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Revealing the potential of a new 3D Hall sensor in advanced inspection robotics

Dragana Popovic Renella[1], Thomas Kaltenbacher[1], Sasa Spasic[1], Andrea Cavelti[2], Giorgio Valsecchi[2], Lennart Nachtigall[2], Marco Hutter[2]

[1] *SENIS Group, Switzerland*
[2] *RSL ETH Zurich, Switzerland*

ABSTRACT
This paper presents a novel CMOS magnetic field sensor designed for the simultaneous measurement of all three magnetic field components (Bx, By, and Bz) at a single location. The sensor incorporates three sets of mutually orthogonal horizontal and vertical Hall-effect elements, each equipped with dedicated biasing circuits and amplifiers. With a compact field-sensitive volume of only 100 x 100 x 10 µm³, the 3D sensor achieves exceptional spatial resolution. Leveraging CMOS technology ensures precise angular accuracy and orthogonality of the three measurement axes. Additionally, the sensor utilizes a spinning-current technique to effectively address challenges such as offset, low-frequency noise, and planar Hall effect. With a wide analog bandwidth spanning from DC to 300 kHz and an integrated temperature sensor, the sensor is versatile and applicable to a range of uses, including 3D positioning sensors, proximity sensors, current sensors, and magnetometry. To demonstrate its practical application, this paper explores the utilization of the 3D sensor for enhanced adhesion control in inspection robots. The innovative features of this CMOS magnetic field sensor make it a promising solution for diverse scientific and industrial applications.

Section: RESEARCH PAPER

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Corresponding author: Dragana Popovic Renella, e-mail: info@senis.swiss

1. INTRODUCTION

Magnetic field sensors play a crucial role in numerous industries, including robotics, automotive, and medical applications, where accurate measurement of magnetic fields is paramount. While Hall-effect sensors are widely employed for their magnetic field measurement capabilities, conventional sensors face limitations in simultaneously capturing magnetic fields in all three dimensions at a single location. This capability is essential for accurately measuring high-gradient magnetic fields produced by permanent magnets, electromagnets, and magnet assemblies.

In response to this challenge, this article introduces a new CMOS magnetic field sensor designed to concurrently measure all three magnetic field components (Bx, By, and Bz) at virtually a single point. The integration of both vertical and horizontal Hall elements ensures precise angular accuracy and orthogonality of the three measurement axes. Employing a spinning-current technique in the biasing of the Hall elements effectively mitigates issues such as offset, low-frequency noise, and planar Hall effect.

The presented compact 3D Hall magnetic sensor boasts a wide analog bandwidth, and high magnetic field resolution, and incorporates a built-in temperature sensor. Its versatility extends its applicability to various fields, including 3D positioning sensors, angular sensors, current sensors, and magnetometry. As an illustrative example, this paper explores the application of the 3D sensor in enhancing adhesion control for inspection robots. The innovative features of this CMOS magnetic field sensor position it as a promising solution for advancing magnetic field measurement capabilities in diverse scientific and industrial settings.

2. CLASSICAL HORIZONTAL HALL SENSORS AND VERTICAL HALL SENSORS

While traditional horizontal Hall sensors are adept at measuring magnetic fields that act perpendicularly to the sensor, there arises a limitation when it comes to in-plane magnetic fields. To address this gap, a vertical Hall device has been integrated into the sensor, an innovative concept initially introduced by Popovic more than two decades ago [1]. This concept has undergone continuous refinement, leveraging CMOS silicon technology to enhance the capabilities of both horizontal and vertical Hall sensors.

The latest advancement in this line of development showcases a vertical Hall device with a significantly improved signal-to-noise ratio compared to its counterparts available in the current market. Demonstrating its prowess, this device achieves a remarkable noise voltage spectral density of 0.8μV/sqrt(Hz) at 1kHz after signal processing [2], leading to the magnetic resolution of 1μT of the novel 3D sensor [3], described in Section 3. This is 20 times better compared to some published results of vertical Hall sensors, which have a resolution of 20μT at 1kHz [4]. The integration of CMOS technology plays a pivotal role in seamlessly combining vertical and horizontal Hall elements, presenting a versatile platform for the creation of diverse magnetic sensors tailored to address a wide range of applications.

This technological convergence gives rise to lots of possibilities, including the creation of a compact 3D Hall sensor capable of offering a comprehensive depiction of the magnetic field environment. Additionally, a 2D sensor designed for magnetic angle measurement emerges as another application, showcasing the adaptability of these sensors in various contexts. Furthermore, specific Hall sensors have been developed to facilitate precise electric current measurements, expanding the utility of this integrated CMOS technology in the realm of magnetic sensing. As the development of these sensors continues to evolve, the potential applications in research and industry are poised for exponential growth, heralding a new era in magnetic field measurement technology.

3. THE NEW SENIS 3D HALL SENSOR SENM3DX

The newly developed SENM3Dx 3D Hall sensor [3] represents a device with the ability to measure the three components of the magnetic field (*B*x, *B*y, and *Bz*) concurrently at a specific point. This sensor incorporates three sets of mutually perpendicular Hall-effect elements, each equipped with its own dedicated biasing circuits and amplifiers. This unique design empowers the sensor with an impressive spatial resolution, restricted to a mere 100 × 100 μm², as illustrated in Figure 1.

Utilizing complementary metal-oxide-semiconductor (CMOS) technology for crafting both the vertical and horizontal Hall elements guarantees elevated angular precision and orthogonality across the three measurement axes. Additionally, the sensor incorporates a spinning-current technique, known for its efficacy in addressing concerns like offset, low-frequency noise, and planar Hall effect.

Distinguished by a broad analog bandwidth spanning from DC to 300 kHz, the sensor also encompasses a built-in temperature sensor. Housed within a non-magnetic QFN28 package, as depicted in Figure 2, these attributes render the sensor adaptable to a myriad of applications.

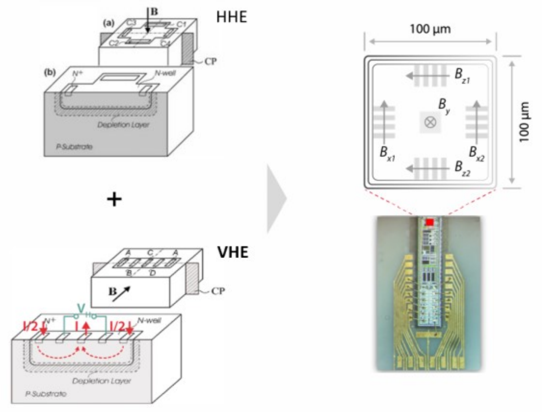

Figure 1. Integration of Classical Horizontal Hall Elements (HHE) and Vertical Hall Elements (VHE) on a silicon chip with a compact sensitive volume. Notable mutual orthogonality. Equivalent performance exhibited by both HHE and VHE.

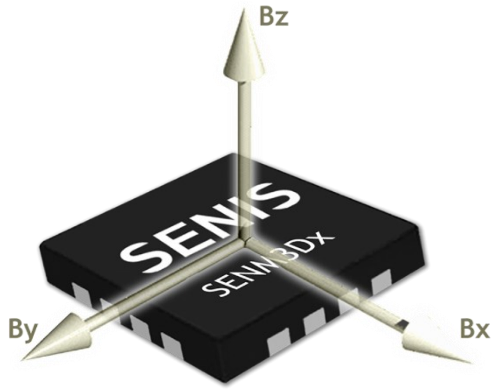

Figure 2. The 3D Hall magnetic sensor SENM3Dx packaged in a non-magnetic QFN28 package.

The Research and Systems Laboratory (RSL) at ETH Zürich has incorporated an advanced SENIS 3D Hall sensor into their inspection robots, specifically the ANYmal model, to greatly improve adhesion control in the context of wall-climbing, as elaborated further in the subsequent discussion.

4. THE NEW 3D HALL SENSOR APPLIED IN THE INSPECTION ROBOT ANYMAL

Autonomous inspection systems are gaining heightened significance in a variety of applications, encompassing pivotal functions like upkeep, surveillance, and examination of essential infrastructure elements, as illustrated in Figure 3. The escalating relevance of inspection robots lies in their ability to perform intricate tasks with precision and efficiency. These autonomous systems play an important role in ensuring the reliability and longevity of critical infrastructure components by executing thorough maintenance routines and continuous monitoring. The utilization of these advanced robotic technologies not only enhances operational efficiency but also minimizes human intervention in potentially hazardous environments. The visual representation in Figure 3 serves as a testament to the expanding role of inspection robots in safeguarding and optimizing vital infrastructure across diverse sectors.

Addressing the complexities inherent in the design and functionality of these robotic systems, a critical obstacle arises in

Figure 3. The climbing robot ANYmal operates in harsh environments [5].

the demand for dependable adhesion control, particularly when navigating through harsh and unpredictable environments.

In the pursuit of bolstering safety, precision, operational efficiency, and cost-effectiveness, climbing robots have increasingly embraced the incorporation of electro-permanent magnet (EPM) grippers [6]. An EPM is a special kind of a 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.

A noteworthy example is depicted in Figure 4, showcasing the magnetic gripper foot of the ANYmal robot, which features an embedded electro-permanent magnet.

In this Figure 4, the magnetic gripper foot is intricately linked to a control electronics board, serving the dual purposes of development and testing. This integration underscores the ongoing efforts to enhance the performance and adaptability of climbing robots in challenging scenarios.

Nonetheless, the prevailing characteristics of inspection robots, characterized by their considerable weight and substantial cost, pose a critical challenge to guaranteeing operational stability and averting unintended falls. In light of these concerns, there is a pressing need to establish a robust feedback system to gauge the actual adhesive force or grip exerted by the electro-permanent magnet (EPM) onto the supporting structure. This feedback mechanism serves not only to optimize energy utilization during climbing activities but also empowers the robot

Figure 5. A simple prototype of the foot for electrical testing. The control board is placed on the top of the electro-permanent-magnet EPM. The image is adapted from [6].

with the capability to intelligently navigate and steer clear of areas that may lack sufficient support.

Within this framework, our innovative approach to estimating the magnetic adhesive force leverages the cutting-edge SENIS 3D Hall magnetic field sensor technology, with a specific emphasis on the advanced SENM3Dx model. This sophisticated sensor technology plays a pivotal role in augmenting the safety and efficacy of inspection robots undertaking complex tasks, such as wall-climbing maneuvers.

To illustrate the practical application of this methodology, Figure 5 showcases a rudimentary prototype of the foot explicitly designed for electrical testing. In this configuration, the control board is strategically positioned atop the electro-permanent magnet (EPM). The lower segment of the prototype features a ring housing four magnetic field sensors, as illustrated in Figure 6. This strategic deployment of sensors allows for a comprehensive analysis of magnetic field dynamics, facilitating accurate estimation of the adhesive force exerted by the EPM in diverse scenarios.

By integrating this advanced sensor technology seamlessly into the structural and control aspects of inspection robots, our objective is not only to elevate their operational safety but also to optimize performance through real-time adjustments guided

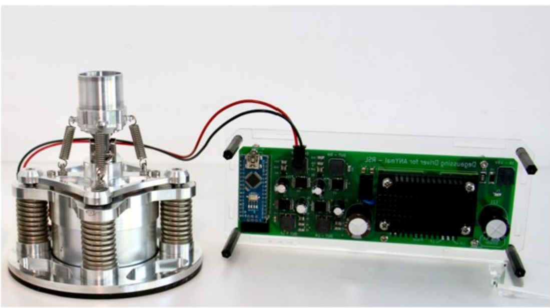

Figure 4. Magnetic gripper foot of ANYmal robot including an electro permanent magnet (EPM) and connected to a control electronics board. The image is adapted from [6].

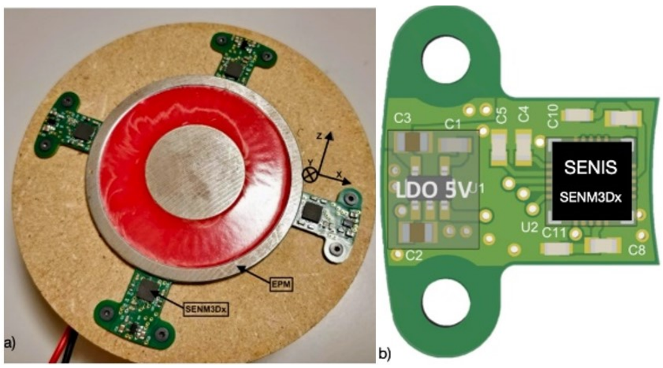

Figure 6. Depicting the prototype of the gripper foot from a lower perspective, featuring four SENM3Dx sensors evenly positioned on PCBs and an electro-permanent magnet (EPM). The magnetic axis definition for one sensor is elucidated in (a), and (b) presents the bottom view of the sensor PCB with SENIS® SENM3Dx. These visual representations have been adapted from the referenced source [6].

by dynamic feedback. This convergence of robotics and innovative sensor technologies paves the way for enhanced capabilities and secure deployment of inspection robots across a spectrum of challenging environments.

Figure 5 shows a simple prototype of the foot for electrical testing. The control board is placed on the top of the EPM. At the bottom a ring with four magnetic field sensors is mounted on it, as shown in Figure 6.

The placement of 3D sensors is carefully orchestrated along the periphery of a gripper foot to explore the fringe field generated by the electro-permanent magnet (EPM). A comprehensive adhesive force model was formulated, and a tangible prototype was assembled utilizing the NAFSA-manufactured EPM VM65/ND [7] in conjunction with four SENM3Dx sensors, as illustrated in Figure 6 a) and b). The strategic positioning of sensors was established through electromagnetic (EM) simulations, pinpointing the areas with the most significant magnetic field variations in close proximity to the gripper foot housing.

Acknowledging the intricate dynamics of the real-world scenario, the adhesive force manifests its complexity through the influence of various parameters. In this model, particular attention is directed towards four pivotal factors that wield a substantial impact on the adhesive force: the strength of the permanent magnet, the air gap existing between the electro-permanent magnet (EPM) and its support, the thickness of the support material (metal), and the surface texture of the support.

Delving into the visualization of the magnetic gripper foot setup and the consequential influences on magnetic holding force, Figure 7 offers a schematic representation. This depiction elucidates how both the thickness of the metal plate and the air gap between the plate and the electro-permanent magnet play instrumental roles in shaping the adhesion force exerted by the magnetic gripper feet. The intricacies of these factors underscore the nuanced interplay that defines the adhesive capabilities of the gripper foot in diverse practical scenarios.

Introducing a novel approach, an innovative solution arises by establishing an angle between the X and Y components, providing insightful perspectives on the air gap distance within a defined range. Notably, this methodology reveals that more substantial air gaps yield an angle of 90°, as shown in Figure 8a. Interestingly, for support structures of varying thickness, the angle remains consistent, independent of the thickness. However, as the air gap diminishes, a noteworthy observation emerges – the presence of relative errors in magnetic field component measurements, potentially leading to outliers, as exemplified in Figure 8a. Consequently, comprehending this intricate relationship becomes essential in precisely estimating adhesive force for climbing robots, ensuring their operational safety and efficiency in diverse environmental conditions. This nuanced understanding enhances the overall efficacy of climbing robots, contributing to their reliable performance in real-world applications.

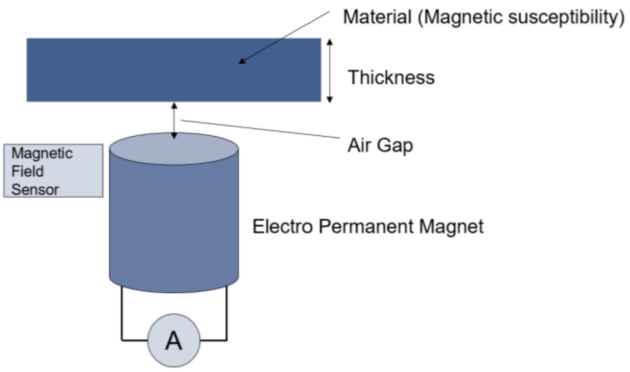

Figure 7. A drawing of the setup of the magnetic gripper foot and the related magnetic holding force influences. The drawing is adapted from [6].

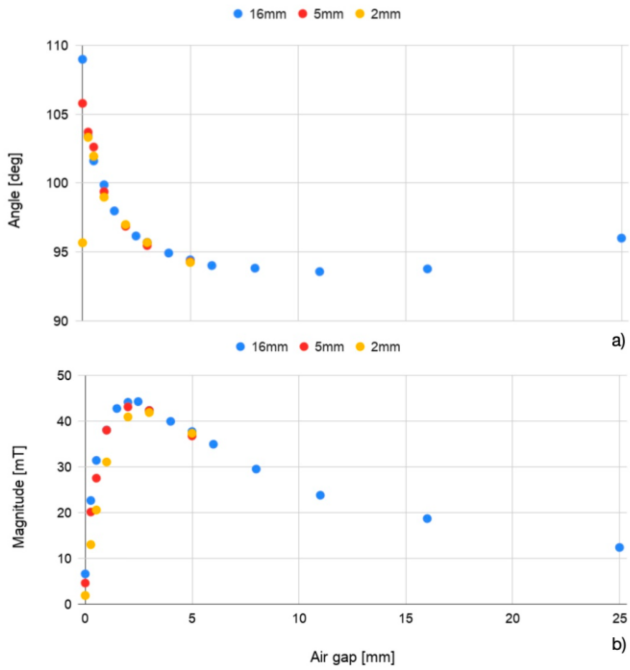

Figure 8. Within the illustration, the magnetic angle takes center stage in (a), offering a visual representation across diverse air gaps. In contrast, (b) shifts the focus to the magnetic field magnitude denoted as M, presenting variations across different air gaps. The experimental setup involved utilizing a 16 mm thick steel plate as the supporting structure. It's pertinent to note that this visual content has been reproduced from the referenced source [6].

The determination of adhesion force involves the utilization of the X and Y components of the magnetic field amplitude or magnitude, denoted as M. Notably, a nearly linear relationship is observed for small air gaps, as illustrated in Figure 8b. In contrast, the magnetic angle, while informative about the air gap distance, provides less reliable data for estimating adhesion force when compared to the magnetic magnitude. Consequently, the magnetic angle is excluded from the construction of a straightforward linear prediction model.

In delineating the interplay between these magnetic parameters, it is discerned that the magnetic angle proves valuable in estimating air gap distance, whereas the magnetic field magnitude becomes instrumental in determining adhesion force. This observation is underpinned by the rough proportionality between adhesion force and magnetic field magnitude for a given air gap.

To formalize this relationship, (1) presents the adhesion force prediction model

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

Leveraging data from a 5 mm thick steel plate, the model incorporates the magnetic magnitude (M) and an independent force measurement derived from 2 mm and 16 mm metal plates. The model is expressed as a function of the air gap width (d), with the subscript denoting the thickness of the metal support. Consequently, the predictive model F5,pred(d) estimates the

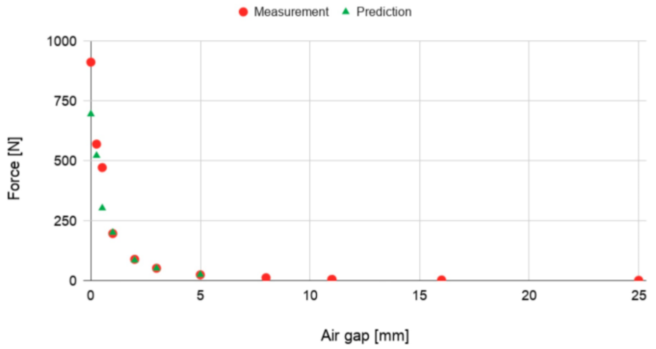

Figure 9. Illustrating the efficacy of the linear prediction model "F" _"5,pred", the figure showcases a comparison between the model's predictions (Prediction) and the corresponding measured adhesion force (Measurement) across different air gap distances (d). The visual representation has been reproduced from the source [6].

adhesion force for a 5 mm thick metal plate using magnetic magnitude (*M*) and force measurements (*F*) from metal supports with thicknesses of 2 mm, 5 mm, and 16 mm. This comprehensive modeling approach contributes to a nuanced understanding of the factors influencing adhesion force, fostering improved predictions for climbing robots across diverse support structures and air gap distances

Within Figure 9, a thorough examination unfolds as the anticipated and actual adhesion force values interplay across varying air gap distances denoted as "d." The comparative analysis reveals a maximum relative error of 23 %, a margin deemed acceptable given the deliberate selection of a robust adhesion force for safety considerations. This intentional safety buffer not only deems the model fitting for deployment in real-world scenarios without necessitating further optimization but also accentuates the reliability of the predictions.

The adaptability of the SENM3Dx sensor amplifies the practical utility of the model. Its swift and dynamic responses pave the way for the implementation of adaptive models capable of continuous training and real-time responsiveness. This feature adds a layer of versatility, ensuring that the model remains effective in dynamic and evolving scenarios.

Moreover, the intrinsic attributes of the SENM3Dx sensor contribute to the convenience of obtaining adhesion force information. As a small and lightweight 3D magnetic field sensor, it stands out as a practical solution for seamlessly integrating adhesion force monitoring into various applications. The synergistic combination of accurate predictions, safety considerations, and real-time adaptability positions the SENM3Dx sensor and its associated linear prediction model as formidable tools in the realm of adhesion force control.

Figure 10 shows the measurement setup containing the novel SENIS 3D Hall sensors positioned around the magnet.

5. CONCLUSION

This article introduces an innovative CMOS Hall magnetic field sensor designed to precisely measure all three components of the magnetic field at a single location. The sensor's architecture incorporates three sets of mutually orthogonal vertical and horizontal Hall-effect elements, each equipped with dedicated biasing circuits and amplifiers. This configuration ensures not only high spatial resolution but also high angular accuracy. The sensor leverages a spinning-current technique to

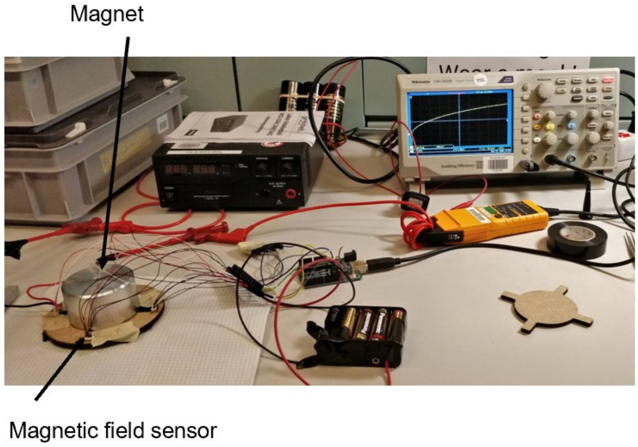

Figure 10. Measurement setup containing the SENIS 3D Hall sensors and a magnet.

effectively address challenges such as offset, low-frequency noise, and planar Hall effect, resulting in exceptional magnetic resolution.

Beyond these features, the sensor boasts a wide analog bandwidth, rendering it versatile for various applications. Its adaptability spans across 3D position sensing and magnetometry, angular sensing, and electrical current sensing. An exemplary application highlights the sensor's role in enhancing adhesion control for inspection robots. The implementation of SENIS 3D Hall sensors proves instrumental in optimizing magnetic gripper control, delivering reliable measurements even in high-field gradient applications.

The remarkable performance and precision exhibited by SENIS® 3D Hall sensors position them as frontrunners in the evolution of magnetic measurement solutions. SENIS introduces innovations that surpass prevailing industry norms, thus broadening the scope of exploration for researchers and engineers. This trajectory of advancement is anticipated to stimulate additional advancements in magnetometry and sensor technology.

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