCTION

An Anisotropic Magnetoresistance sensor (AMR) is a magnetic sensor often used for angular measurements. It is usually configured with two Wheatstone bridges rotated 45° with respect to each other. The bridge outputs should be two perfect sinusoidal signals that depend on the magnetic angle to be measured. However, the actual signals show non-ideal characteristics due to imperfections that occur during the manufacturing of the sensor or in its assembly. This includes offset voltage, amplitude imbalance, and harmonics and phase difference. All of them are considered sources of errors in the angle calculation. [1]

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The error sources should be compensated in order to reduce their effect on the angle calculation. Due to the offset voltage and the amplitude imbalance are the first and second largest contributors of angle error, these are the errors mainly compensated until now [2]. Most of the proposed compensation methods are aimed to compensate these error sources under factory conditions, as will be presented in section 2. Although the error sources drift due to wearing and aging effects, until now it is considered that these variations are not sufficiently significant to affect the angle accuracy. Therefore, compensation factors are usually calculated just at the production line.

However, the future trend is to require more accurate angle measurements, especially in safety-critical applications. This implies that the errors due to wearing and aging effects will affect the sensor accuracy. Consequently, it will be necessary not only calculate compensation factors at the factory but also update their values during the sensor lifetime.

This paper is focused on proposing a compensation method suitable to update the required compensation factors onsite. During the sensor lifetime a specific setup is defined and limited computational power and memory space are available. Therefore, no special requirements on the setup and algorithms with low computational complexity are preferred.

The paper is organized as follows. Section 2 presents some methods that have been proposed to compensate the offset voltage and the amplitude imbalance in AMR sensors. Section 3 explains our proposed method aimed to update the compensation factors during the sensor lifetime. Section 4 shows the results of applying the proposed compensation method to signals calculated with a mathematical model of the AMR sensor, as well as to real voltages measured in commercial sensors. Finally, the results are discussed in Section 5.

II. COMPENSATION IN AMR SENSORS

An AMR sensor aimed to angle measurements is usually configured with two Wheatstone bridges rotated 45°with re-

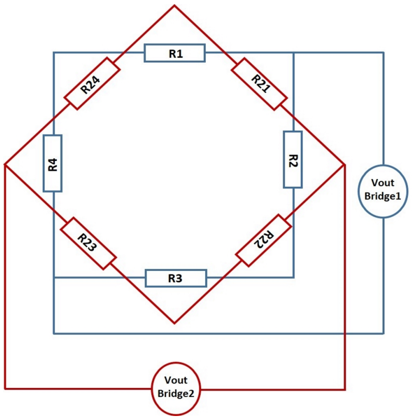


Fig. 1: Schematic of the Wheatstone bridges in an AMR sensor. Each **R** represents a magnetoresistance.

spect to each other (see Fig.1). If the sensor is in saturation state,the bridge outputs show two sinusoidal signals that depend on the magnetic angle and consequently Equation (1) can be used for its determination [3].

$$2\theta = \arctan\left(\frac{vout_{bridge2}}{vout_{bridge1}}\right) = \arctan\left(\frac{A * sin(2\theta)}{A * cos(2\theta)}\right) \quad (1)$$

However, due to imperfections in the manufacturing process and assembly of the sensor, the bridge outputs show no-ideal characteristics. An extra voltage defined as offset is included at each bridge output, the two sinusoidal signals do not have the same amplitude and additional harmonics are also present [1]. Therefore, Equation (1) should be rewritten as indicated in Equation (2).

$$2\theta = \arctan\left(\frac{A2 * sin(2\theta + \alpha) + offset2 + N2}{A1 * cos(2\theta) + offset1 + N1}\right) \quad (2)$$

where A1 and A2 denote the sine and cosine amplitudes, offset1 and offset2 are offsets, α is the phase shift, and N1 and N2 represent the additional harmonics.

The extra components in Equation (2) are sources of error in the angle calculation. These errors do not have a fixed value, but depend on the magnetic angle by showing sinusoidal characteristics as is indicated in Table I.

TABLE I: Expression for error sources present in AMR sensors

error source	**error expression**
Offset	$\Delta O sin(\theta)$
Amplitude imb.	$\Delta A sin(2\theta)$
Harmonic	$-\sqrt{2}K_o cos(\theta + \pi/4) - \sum_{n=2}^{\infty} K_n sin[(n-1)\theta]$

The error sources should be compensated in other to improve the sensor accuracy. The offset voltage is the largest contributor of error in the angle calculation. Therefore, different methods have been proposed to calculate the required compensation factors for its compensation, as follows:

Offset compensation based on applying and removing a magnetic field. It is based on apply and remove a magnetic field over the sensor to measure the sensor outputs afterwards. These measures indicate the offset voltages and hence the compensation factors. The method cannot be used during the sensor lifetime because the magnetic field is always present [4].

Offset determination based on two sensing elements. It proposes the usage of a low-offset magnetic sensing element and a highly sensitive magnetic element. The offset is determined by detecting the zero crossing at the output of the low-offset magnetic sensing element and measuring the offset voltage at the highly sensitive magnetic element [5].

With this method, it is possible to calculate the compensation factors online, but the main disadvantage is the need of an extra magnetic field and it doubles the amount of Wheatstone bridges in the sensor.

Maximum and minimum. The offset voltage is determined from the maximum and minimum output voltages of the bridges. The mean of the extreme values corresponds to the offset voltage. The sampling of the bridge outputs should be accurate enough in order to detect the correct extreme values and not other values, as shown in figure (see Fig.2). Consequenlty, the main drawback of this method is the accuracy and time required to detect the extreme values [6]. Although at the factory other methods could be used to verify the extreme values, it is not the same during the sensor lifetime.

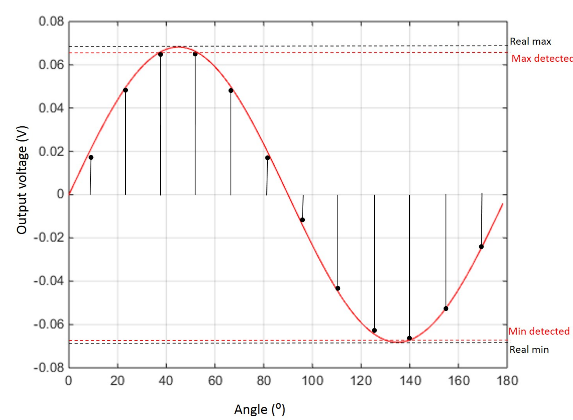


Fig. 2: Effect of the accuracy in the data adquision, over the detection of the real maximum values

The amplitude imbalance is the second largest source of angle error. The required factors for its compensation are usually determined from the mean of the subtraction of the extreme values of the sensor outputs.

The methods mentioned before could be very efficient to calculate compensation factors at the factory. However taking into consideration their requirements regarding to setup, processing or timing, they are not the best option to determine compensation factors online during the sensor lifetime.

III. OUR COMPENSATION METHOD

The accuracy of the angles measured with AMR sensors is affected by undesired parameters as offset voltage and amplitude imbalance. A method to compensate these error sources is proposed next. This is based on the fact that a Lissajous curve made with the two sinusoidal signals at the sensor outputs should be a circle. Its radius indicates the signal amplitudes and the centre the offset voltages, which should be (0,0).

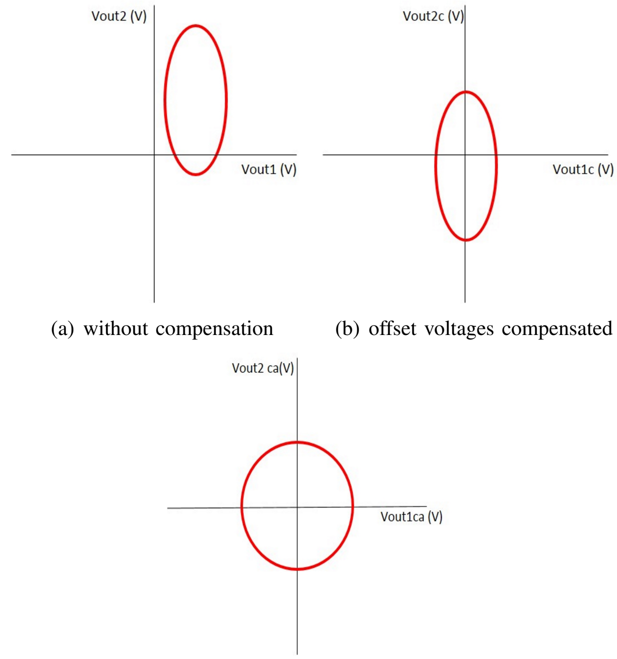
Figure 3(a) shows a Lissajous curve could be obtained with the actual sensor outputs. This tends not to be a circle centred at the origin, due to the amplitude imbalance and the offset voltages present at the bridge outputs. Therefore, some corrections should be performed. The compensation of the offset voltages shifts the centre of the Lissajous curve to the origin (See Fig.3(b)). Next, the compensation of the amplitude imbalance allows to obtain a Lissajous curve more similar to a circle centred at (0,0) (See Fig.3(c)), which implies higher accuracy in the measured angles.

Figure 4 shows the architecture of the proposed compensation method, which consists of three modules. Two modules to apply the compensation factors and the other to calculate them.

The factors for the offset voltages are calculated from Equations (3) and (4) both based on an equation systems presented in [7]. Each equation requires as input, the sensor outputs at three different angles. The offset voltages are not fixed values but show small variations depending on the angle. The values obtained with Equations (3) and (4) could be considered instant values. The compensation factors could be defined as the mean of the instant values obtained by applying the equations to different sensor outputs belonging to a cycle of the output signals. The advantage of using the mean values is that the same compensation factor is used afterwards for all angles, as indicated in Equations (5) and (6).

$$off1 = \frac{A*C - B*D}{2*(C*E - D*F)} \tag{3}$$

$$off2 = \frac{B*E - A*F}{2*(C*E - D*F)} \tag{4}$$



(a) without compensation (b) offset voltages compensated

(c) offset voltages and amplitude imbalance compensated

Fig. 3: Schematic diagram of the compensation process

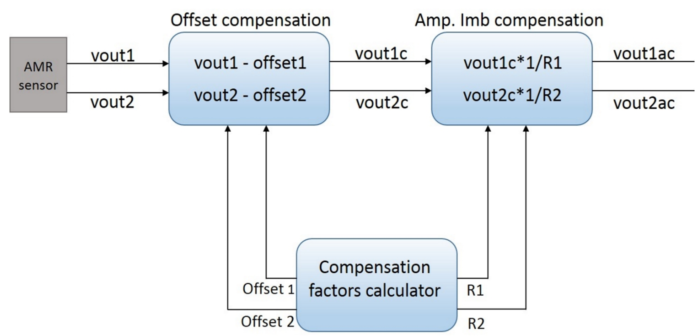


Fig. 4: Architecture of the proposed compensation method

where A till F denote:

$$A = vout1_b^2 + vout2_b^2 - vout1_a^2 - vout2_a^2$$
$$B = vout1_c^2 + vout2_c^2 - vout1_a^2 - vout2_a^2$$
$$C = vout2_c - vout2_a$$
$$D = vout2_b - vout2_a$$
$$E = vout1_b - vout1_a$$
$$F = vout1_c - vout1_a$$

where $vout1_a, vout1_b, vout1_c$ and $vout2_a, vout2_b, vout2_c$, represent the output voltages of bridge 1 and bridge 2 in three different angles.

$$vout1c = vout1 - mean(off1) \tag{5}$$

$$vout2c = vout2 - mean(off2) \quad (6)$$

The calculation of the compensation factors for the amplitude imbalance is made from Equations (7) and (8) and the voltages obtained after compensate the offset voltage. The factors are equals to the mean of the values obtained by applying several time these equations to different voltages belonging to a cycle of the signals, as indicate Equations (9) and (10). The same factors can be applied to compensate all the angles.

$$t^2 = \frac{(vout1c_b * vout2c_a)^2 - (vout1c_a * vout2c_b)^2}{mean(R) * (vout2c_a^2 - vout2c_b^2)} \quad (7)$$

$$t1^2 = \frac{(vout1c_b * vout2c_a)^2 - (vout1c_a * vout2c_b)^2}{mean(R) * (vout1c_b^2 - vout1c_a^2)} \quad (8)$$

with

$$R = (vout1c)^2 + (vout2c)^2$$

$$vout1ca = \frac{vout1c}{mean(t)} \quad (9)$$

$$vout2ca = \frac{vout2c}{mean(t1)} \quad (10)$$

where $vout1c_a, vout1c_b$ and $vout2c_a, vout2c_b$, represent two different output voltages after offset compensation in bridge 1 and 2 respectively.

IV. EXPERIMENTAL RESULTS

The proposed compensation method has been implemented in MATLAB. It was verified using voltages obtained from a mathematical model of the sensor, but also from commercial sensors. In all the cases decreases the offset voltages, the amplitude imbalance and hence the maximum angle error.

Table II presents the offset voltages before and after compensation in 5 simulated cases. The offset decreases in both bridges showing values in the order of 10^{-3} V and 10^{-6}V before and after compensation. Taking into consideration both bridges, case 2 shows the largest reduction.

Table III shows the amplitude of the bridge outputs before and after compensation. Before compensation, the amplitude differences between the bridge outputs were in the range of 0.1 mV to 2.8 mV shown in case 5. However after compensation both bridges show the same amplitude in all cases.

Table IV shows three types of maximum angle errors, without compensation (Error1), after the compensation of the offset voltage (Error2) and after the compensation of the offset voltage and the amplitiude imbalance (Error3). In all cases the maximum errors decrease after compensation, being case 2 the one that shows the largest reduction if compared Error1 and Error3.

TABLE II: OFFSET VOLTAGES BEFORE AND AFTER COMPENSATION

case	offset voltage 1 (V)		offset voltage 2 (V)	
	before	after	before	after
1	-0.8 10^{-3}	0.7 10^{-6}	2.2 10^{-3}	-1.3 10^{-6}
2	-3.4 10^{-3}	3.0 10^{-6}	3.9 10^{-3}	-0.6 10^{-6}
3	-6.4 10^{-3}	4.0 10^{-6}	-1.9 10^{-3}	2.3 10^{-6}
4	1.4 10^{-3}	3.8 10^{-6}	0.1 10^{-3}	0.2 10^{-6}
5	4.8 10^{-3}	-17 10^{-6}	-3.8 10^{-3}	-3.8 10^{-6}

TABLE III: AMPLITUDE OF THE BRIDGE SIGNALS BEFORE AND AFTER COMPENSATION

case	amplitudes before		amplitudes after	
	bridge1(V)	bridge2(V)	bridge1(V)	bridge2(V)
1	$\pm$ 68.0 10^{-3}	$\pm$ 68.1 10^{-3}	$\pm$ 68.1 10^{-3}	$\pm$ 68.1 10^{-3}
2	$\pm$ 68.7 10^{-3}	$\pm$ 67.8 10^{-3}	$\pm$ 68.2 10^{-3}	$\pm$ 68.2 10^{-3}
3	$\pm$ 68.2 10^{-3}	$\pm$ 68.1 10^{-3}	$\pm$ 68.2 10^{-3}	$\pm$ 68.2 10^{-3}
4	$\pm$ 68.4 10^{-3}	$\pm$ 67.1 10^{-3}	$\pm$ 67.8 10^{-3}	$\pm$ 67.8 10^{-3}
5	$\pm$ 68.9 10^{-3}	$\pm$ 66.1 10^{-3}	$\pm$ 67.5 10^{-3}	$\pm$ 67.5 10^{-3}

TABLE IV: VARIATION OF THE MAXIMUM ANGLE ERROR AFTER APPLY THE COMPENSATION METHOD

case	Error1 (degrees)	Error2 (degrees)	Error3 (degrees)
1	1.01	0.03	0.0017
2	2.38	0.19	0.0029
3	2.83	0.01	0.0051
4	0.81	0.28	0.0038
5	3.21	0.61	0.01

Error1: maximum angle error without compensation.
Error2: maximum angle error after offset compensation.
Error3: maximum angle error after amplitude imbalance compensation.

The proposed compensation method has been also verified by analysing the spectrum of the angle errors. As is indicated in Table I, the angle errors show sinusoidal characteristics with different frequencies. The angle error due to offset voltage shows the same frequency as the sensor output, while the error signal due to amplitude imbalance has a frequency equal to the double of sensor frequency.

Figure 5 shows the spectrum of the angle errors in case 5. At the top (A) of the figure is the spectrum of the angle error without compensation with the largest component at 2Khz, frequency of the sensor. In middle (B) is the spectrum after offset voltage compensation, which shows a smaller value at 2khz and the largest component is at 4Khz related to the error due to amplitude imbalance. At the bottom (C) is shown the angle error after the compensation of offset voltage and amplitude imbalance. The frequency components are smaller than before being these mainly because of additional harmonics included at the sensor outputs.

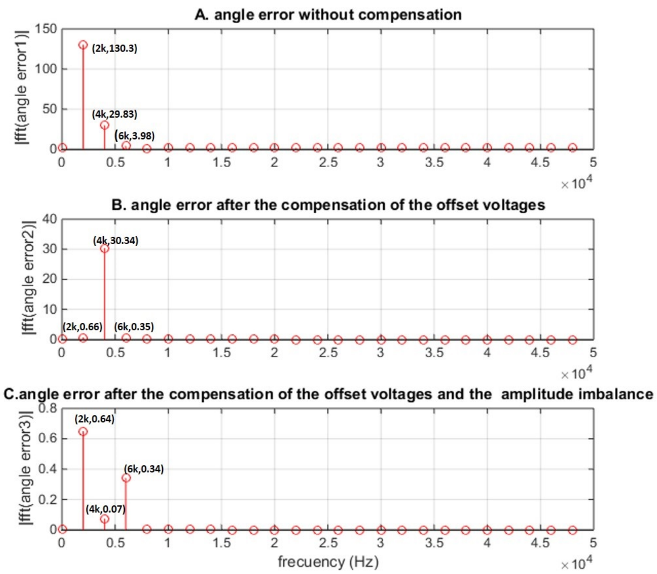


Fig. 5: Spectrum of the maximum angle error in Case 5

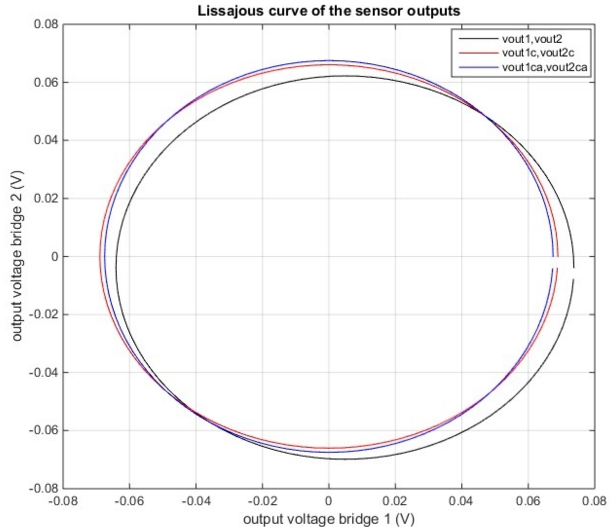


Fig. 6: Lissajous curves in case 5. *(vout1,vout2)*,without any compensation. *(vout1c,vout2c)*, after offset voltage compensation. *(vout1ca,voutca)*,after amplitude imbalance compensation

Figure 6 shows the Lissajous curves of case 5 without compensation (vout1,vout2), after the compensation of the offset voltage (vout1c,vout2c) and after the compensation of the offset voltage and the amplitude imbalance (vout1ac,vout2ac). After all compensations have been made, the final Lissajous curve is more similar to a circle centred at (0,0), which implies more accurate measurements.

The compensation method has been also applied to voltages measured in commercial sensors. Table V presents the maximum angle errors in 5 sensors. It is included the maximum angle error without compensation (Error1), after the compensation of the offset voltage (Error2) and after the compensation of the offset voltage and the amplitude imbalance (Error3). In all the sensors decrease the maximum angle errors after carry out the compensations. The sensor 4 shows the largest reduction if compared error 1 and error 3.

The method of maximum and minimum is the most commonly used nowadays to determine compensation factors at the factory. However, its main drawback is the required accuracy on the data acquisition in order to determine the correct extreme values at the sensor outputs. The efficiency of this method and the proposed compensation method have been compared. The efficiency of the compensation method is determined by the reduction of the angle error if it is compared before and after compensation. The comparison of the two compensation methods has been focused on the effect of the accuracy of data acquisition over the reduction of the angle error.

TABLE V: VARIATION OF THE MAXIMUM ANGLE ERROR AFTER APPLY THE COMPENSATION METHOD

Sensor	Error1(degrees)	Error2(degrees)	Error3(degrees)
1	0.8635	0.1138	0.1005
2	0.4332	0.1326	0.1287
3	0.4823	0.1248	0.1129
4	0.9867	0.1206	0.0998
5	0.3411	0.1353	0.1099

Error1: maximum angle error without compensation.
Error2: maximum angle error after offset compensation.
Error3: maximum angle error after amplitude imbalance compensation.

Table VI shows the maximum angle errors obtained by applying both methods in sensor 1. Two cases has been considered. In *Case 1* were detected extreme voltages very close to the real extreme values. In *Case 2* the maximum voltages detected show an offset of 4° approximately compared to the angles with the real extreme values. With the proposed method the efficiency remained almost equal in both cases. However for the method of maximum and minimum, the efficiency decreases about 3 times in *Case 2*.

V. DISCUSSION

A new compensation method aimed to update compensation factors during the sensor lifetime has been proposed. It has been verified using simulated data as well as data from commercial sensors. Results show it is able to reduce the offset voltage, the amplitude imbalance between the sensor

TABLE VI: VARIATION OF THE MAXIMUM ANGLE ERROR AFTER APPLY THE COMPENSATION METHODS

Cases	E1	E2	E3	E4	E5
1	0.8635	0.1138	0.1005	0.0800	0.0816
2	0.8635	0.1161	0.1141	0.2492	0.2144

Case 1: detected real extreme values at the sensor outputs.
Case 2: undetected real extreme values at the sensor outputs.
The maximum angle errors (E) are represented in degrees.
E1:without compensation.
E2:offset compensated with proposed method.
E3:offset and amplitude compensated (proposed method).
E4:offset compensated (maximum and minimum method).
E5:offset and amplitude compensated (max and min method)

outputs and the error in the angle calculation.

The method is based on the fact that a Lissajous curve constructed from the two sinusoidal signals at the sensor outputs, should be equal to a circle centred at (0,0). Although it is not true with the actual sensor outputs, this Lissajous curve could be improved by compensating the offset voltage and the amplitude imbalance present at the sensor outputs. This would imply less error in the angle calculation. With the uses of compensation factors is compensated first the offset voltage and then the amplitude imbalance. The compensation factors are calculated with equations based on the geometrical characteristics of the Lissajous curve.

The objective is to propose a compensation method able to update the compensation factor during the sensor lifetime. Compared to other methods already proposed, our method does not require any special setup, so it can be used on-site. With regards to data processing, our method could require more mathematical operations than others, but it does not need a high accuracy on data acquisition as instance the method of maximum and minimum. Its efficiency depend on the detection of the real extreme values at the sensor output, as is shown in Table VI. The accuracy of the data acquisition does not represent a problem at the factory but it is not the same during the sensor lifetime when there is no other option to estimate the angle and the signal processing resources are limited.

Until now, the compensation factors for AMR sensors are usually calculated in a calibration process at the factory. The accuracy demanded from the sensor allow having an extra error during the sensor lifetime due to wearing and aging effects. However, the future trend indicates it will be necessary to carry out more accurate angle measurements, especially in safety-critical applications. This implies it will be necessary to estimate the compensation factors in the factory but also update their values during the sensor lifetime.

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