

Development of a Magneto-Resistive Angular Position Sensor for Space Mechanisms

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Abstract

Magnetic microsystems in the form of magneto-resistive (MR) sensors are firmly established in automobiles and industrial applications. They are used to measure travel, angle, electrical current, or magnetic fields. MR technology opens up new sensor possibilities in space applications and can be an enabling technology for optimal performance, high robustness and long lifetime at reasonable costs. In some science missions, the technology is already applied, however, the designs are proprietary and case specific, for instance in case of the angular sensors used for JPL/NASA's Mars rover Curiosity [1].

Since 2013 HTS GmbH and Sensitec GmbH have teamed up to develop and qualify a standardized yet flexible to use MR angular sensor for space mechanisms. Starting with a first assessment study and market survey performed under ESA contract, a very strong industry interest in novel, contactless position measurement means was found. Currently a detailed and comprehensive development program is being performed by HTS and Sensitec. The objective of this program is to advance the sensor design up to Engineering Qualification Model level and to perform qualification testing for a representative space application.

The paper briefly reviews the basics of magneto-resistive effects and possible sensor applications and describes the key benefits of MR angular sensors with reference to currently operational industrial and space applications. The key applications and specification are presented and the preliminary baseline mechanical and electrical design will be discussed. An outlook on the upcoming development and test stages as well as the qualification program will be provided.

Introduction

Magnetic microsystems in the form of magneto-resistive (MR) sensors are firmly established in automobiles, mobile telephones, medical devices, wind turbines, machine tools or industrial robots: be it for the measurement of travel, angle or electrical current, or as an electronic compass. Originally developed for data storage applications, the various MR effects open up new measurement possibilities for sensors, not only in terrestrial applications, but also in space applications.

MR sensors are robust, reliable, precise and miniaturized. This combination of features is leading to continuous growth in the application field of MR sensors. The extremely low power consumption of MR sensors make them ideal for wireless, autonomous sensor applications. They present completely new possibilities to the developers of many different types of mechanisms or instruments to measure angle, path, electrical currents, or magnetic fields.

The interest in MR technology from the space community is growing, in particular since the successful application of 40 MR angle sensors to control the motion of electric motors on the Mars Rover "Curiosity" as part of the Mars Science Laboratory Mission [1]. This was not the first application on Mars – MR

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sensors were already used on the Mars Exploration Rovers Mission to control numerous motors on “Spirit” and “Opportunity”.

All these sensors were designed and manufactured by Sensitec GmbH, located in Lahnu, near Wetzlar, Germany. MR sensors from Sensitec will also be used for the precise positioning of a miniaturized low-mass optical shutter for the MERTIS thermal infra-red imaging spectrometer within the BepiColombo mission to Mercury. Furthermore, MR-based current sensors are likely to be part of the power electronics driving the Thrust Vector Actuators of the Ariane 6 launcher.

Until now the growth in MR applications in space has been opportunistic, with the result that there has been considerable duplication of effort when developing sensor solutions specifically for use in space. In order to focus the effort and to fully exploit the benefits of MR technology for European space mechanisms and applications, HTS GmbH and Sensitec GmbH initiated a close collaboration, leading to dedicated activities for the design and qualification of MR-based angular sensors for space applications. HTS GmbH is located in Coswig, Germany specializing in the development and manufacturing of mechanisms for spacecrafts.

Magneto-Resistive Effects and Sensor Application

The magneto-resistive effect has been known for more than 150 years. The British physicist William Thomson, later known as Lord Kelvin, discovered that the electrical resistance of a conductor changes under the influence of a magnetic field. This effect would first be used industrially more than 120 years later during the late 1970s in combination with thin-film technologies derived from the semiconductor industry. The intelligent arrangement of thin-film structures within a sensor enabled the development of many sensor types for measuring the angle, strength or gradient of a magnetic field. The effect discovered by Thomson was named the “anisotropic magneto-resistive effect” (AMR) and resulted in a resistance change of just a few percent. Nevertheless, this effect was used million-fold in the production of read-heads for hard discs. At the end of the 1980s, the “giant magneto-resistive effect” (GMR) was discovered independently by Prof. Grünberg at the Forschungszentrum Jülich in Germany and by Prof. Fert at the University of Paris in France. Here the resistance change was more than 50%, which opened up even more applications for MR sensors. This discovery was awarded the Nobel Prize for Physics in 2007.

Sensitec manufactures AMR- and GMR-based sensors for industrial and automotive applications and specific terrestrial applications in very harsh environments. The anisotropic magneto-resistive effect may be considered the most obvious and simple effect. It can be observed in ferromagnetic materials such as iron, nickel and cobalt. The specific resistivity R of these materials is dependent on the angle α between the current I and the magnetization vector M . If the directions of the current and magnetization are in parallel, the resistivity is at its maximum, whereas if the directions are perpendicular, then the resistivity is at its minimum. Based on this relation, illustrated in Figure 1, the resistances R considering the AMR-effect can be described by the following equation:

$$R(\alpha) = R_m + \frac{\Delta R}{2} \cos(2\alpha)$$

The function $R(\alpha)$ for $0^\circ \leq \alpha \leq 360^\circ$ is shown in Figure 1(b). It can be seen from Figure 1 that the resistance R varies around the mean resistance R_m as a function of the double angle 2α .

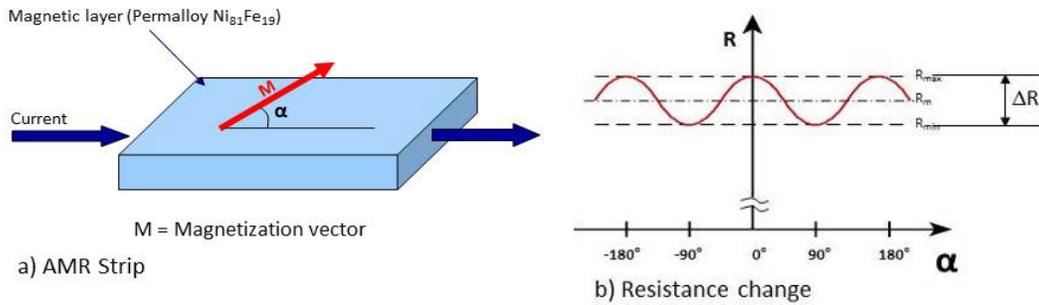


Figure 1. Anisotropic Magneto-resistive Effect [2]

The structure of an AMR angle sensor is comparatively simple (see Figure 2). This is one of the reasons that the passive resistive elements are fundamentally reliable. A silicon oxide layer provides the isolation between a silicon wafer (which only acts as a substrate for the thin-film metallic sensor – it has no semiconducting function) and the MR layer. The MR layer consists of a nickel-iron alloy (e.g., Permalloy). This alloy has a high resistivity and demonstrates very low magneto-striction. The next layer comprises an aluminium or gold layer providing the conductors within the sensor as well as the bond contacts. A passivation layer provides protection against the environment in which the sensor chip is applied. Modern production processes in the wafer production, as well as well-matched material pairings allow the temperature coefficients for the output signal amplitude, the offset voltage, and the resistance to be reduced to a minimum. This allows the MR sensor chips to be used in applications at both low and high temperature without significant changes in performance.

To reduce the influences of temperature on the sensor chip even further the sensor structure typically features four resistances connected in a Wheatstone bridge arrangement.

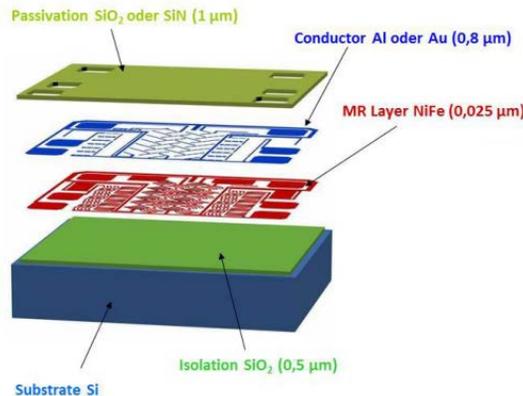


Figure 2. Structure of Sensitec's AMR Angle Sensor [2]

In AMR angle sensors, two bridges at an angle of 45° to one another are interlaced in order to generate a sine and cosine output signal as a function of angle. This signal type is generally also known from other angular sensor concepts, e.g., resolvers or optical encoders.

The advantage of the MR sensors is that an unambiguous angular output can be provided even without any signal conditioning. A pre-amplified analog output signal possesses theoretically infinite resolution and could be directly fed into the controller of the application.

However, for the sake of simplicity the sine-cosine output voltage signals are typically pre-processed by means of front end electronics to deliver digital output signals according to the typical interfaces used in industry. For industrial and terrestrial purposes, commercial amplifiers and interpolation ICs are used. For

high performance demands microcontrollers are implemented. However, it is also possible to use passive discrete devices only to provide a digital output, yet knowing that the resolution will be limited. Still this makes the MR sensors ideal candidates for cost efficient position sensors in many space applications where moderate performance is required.

Sensor Specification

In general, MR-based sensors possess the unique advantage that in order to comply with low or medium performance demands (i.e., up to 11 bit resolution), basically no front end signal conditioning is required to provide the user with a reasonable angular signal due to the intrinsic sine-cosine output signal. In order to achieve discrete (hence TTL compatible) sensor output signal, only a reduced signal processing is required. This is desired by most potential users and makes this concept an ideal candidate for low to medium performance 360° incremental encoders with a reference pulse. Such sensor can be used to replace potentiometers in mechanisms in order to improve reliability, performance and to keep the costs at low level, or to enable closed-loop motor control for improved mechanism performance and reduced microvibrations. Such medium performance encoder could be used for instance for:

- Antenna pointing mechanisms
- Shutter mechanisms
- Calibration mechanisms
- Reaction wheels (e.g., as wheel speed sensors)
- Robotic exploration (e.g., wheel position sensors, as already used in case of the Curiosity Rover [1])

As a baseline for the design of the Magneto-Resistive Angular Sensor for Space Applications (MRS), a dedicated pilot application was selected, and the technical requirements were derived. The baseline specification is given in Table 1.

It is worthwhile to highlight that the AMR and GMR sensors developed and produced by Sensitec allow for various sensor concepts; hence it is also possible to design and qualify mission-specific or user-specific encoders, allowing for true power on absolute angular measurements, or high resolution and high accuracy angular measurement.

Table 1. MRS Key Requirements Specification

Requirement	Value
Angular Range	360° (no deadband)
Rotational speed	> 100 RPM
Resolution	> 10 bit (~0.3°)
Repeatability	< 0.5° (goal: 0.1°, TBC)
Measurement type	Incremental with reference pulse
Output signal	Digital ABZ (TTL)
Power consumption	< 150 mW (TBC)
Lifetime	on ground: > 15 years, in orbit operation: > 15 years
Temperature, operational	-50°C ... +100°C
Temperature, non-operational	-60°C ... +110°C
Radiation hardness	> 250 krad
Mass	< 150 g
Mechanical I/F	End of shaft configuration: -shaft diameter:5 mm -outer diameter: 50 mm -height: 40 mm Alternative hollow shaft configuration: - shaft diameter:30 mm -outer diameter: 75 mm -height: 25 mm

Preliminary Sensor Design

Based on the baseline specification, a preliminary MRS design has been developed. In its baseline configuration, the encoder will be attached at one end of the shaft, e.g., at the secondary shaft of an actuator, to allow for closed-loop control. In this configuration, the MRS is most compact and small, yet provided sufficient performance (> 10 bit resolution). This concept is illustrated in Figure 3.

The MRS consists of a magnetic measurement scale (also referred to as pole ring) with a diameter of 45 mm and two parallel magnetic tracks. One magnetic track has 282 magnetic poles that are used for the incremental position measurement. The second magnetic track has one pole pair that is used as a reference pulse, giving precisely the 0° position. The position is measured by an AMR sensor and a GMR sensor for the reference pulse. The MRS is designed to be fully redundant. The MR sensors provide an analog sine-cosine signal. In fact, for each pole pair two full sine-cosine periods are provided.

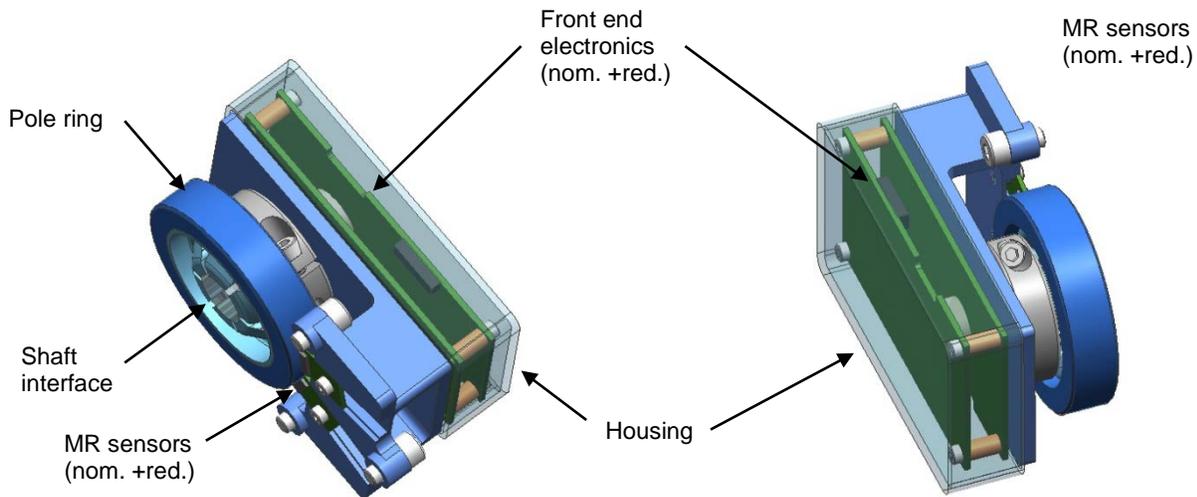


Figure 3. Preliminary baseline MRS design

The sensors will be housed in a dedicated LTCC package, conforming to ECSS outgassing and quality standards. The sine cosine signals can directly be delivered to the motor controller. However, often a discrete signal (e.g., TTL signal) is required by the controller. In order to provide this interface, a dedicated front end electronic board is included in the sensor (nominal and redundant), which transforms the sine-cosine signals into a TTL-compatible pulse signal (ABZ, 0 - 5V). This is achieved by a set of comparators and operation amplifiers, which allow to deduce from the pre-amplified sine-cosine signals, a pulsed signal (AB, view Figure 4) with four pulses per pole, resulting in a resolution of about 0.3° . The A and B pulses are phase shifted, allowing determination of the rotation direction.

In the baseline configuration the PCB boards are located in parallel to the pole ring, behind the end of the shaft to minimize the envelope.

A higher resolution can be achieved if a larger measurement scale (i.e., pole ring) is used with the same sensors and front end electronics. In order to reduce the costs of the final product, off-the-shelf ferrite pole rings will be used. The largest off-the-shelf pole rings currently available have an outer diameter of 72 mm (inner diameter 54 mm), giving roughly 0.2° resolution. This enables a hollow shaft configuration, where the electronic boards are attached radially (view preliminary design in Figure 5).

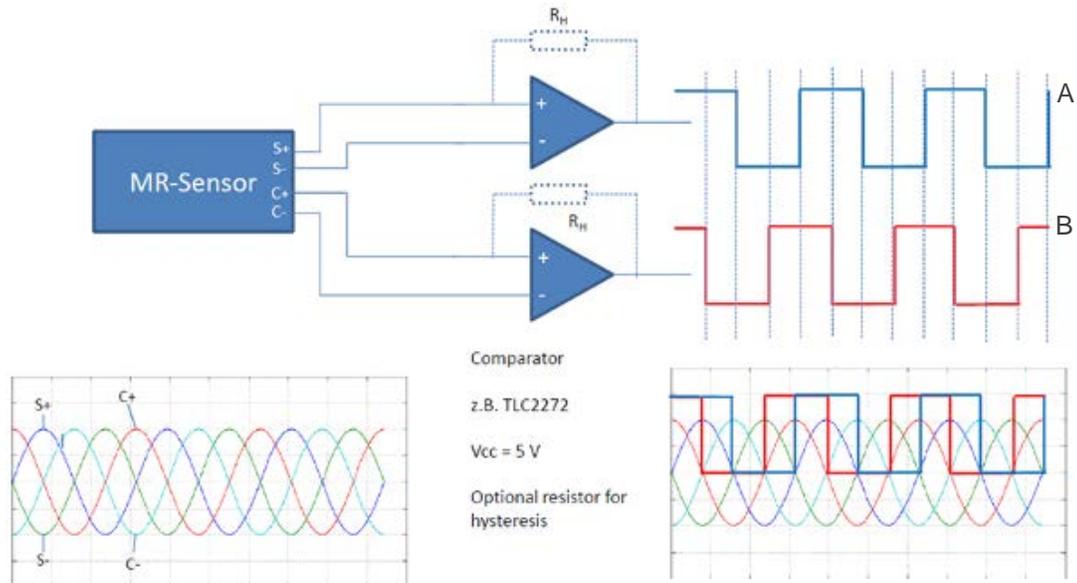


Figure 4. Signal conditioning approach

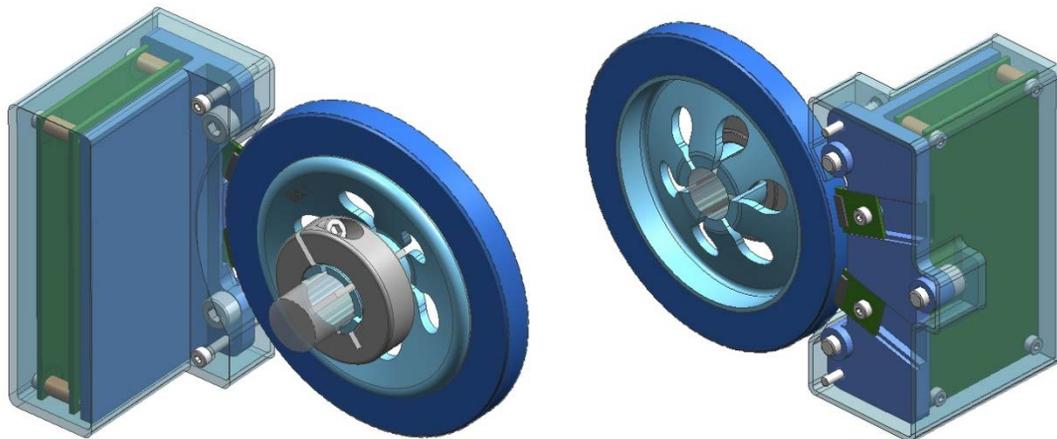


Figure 5. Alternative hollow shaft configuration of MRS with 72-mm pole ring

Development and Qualification Approach

The ultimate objective of this development is to develop and qualify an MR-based contactless angular position sensor in order to achieve swift and efficient entry into the market.

The technical requirement specification has already been consolidated and finalized based on a relevant reference application. Currently, the MRS design is further elaborated, and it is planned to build and to test the MRS at breadboard level soon. Breadboard models and several tests are foreseen to validate the measurement and signal conditioning concept. These tests include functional and performance tests of the electronics, as well as full-scale functional and performance tests in reduced and elevated temperature.

Ultimately, Engineering Qualification Models of the MRS will be built and qualification tests shall be performed in order to achieve TRL 6. The qualification tests to be performed include functional performance tests at ambient and thermal vacuum, vibration and shock tests, electro-magnetic compatibility and electro-static discharge tests (EMC, ESD) as well as outgassing tests and radiation tests.

Conclusion

The baseline requirements, pilot applications, and a preliminary flight design of an MR-based contactless angular position sensor dedicated to space mechanisms were completed. Breadboard activities will be initiated to validate the concept. This will be followed by a dedicated qualification test campaign using qualification models in late 2016 / early 2017. It is planned to present the qualified MRS mid 2017.

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