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Novel 3D Hall sensor and its application in inspection robots

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Abstract – This paper describes a novel CMOS magnetic field sensor that can measure all three magnetic field components (Bx, By, and Bz) simultaneously at a single location. The sensor employs three groups of mutually orthogonal horizontal and vertical Hall-effect elements, each with dedicated biasing circuits and amplifiers. The field sensitive volume of the 3D sensor is very compact, only 100 x 100 µm2, which enables high spatial resolution. The use of CMOS technology ensures high angular accuracy and orthogonality of the three measurement axes. The sensor also employs a spinning-current technique that effectively mitigates issues such as offset, low-frequency noise, and planar Hall effect. The wide analog bandwidth from DC to 300 kHz and built-in temperature sensor make the sensor suitable for various applications, including 3D positioning sensors, proximity sensors, current sensors, and magnetometry. As an example, the paper discusses an application of the 3D sensor for improved adhesion control in inspection robots.

I. INTRODUCTION

Magnetic field sensors are vital for numerous applications across various industries, such as robotics, automotive, and medical fields, where the precise measurement of magnetic fields is critical. While Hall-effect sensors have gained popularity for their ability to measure magnetic fields, conventional sensors have limitations in measuring magnetic fields in all three dimensions simultaneously and at the same location, which is essential to precisely measure high gradient magnetic fields of permanent magnets, electro magnets and magnet assemblies. To address this limitation, a novel CMOS magnetic field sensor has been developed, capable of measuring all three magnetic field components (Bx, By, and Bz) simultaneously at virtually a single spot. The integrated vertical and horizontal Hall elements ensure high angular accuracy and orthogonality of the three measurement axes. The spinning-current technique used in the biasing of the Hall elements reduces issues such as offset, low-frequency noise, and planar Hall effect. This paper presents a compact 3D Hall sensor that has a wide analog bandwidth, high magnetic field resolution, and a built-in temperature sensor. The sensor's versatility makes it suitable for various applications, such as 3D positioning sensors, angular sensors, current sensors, and magnetometry. The paper also outlines an application of the 3D sensor for improved adhesion control in inspection robots.

II. HORIZONTAL AND VERTICAL HALL SENSORS

Hall sensors are commonly used to measure magnetic fields, but traditional Hall sensors only detect fields that act perpendicular to the sensor. To measure in-plane magnetic fields, a vertical Hall plate device must be integrated into the sensor. This idea was first introduced by Popovic [1] over 20 years ago and has been further developed using CMOS silicon technology to improve both horizontal and vertical Hall sensors.

The latest version of the vertical Hall device has a significantly better signal-to-noise ratio than any other vertical Hall device on the market, with a noise voltage spectral density of 0.8µV/Hz at 1kHz after signal processing [2]. The vertical and horizontal Hall elements can be combined in integrated CMOS technology to create various magnetic sensors for a wide range of applications: e.g. a compact 3D Hall sensors for providing a complete picture of the magnetic field environment; a 2D sensor for magnetic angle measurement or Hall sensors for electric current measurements.

III. THE 3D HALL SENSOR SENM3DX

The novel 3D Hall sensor SENM3Dx [3] is an advanced device that is capable of measuring all three components of the magnetic field (Bx, By, and Bz) at a single location simultaneously. The sensor is designed with three groups of mutually orthogonal Hall-effect elements, each of which has its own dedicated biasing circuits and amplifiers. This enables the sensor to have a high spatial resolution of only 100 x 100 µm2, see Fig. 1.

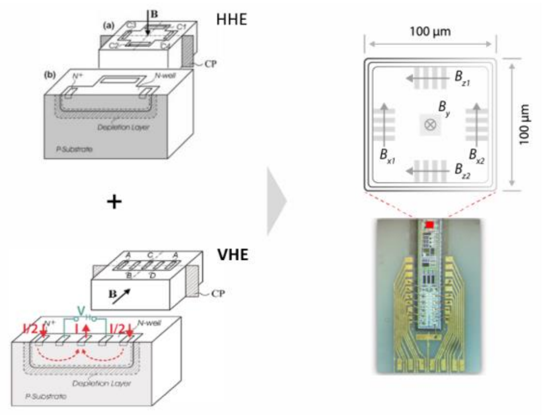

Fig. 1. Horizontal Hall Elements (HHE) and Vertical Hall Elements (VHE) integrated on silicon chip: Small sensitive volume. High mutual orthogonality. Equal performance for HHE and VHE.

The use of complementary metal-oxide-semiconductor (CMOS) technology in the fabrication of both the vertical and horizontal Hall elements and ensures high angular accuracy and orthogonality of the three measurement axes. The sensor also employs a spinning-current technique, which is effective in mitigating issues such as offset, low-frequency noise, and planar Hall effect.

The sensor is characterized by its wide analog bandwidth, ranging from DC to 300 kHz, and includes a built-in temperature sensor. The sensor chip is packaged in non-magnetic QFN28 package, see Fig. 2. These features make the sensor suitable for various applications.

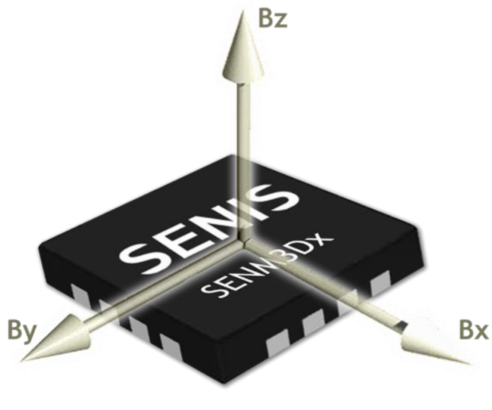

Fig. 2. SENM3Dx sensor packaged in non-magnetic QFN28 package

The RSL at ETH Zürich has integrated a 3D Hall sensor into their inspection robots to significantly enhance adhesion control during wall-climbing, as discussed below.

IV. 3D SENSOR APPLIED IN INSPECTION ROBOTS

Inspection robots are becoming increasingly important for tasks such as maintenance, monitoring, and inspection of critical infrastructure. One of the major challenges in the design and operation of these robots is the need for reliable adhesion control, especially in harsh and unpredictable environments.

To enhance safety, accuracy, efficiency, and cost-effectiveness, climbing robots equipped with electro-permanent magnet (EPM) grippers have been widely adopted [4], [5]. However, these robots are typically heavy and expensive, making it crucial to ensure that they do not fall during operation. To address this issue, obtaining feedback on the actual adhesive force or grip of the EPM to the support structure is essential. This feedback would not only allow for energy-saving during climbing but also enable the avoidance of areas that provide insufficient support. In this context, the proposed method for estimating the magnetic adhesive force utilizes SENIS 3D-magnetic field sensors SENM3Dx.

The 3D sensors are strategically placed on the edge of a gripper foot to probe the fringe field of the EPM. An adhesive force model was developed and a prototype was constructed using the EPM VM65/ND manufactured by NAFSA [6] and four SENM3Dx sensors, as shown in Figure 3 a) and b). The optimal sensor position was determined by electro-magnetic (EM) simulations, which identified the location of maximal magnetic field changes adjacent to the gripper foot housing.

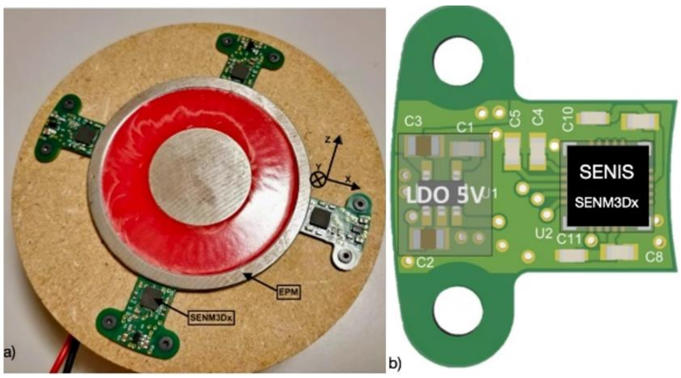

Fig. 3. The gripper foot prototype is shown in the bottom view with four equally distanced SENM3Dx sensors on PCBs and the electro permanent magnet (EPM). The magnetic axis definition is displayed for one sensor in (a), while (b) shows the sensor PCB's bottom view with SENIS® SENM3Dx. Both images are adapted from [4]

By taking into account the complexities of the real world, the adhesive force is influenced by various parameters. In this model, the focus is on four key factors that significantly impact the adhesive force: the strength of the permanent magnet, the air gap between the EPM and support, the thickness of the support (metal), and the texture of the support surface.

A novel solution involves defining an angle between the X and Y components, which offers valuable insight into air gap distance up to a certain range. Specifically, larger air gaps result in an angle of 90°, as seen in Fig. 4a, whereas for thicker support structures, the angle remains independent of thickness. However, for decreasing air gaps, the relative error in magnetic field component measurements can cause outliers, as shown in Fig. 4a. Therefore, understanding this relationship is key in accurately estimating adhesive force for climbing robots and ensuring their safe and efficient operation.

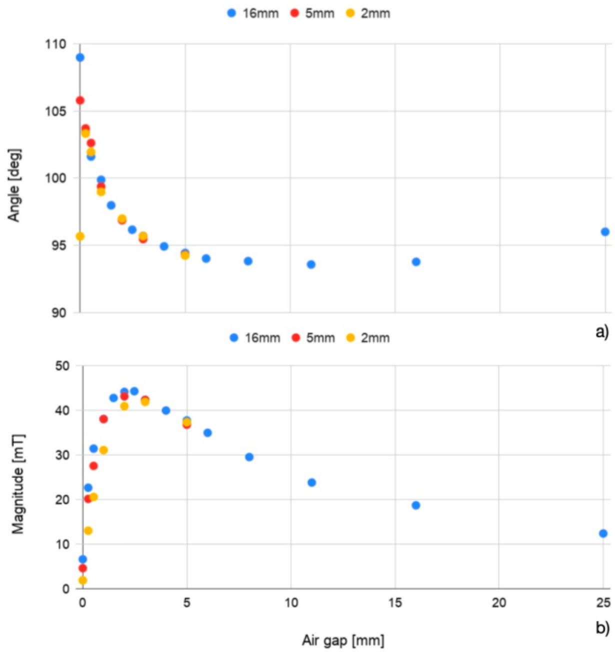

Fig. 4. The magnetic angle is illustrated for various air gaps in (a), while (b) displays the magnetic field magnitude M for different air gaps. A 16 mm thick steel plate was used as support. The image is reprinted from [4]

The X and Y components of the magnetic field amplitude or magnitude M can be used to determine the adhesion force, as it exhibits a nearly linear relationship for small air gaps (see b) Fig. 4). In contrast, the magnetic angle provides less reliable data for estimating the adhesion force compared to the magnetic magnitude, and hence was not utilized in building a simple, linear prediction model. Thus, the magnetic angle can be used to estimate the air gap distance, while the magnetic field magnitude can be used to determine the adhesion force. This is supported by the fact that the adhesion force is roughly proportional to the magnetic field magnitude for a given air gap.

Eqn. 1 presents the adhesion force prediction model, which utilizes data from a 5 mm thick steel plate, based on the magnetic magnitude and an independent force measurement obtained from the 2 mm and 16 mm metal plates. The model is expressed as a function of the air gap width (d), where the subscript indicates the thickness of the metal support. Therefore, the model $F_{5,pred}$ (d) predicts the adhesion force for a 5 mm thick metal plate using the magnetic magnitude (M) and force measurements (F) of 2, 5, and 16 mm thick metal supports.

$$F_{5,pred}(d) = F_2(d) + \frac{F_{16}(d) - F_2(d)}{M_{16}(d) - M_2(d)}\left(M_5(d) - M_2(d)\right) \qquad (1)$$

In Fig. 5, the predicted and measured adhesion force values are compared as a function of the air gap distance d, with a maximum relative error of 23%. This level of accuracy is considered acceptable since the magnet's strong adhesion force is chosen for safety reasons. This safety margin allows for the use of the model in real-world applications without further optimization. Additionally, the fast and dynamic responses of the SENM3Dx sensor enable the use of adaptive models that can train and react in real-time. Furthermore, it is highly convenient to obtain adhesion force information from a small, lightweight 3D magnetic field sensor.

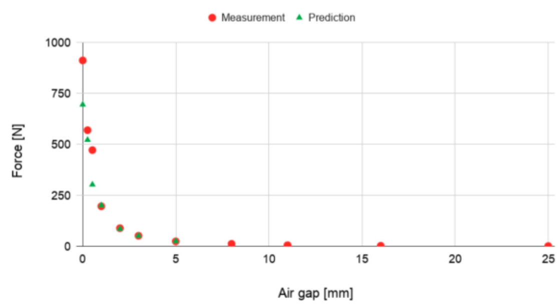

Fig. 5. The performance of the linear prediction model $F_{5,pred}$ is demonstrated, and the model (Prediction) is compared to the measured adhesion force (Measurement) for various air gaps d. The image is reprinted from [4].

V. CONCLUSIONS AND OUTLOOK

This paper presents a novel CMOS magnetic field sensor that can accurately measure all three components of the magnetic field at a single location. The use of three groups of mutually orthogonal vertical and horizontal Hall-effect elements, each with dedicated biasing circuits and amplifiers, ensures high spatial resolution and angular accuracy. The spinning-current technique employed in the sensor effectively mitigates issues such as offset, low-frequency noise, and planar Hall effect. The wide analog bandwidth and built-in temperature sensor make the sensor suitable for a variety of applications, including 3D position sensing and magnetometry, angular sensing and electrical current sensing.

As an example, an application of the 3D sensor for improved adhesion control in inspection robots is presented. The use of SENIS 3D Hall sensors has proven to be a powerful tool in optimizing the control of magnetic grippers, providing reliable measurements even in high field gradient applications.

With its unmatched performance and precision, SENIS® 3D Hall sensors are poised to play a leading role in the next generation of magnetic measurement solutions. As SENIS continues to push the limits of what is currently possible and available on the market, the range of possibilities for researchers and engineers alike will expand, leading to further advances in magnetometry and sensor technology.

REFERENCES

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[2] Patent EP14176835.8 Vertical Hall Device (granted: USA, CN, JP, EU). Application: High-resolution CMOS integrated vertical Hall device.

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[4] A. Cavelti, G. Valsecchi, L. Nachtigall, and M. Hutter, “Magnetic gripper feet - Integration of the control electronics and estimation of magnetic adhesive force,” 2020, Student Thesis, RSL, ETH Zurich

[5] EPM: An electro-permanent magnet, also known as EPM, is a special kind of permanent magnet that allows the activation or deactivation of its external magnetic field through the application of an electric current pulse in a wire winding wrapped around a section of the magnet.

[6] https://www.nafsa-solenoids.com/products/holding-electromagnets/round-magnetic/vmnd-series/, accessed 15th of March 2023