A Dependable AMR Sensor System for Automotive Applications

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***Abstract*—The increasing replacement of mechanical parts by x-by-wire systems in automotive applications allows improving driver safety. These systems demand highly dependable sensors that ensure their functionality despite the harsh operating conditions. This means that the sensors should be capable of working continuously despite catastrophic faults and keeping the performance over time. An anisotropic magnetoresistance (AMR) sensor is a magnetic sensor commonly used for angle measurements in cars. It is affected by catastrophic faults and performance degradation due to undesired parameters included at the sensor outputs. Until now, physical redundancy is often used to handle catastrophic faults. For the performance, compensation factors for the undesired parameter, such as offset voltage, are estimated at the start of the sensor life. Although the undesired parameters drift due to aging effects, the sensor performance remains within the allowed tolerant band. However, this tolerant band will decrease in the future because the dependability requirements are continuously increasing. Therefore, it is necessary to consider strategies to guarantee the sensor performance over time. This paper proposes a system to improve the sensor dependability using analytical redundancy for catastrophic faults but also with self-x properties to maintain the sensor performance over time. Results indicate a dependability improvement in terms of reliability, with a reduction of 50% in the rate of uncovered failures. The safety requirement ASIL level D is satisfied, and with regard to maintainability, the sensor performance is maintained over time.**

***Index Terms*—Dependability; self-x capabilities; fault-tolerant; angle error; AMR sensors**

I. INTRODUCTION

The increasing usage of electronic systems in automotive applications aims to enhance the vehicle driving performance as well as its safety. Mechanical or hydraulic systems, such as braking or steering, have been replaced by x-by-wire systems, which are electronic systems that consist of sensors, microprocessors, and front-end electronics. Because automotive applications are considered safety critical, they demand reliable, high-performance, and low-cost electronic components that are capable of operating for a long time in a highly dependable manner. Therefore, the sensors required should be reliable to provide the correct service despite the harsh operating conditions [1].

Magnetic sensors represent an excellent option to be applied in almost all cases where wear-affected potentiometric techniques are traditionally used; examples are pedal position, engine control, and transmission control [2]. They offer several key advantages including mechanical robustness due to its non-contact measurement principle, very wide operating temperature range, and low manufacturing costs [3]. Magnetic sensors based on Magnetoresistance effect (AMR sensors) are often used for angle measurements. The angle is estimated from the two sinusoidal signals at the sensor outputs. However, these signals include undesired characteristics such as offset voltage, amplitude imbalance and additional harmonics that affect the accuracy of the calculated angle and hence the performance of the sensor.

Until now, the offset voltage is the parameter mainly compensated because it is the largest source of angle error. Most of the proposed compensation methods, such as in [4] and [5] are aimed to calculate the compensation factors in factory conditions. The compensation factors are estimated at the start of the sensor life but are not updated during its lifetime. Although the undesired parameters drift due to wearing and aging effects, they remain within the allowed tolerance band nowadays, as detailed in the next section. However, it is expected that the tolerant band will get smaller in the future. Besides performance degradation, the sensor can be also affected by catastrophic faults resulting from short or broken condition at any of the magnetoresistance. So far, most of the published research such as [5] [6] focus on physical redundancy to guarantee the sensor operation in case of a catastrophic fault.

Dependability, as well as, the accuracy requirements demanded by x-by-wire systems are constantly increasing, especially with the future trend of autonomous cars. Therefore, to guarantee that AMR sensors will satisfy these requirements, it is necessary to embrace strategies that allow the sensor to handle performance degradation as well as catastrophic faults. This can be accomplished by combining methods such as fault-tolerant and self-x properties. In [7] it is proposed

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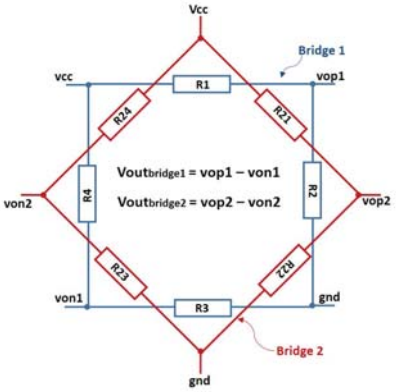

Fig. 1: Schematic of the Wheatstone bridges in an AMR sensor. Each **R** represents a magnetoresistance.

to include self-x properties to improve the dependability of AMR sensors used to measure the strength of a magnetic field.

This paper proposes a dependable AMR sensor system for angle measurements in automotive applications. The system includes fault-tolerant strategies to handle catastrophic faults and self-x characteristics such as self-monitoring and self-calibration to maintain the sensor performance during its lifetime. Besides is considered an interface IEEE 1687, so the sensor is able to communicate with other components of the x-by-wire systems where it is integrated.

The outline of the paper is as follows. Section II is an introduction to AMR sensors. Section III explains dependability in automotive applications. Section IV discusses our proposed system. Section V presents the results and Section VI presents the discussion.

II. AMR SENSORS

An anisotropic magnetoresistance (AMR) sensor is a magnetic sensor often used for angle measurements. In this case, it is configured with two Wheatstone bridges rotated 45° with respect to each other, as shown in Fig. 1. When the sensor is in saturation state, its outputs should be two perfect sinusoidal signals that can be used to estimate the magnetic angle, as shown in equation (1) [8].

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

However, the actual sensor outputs show undesired characteristics. These include extra voltages defined as offset voltages. The two output signals do not show the same amplitude, defined as amplitude imbalance, and additional harmonics are also included. Therefore, equation (1) should be rewritten as indicated in equation (2):

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

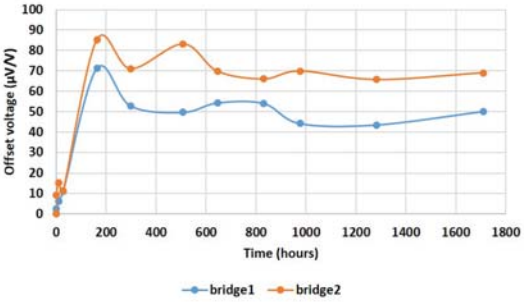

Fig. 2: Drift of the offset voltage of bridge 1 in a set of commercial sensors during an aging test of 1800 hours

where A1 and A2 denote the sine and cosine amplitudes, offset1 and offset2 are offset voltages and N1 and N2 represent additional harmonics. The extra components affect the accuracy of the calculated angle, with the offset voltage and the amplitude imbalance as the first and second largest sources of error in the angle calculation.

Until now, the offset voltage is the parameter mainly compensated. The compensation factors are usually estimated at the start of the sensor life but are not updated during its lifetime. In [9] it is indicated that the drift of the offset voltage over 1000 hours at high temperature should be in the range of some μV/V to guarantee an accuracy smaller than 1° during the sensor lifetime. Figure 2 shows the drift of the offset voltages in a commercial sensor during an aging test. The drift starts at 0 V because it is assumed that the offset voltages are compensated at the start of the test. The drift is below 100 μV/V; hence, the current requirement is satisfied. However, it is likely that this tolerant band for drifting will get smaller in the future, especially for autonomous cars(few μV/V).

Besides performance degradation, AMR sensors can also be affected by catastrophic faults that make them stop working. These faults can occur mainly because of two reasons. An invalid input signal (1) due to loss of the magnet that generates the magnetic field and (2) due to open or short conditions in the bridge resistances of the sensor [5]. Any of these conditions result in a loss of the trigonometric signals at the sensor outputs, and consequently, the magnetic angle can no longer be calculated.

III. DEPENDABILITY IN AUTOMOTIVE APPLICATIONS

The dependability of a system indicates its reliance to perform the intended functions under certain conditions during a period of time. Dependability cannot be measured by one quantity but rather by several attributes like reliability, availability, maintainability and safety [10] [11].

Due to automotive applications are considered safety-critical, they demand highly dependable systems, especially concerning to reliability and safety attributes. The reliability goal is to match the failure rate of 1.10^{-9} of a simple mechanical component [11]. About safety, it is considered the system should satisfy the ASIL level D, which indicates a failure rate smaller than 1.10^{-8} per hour [12].

A highly dependable system could be obtained using fault-tolerant strategies, so the system can continue working despite of faults. In automotive applications, a fault-tolerant sensor should be at least fail-operational (FO), meaning one failure is tolerated. This can be accomplished by physical redundancy with the same type of sensors or by analytical redundancy with different sensors or process models. Mainly because of cost, space and weight, a suitable compromise between the degree of fault tolerance and the number of redundant components has to be found for automotive drive-by-wire systems [13].

A fault-tolerant system can be implemented with a dual system that continues working even if one of the components fails. In these systems two type of failures should be considered. The two components fail (failure rate) or a component fails but is undetected (uncovered failure) [11]. Therefore,a system that for instance has components with a failure rate of 10^{-4} failures per hour, the system failure rate becomes 10^{-8}. If the coverage of the failure of a component is 90%, then the probability of failure due to an uncovered failure is 10^{-5} (10%x10^{-4}). The failure uncovered is a greater cause of a system failure than the system failure rate. Therefore, for dependable systems, the failure detection coverage must be excellent, using for instance self-test.

In order to maintain the system performance over time despite aging effects, self-x properties can be applied. Therefore, the system can perform certain functions on its own to detect whether it is working in optimal conditions and return to them if degradation occurs. [7].

IV. PROPOSED SYSTEM

The proposed system is aimed to develop a dependable AMR sensor system for angle measurements. Based on digital processing, the sensor system keeps its performance over time and handle catastrophic faults. Figure 3 shows the system architecture, which includes a real-time compensation module, a fault-tolerant module and a performance-monitoring module. Due to the sensor is usually part of a larger system, such as, steer-by-wire systems, or brake-by-wire system, an interface IEEE 1687 is included, so the sensor can communicate with other system components.

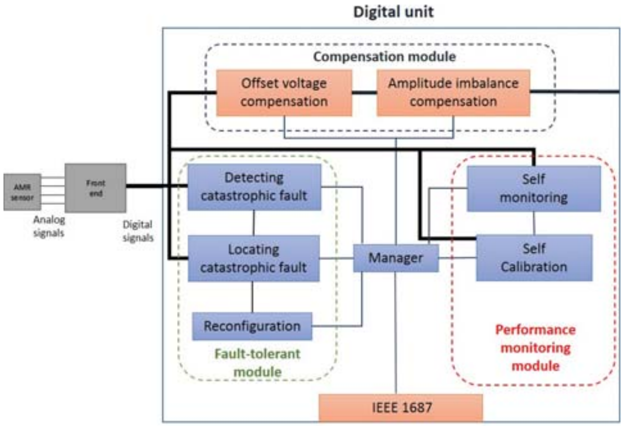

Fig. 3: Architecture of the proposed system.

Next, each module shown in Fig. 3 is explained in detail. In general, the system functionality can be described as follow: Once the sensor outputs are measured, first it is verified whether there is a catastrophic fault in the fault-tolerant module. In case there is a fault, the diagnostic module determines its location. The reconfiguration module indicates the output voltages should be used, so the sensor can continue working.

In the absence of a catastrophic fault, the sensor outputs are compensated and then sent to the module that estimates the magnetic angle. The sensor performance is monitored by the self-monitoring module, which verifies the maximum angle error due to the offset voltage to determine if new compensation factors are required. If necessary, new factors are estimated by the self-calibration module and then sent to the online compensation module. A system manager controls all the operations. The interface IEEE 1687 handles the connection with external components.

A. *Online-compensation module:*

This module compensates in real time the sensor outputs for offset voltage and amplitude imbalance. It is connected to the manager who receives information concerning what output voltages and compensation factors should be used.

B. *Fault-tolerant module:*

This is based on a fault-tolerance system we proposed in [14]. It consists of three sub-modules to detect, locate and recover in case of a catastrophic fault. Table I shows the fault conditions, the voltages used to determine its location and the analytical reconfiguration required so the sensor continues working.

The sub-module for detection verifies the output voltage at each half-bridge to detect a fault condition. Once a fault is detected, the locating sub-module determines its location based on what the half-bridge is showing an abnormal voltage. This means a value close to zero or close to the voltage of the power supply. The reconfiguration sub-module indicates that the new voltages should be used to calculate the angles. This information together with the new compensation factors is transferred to the online compensation module. As the offset voltage per each half-bridge is known, it is possible to use updated factors to compensate the offset voltages. Via the IEEE 1687 interface, it is possible to indicate that a fault occurred and if the fault was corrected or not.

C. Performance monitoring module:

This module includes two sub-modules: one for self-monitoring and another for self-calibration. The self-monitoring verifies the maximum angle error due to the offset voltage with the use of Equation (3) we proposed in [15]. This is the monitored parameter because it is the largest source of angle error with also the largest drift due to aging effects, as indicated in [16]. The equation provides an accurate estimation of the angle error, but it cannot be applied in real time, as it requires as input the sensor outputs at different angles during a period of the sinusoidal signals. Therefore, an additional method is included to indicate online that the angle error should be verified. This detects variations in the components of the offset voltage. The offset voltage has a component per each half bridge, such as the bridge outputs indicated in Fig. 1. The addition of the two offset components is easily obtained by subtracting the voltages of two resistances placed in the same direction in the Wheatstone bridge. If this addition changes, it is because the offset components change and consequently the offset voltage also changes.

$$angle_{error} = \frac{RMS(R1_{AC})}{R1_{DC}} * 20 \qquad (3)$$

where:
$R1 = vout1^2 + vout2^2$. *vout1* and *vout2* represent the sensor outputs without any compensation; RMS($R1_AC$) the Root Mean Square of the AC component of R1 and ($R1_{DC}$) the DC value of R1

The self-calibration sub-module estimates online the compensation factors for offset voltage and amplitude imbalance. Table II shows a set of equations we have proposed in [17], based on the geometric relationship of the sensor outputs. To estimate the compensation factors for offset voltage, *off1*,*off2* (see Table II) are calculated several times using voltages belonging to a cycle of the sinusoidal signals at the bridge outputs. The obtained values are considered instant values and the compensation factors are equal to the mean of the instant values. The equations to calculate the compensation factors for amplitude imbalance required as input the sensor outputs after offset voltage compensation. The equations shown in Table II are also execute several times with different inputs to calculate what are considered instant values. Then, the compensation factors are equal to the mean of the instant values.

D. IEEE 1687 module

The IEEE 1687 is a standard created to access embedded instruments in integrated systems. The proposed system can be considered as an instrument in the sense that it takes measurements to verify the functionality of the AMR sensor. This module is aimed to provide an interface, so the sensor can communicate with other components of the system, such as brake-by-wire system, in which it is integrated. Thus, it is possible to indicate whether a fault occurred, its type, and if it was corrected or not. In case the vehicle is equipped with fault management, it is possible to provide information related to the location of a catastrophic fault and to the performance of the sensor.

V. RESULTS

The different modules of the proposed system have been verified using data obtained from an analytical model of the sensor, but also with data measured from commercial sensors. With regard to the fault-tolerant module, the results indicate the sensor system can continue working despite a catastrophic fault. Figure 4 compares the angles calculated with normal configuration to the proposed reconfigurations. The difference between the set magnetic angles 100-120 degrees is due to the 45° phase of the output voltages used under faulty conditions. However, because the phase is known in advance it can be compensated.

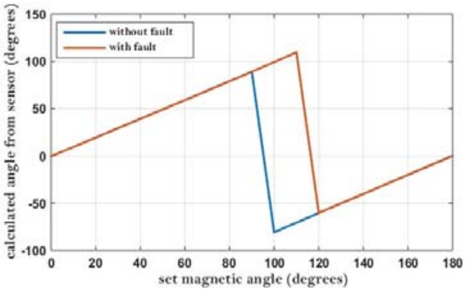

Fig. 4: Angles calculated with and without faulty conditions in any of the bridge resistances of an AMR sensor.

With regards to the self-x properties to maintain the sensor performance, Fig. 5 compares the exact values of the maximum angle errors to the obtained results with the formula applied by self-monitoring. The mean value of the difference between them is 0.04°, which means that the formula provides a good estimation of the maximum angle error due to the offset voltage.

In terms of maintainability, the sensor system can keep the performance over time. The results show that the proposed

TABLE I: Fault-tolerant system for catastrophic faults in AMR sensors

Fault Condition	**Fault Detection**				**Fault Recovery**	
	vop1	von1	von2	vop2	Voutbrigde1	Voutbrigde2
Fault Free	VDD/2 ± AMR	VDD/2 ± AMR	VDD/2 ± AMR	VDD/2 ± AMR	vop1-von1	vop2-von2
R2(short) or R1(open)	≈0	VDD/2 ± AMR	VDD/2 ± AMR	VDD/2 ± AMR	vop2-von1	von2-von1
R2(open) or R1(short)	≈VDD	VDD/2 ± AMR	VDD/2 ± AMR	VDD/2 ± AMR	vop2-von1	von2-von1
R3(short) or R4(open)	VDD/2 ± AMR	≈0	VDD/2 ± AMR	VDD/2 ± AMR	vop1-von2	vop1-vop2
R3(open) or R4(short)	VDD/2 ± AMR	≈VDD	VDD/2 ± AMR	VDD/2 ± AMR	vop1-von2	vop1-vop2
R23(short) or R24(open)	VDD/2 ± AMR	VDD/2 ± AMR	≈0	VDD/2 ± AMR	vop2-von1	vop1-vop2
R23(open) or R24(short)	VDD/2 ± AMR	VDD/2 ± AMR	≈VDD	VDD/2 ± AMR	vop2-von1	vop1-vop2
R22(short) or R21(open)	VDD/2 ± AMR	VDD/2 ± AMR	VDD/2 ± AMR	≈0	vop1-von2	von2-von1
R22(open) or R21(short)	VDD/2 ± AMR	VDD/2 ± AMR	VDD/2 ± AMR	≈VDD	vop1-von2	von2-von1

The information is linked with Fig 1. AMR represents the voltage due to magnetoresistance.

TABLE II: equations used to estimate compensation factors for offset voltage and amplitude imbalance

Compensation factors	**Bridge 1**	**Bridge 2**	**component details**
Offset voltage	off1 = $\frac{A*C-B*D}{2*(C*E-D*F)}$	off2 = $\frac{B*E-A*F}{2*(C*E-D*F)}$	$A = vout1_b^2 + vout2_b^2 - vout1_a^2 - vout2_a^2$ $B = vout1_c^2 + vout2_c^2 - vout1_a^2 - vout2_a^2$ $C = vout2_c - vout2_a$ $D = vout2_b - vout2_a$ $E = vout1_b - vout1_a$ $F = vout1_c - vout1_a$
Amplitude imbalance	$t^2 = \frac{(I*H)^2-(G*J)^2}{mean(R)*(H^2-J^2)}$	$t1^2 = \frac{(I*H)^2-(G*J)^2}{mean(R)*(I^2-G^2)}$	$G = vout1c_a$; H = $vout2c_a$ $I = vout1c_b$; $J = vout2c_b$ $R = vout1c^2 + vout1c^2$

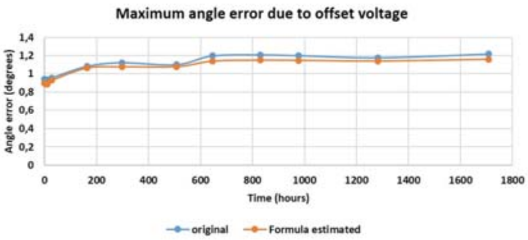

Fig. 5: Maximum angle error due to offset voltage.

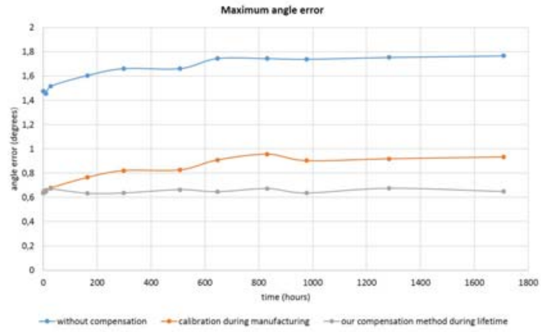

Fig. 6: Remaining angle error in a commercial sensor.

system is able to compensate the drift due to aging effects. Figure 6 shows the drift of the maximum angle error of a commercial sensor considering three different conditions: (1) the maximum angle error without compensation, (2) the remaining angle error after compensating the offset voltage and the amplitude imbalance using compensation factors calculated during manufacturing, and (3) the remaining angle error after compensating the offset voltage and the amplitude imbalance using the proposed self-calibration module to update the compensation factors over time. The first two cases show a drift due to aging effects of approximately 30% of the initial angle error without compensation. However, the third case is fairly constant over time showing a drift of 1% approximately. The remaining angle error after compensation is mainly because of the setup used to measure the voltages at the sensor outputs.

With respect to the improvement of the sensor dependability in terms of reliability and safety, it has been considered that the failure rate of an AMR sensor is 10^{-7} per hour, a value often used for sensors [11]. As an AMR sensor is made up of magnetoresistance basically, then it can be assumed this is the failure rate of the magnetoresistance component as well. As the proposed system can be seen as a dual system, it has been verified the rate of failure and uncovered failure.

In a traditional dual system with two AMR sensors for redundancy, the failure rate is 10^{-14}. The failure rate of uncovered failure could be 10^{-8} or 2.10^{-10}, depending on whether the coverage for failure is 90% or 99.9% (self-test included). With the proposed system can be obtained a rate of failure of 10^{-14} and a rate of uncovered failure equal to 10^{-10} (0.1%x10^{-7}), which means a better rate of uncovered failure. In terms of safety is satisfied the ASIL D requirement of a failure rate smaller than 1.10^{-8}.

VI. DISCUSSION

A system has been proposed to improve the dependability of AMR sensors used for angle measurements. It can handle catastrophic faults and keep the sensor performance over time. The interface IEEE 1687 allows the sensor system to connect with other components where it is integrated, for instance, a brake-by-wire system.

In terms of reliability, the uncovered failure rate is reduces by 50% compared to the traditional dual system based on physical redundancy. As the proposed fault-tolerant method is based on analytical redundancy, it does not require hardware duplication. This is an advantage in terms of space and production costs of the sensor, both sensitive aspects in automotive applications. With respect to safety requirements, the rate of failure (10^{-14}) and unconvered failure (10^{-10}) satisfy the ASIL D requirement.

The addition of self-x properties allow to improve the maintainability. Due to is possible to compensate the aging and wearing effects, the sensor maintains its performance over time. In the results shown previously, the percentage of drift of the initial angle error decreases from 30% to 1% using the proposed system. The self-monitoring module provides an accurate estimation of the maximum angle error due to offset voltage. This is used to determine weather an updated of the compensation factors is needed. The self-calibration module estimates online compensation factors for offset voltage and amplitude imbalance. It has been verified by simulation but also with an FPGA implementation. The accuracy of the calculation can be affected by the number of samples in a cycle of the signals used during the calculation and by the number of bits used by the digital system. Although the compensation factors cannot be calculated in real time, this is not necessary because the undesired parameters such as the offset voltage drift slowly over time. As processing resources are limited during the sensor lifetime, it is better to compensate in real time the sensor outputs but calculate the compensation factors only when it is actually required.

With a traditional redundant system, it is possible to satisfy the dependability requirements of reliability and safety in automotive applications. However, in terms of maintainability, this system will demand more resources to keep the sensor performance over time. The proposed system can provide the same failure rate, improve the uncovered failure, and demand fewer resources to maintain the sensor performance. This is especially important with the current trend to include more and more x-by-wire systems, which demand dependable sensors capable of keeping their performance despite undesired wearing and aging effects.

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