Novel Rotary Encoder with Multi-Axis Hall Sensors

Bruno Brajon $^1$, Christian Schott $^1$, and Gael Close $^1$

$^1$Affiliation not available

December 7, 2023

Abstract

We present a novel high-accuracy rotary magnetic sensor system composed of a two-track coded multi-pole magnet and a dual-spot multi-axes magnetic sensor. The novelty is the measurement of two orthogonal magnetic field components in each of the two sensing spots of the sensor, one associated with each magnet track. As the two orthogonal signals in each spot are naturally in quadrature, i.e. they represent a sine and a cosine signal, the measurement principle is virtually independent of the magnet pole size and pitch. We can therefore design a magnet with much larger poles which in turn generate stronger magnetic flux, allowing for an increased air gap between sensor and magnet. The calibrated encoder system was characterized to deliver 13 bits of absolute accuracy and 17 bits of resolution over the full 360° range.

Article ACCEPTED for publication in 2023 IEEE Sensors.
A novel magnetic absolute angular encoder for robotic applications

AUTHORS: Bruno Brajon, Christian Schott, Gael Close
Melexis Technologies SA, Chemin de Buchaux 38, CH-2022 Bevaix, Switzerland
CONTACT: bur@melexis.com

IEEE SENSORS 2023
Vienna, Austria

The Signal Processing Chain

System Components

The Magnet
The dual-track magnet is an outside diameter of 24mm and an inside diameter of 14mm. The two magnetic tracks are separated by a 1mm code-free region. The track contains 16 alternating north/south poles (8 pole pairs). The inner Nonius track is strong enough to determine the sector on the Master track and weak enough to generate only small crosstalk to the Master track sensor. The large poles allow for an operating airgap of 1.5 +/- 0.5mm between the sensor surface and the magnet surface. This allows for larger coarse than typical state-of-the-art magnetic systems.

The Sensor
The sensor is composed of two Melexis triaxis magnetic sensors assembled side-by-side on the leadframe of a standard TSSOP16 package with a footprint of 5x5mm. The integrated CMOS circuits contain all necessary electronics for transducing the magnetic field components into electrical signals, and signal amplification. Filtering, AD conversion and SPI SPI communication interface.

This Work
The key feature of this work is the use of only one master and one nonius sensing spot each measuring two orthogonal magnetic field components (B_t and B_a) that are naturally in quadrature (e.g., one represents a SIN function and the other one a COS function).

The Demonstrator
The image shows an implementation of the system together with a reference system. Notice here, the reference system requires a very small air gap due to the very fine pole pitch used by this technology. The system accuracy is better than 0.03° over the full 360° rotation. The achieved RMS resolution at the nominal airgap is 17 bit (0.003°).

State-of-the-Art

Angular Encoder Benchmark

Residual Angular Error vs. Calibration Steps

References


1. Pole pitch
2. Larger overall assembly tolerances
3. Long reach of field
4. Large airgap possible
5. Large poles
6. Small poles
7. Short reach of field
8. Small airgap required

In a first step the amplitude and phase of the two Master track components are measured by a linear combination of all four magnetic field signals.

In a second step the coarse angle and Nonius angle are computed and composed to yield the fine angle.

By the fourth and last step the imperfections of the magnet are compensated via the correction values stored inside a look-up-table (LUT).

Each of the two sensors is exposed to a mixture of magnetic field components on both of its orthogonal axes.

In a first step the amplitude and phase of the two Master track components are measured by a linear combination of all four magnetic field signals.

In a second step the coarse angle and Nonius angle are computed and composed to yield the fine angle.

The third step consists of compensating the two structural error components arising from cross-talk between the tracks as well as from eccentricity.

The cross-talk compensation removes the 1st and 15th harmonics.

The linearization step corrects the remaining non-linearities.

The uncalibrated angle error is mainly affected by a 16th harmonic.

The 16th harmonic is removed by amplitude and offset correction. We are left with the 15th and 1st harmonics.
Novel rotary Encoder with multi-axis Hall Sensors

Bruno Brajon  
Melexis Technologies SA  
Bevaix, Switzerland  
br@melexis.com

Christian Schott  
Melexis Technologies SA  
Bevaix, Switzerland  
csc@melexis.com

Gaël Close  
Melexis Technologies SA  
Bevaix, Switzerland  
gcl@melexis.com

Abstract—We present a novel high-accuracy rotary magnetic sensor system composed of a two-track coded multi-pole magnet and a dual-spot multi-axes magnetic sensor. The novelty is the measurement of two orthogonal magnetic field components in each of the two sensing spots of the sensor, one associated with each magnet track. As the two orthogonal signals in each spot are naturally in quadrature, i.e. they represent a sine and a cosine signal, the measurement principle is virtually independent of the magnet pole size and pitch. We can therefore design a magnet with much larger poles which in turn generate stronger magnetic flux, allowing for an increased air gap between sensor and magnet. The calibrated encoder system was characterized to deliver 13 bits of absolute accuracy and 17 bits of resolution over the full 360° range.

Index Terms—Encoder, Magnet, Vernier, Nonius, Multipole, Off-axis

I. INTRODUCTION

Absolute angular encoders are widely spread in industrial applications with the robotic market as an important emerging segment [1]. Contactless rotary position sensing is dominated today by three distinct technologies: optical, magnetic and inductive [Table I]. Optical encoders are well known to deliver overall accuracy of up to 16 bits and resolution to over 20 bits due to the implementation of many tracks with very fine structures [2]. However, as they are error-prone to contamination by dust particles, droplets etc, the encoders must be hermetically sealed which makes them bulky and expensive [3]. Inductive encoders yield similar resolution and accuracy, however they require large area for good coupling and full circular PCB for through-shaft applications [4]. Magnetic encoders on the other hand come in many flavors today. From the simple end-of-shaft components with dipole magnets [5] to circular magnetic scales with several pole pairs along the perimeter [6]. This is an ideal concept to map a rotary angle of 360 electrical degrees to a mechanical angle of 360°/n and so to increase resolution and accuracy by a factor of n. For the sensing of such a track, a small sensor chip having two or more sensing elements within a few millimeters distance is typically used [7]. The sensing elements are integrated horizontal Hall devices measuring the field component perpendicular to the chip surface. Two sensing elements per track are spaced at a distance corresponding to half a pole length and thus generate a sine and a cosine signal through which the angular position with the pole-pair is calculated. This fixed distance restricts the system use to a single pole pitch and very small radial misalignment causes significant orthogonality errors which require compensation [8]. By combining two magnetic scales into a Vernier configuration where a Master track with n pole pairs and a Nonius track with n – 1 pole pairs are used, the magnet is made asymmetric and true 360° measurement capability is enabled [9]. Due to the small distance between the sensing elements on the integrated chip, the poles of the magnetic scale are typically between 1 and 2mm long [10] and the sensor chip operates at a distance of 0.5 to 1mm from the magnetic scale surface. If a single-track magnetic scale with coded poles is used then the poles are even smaller and consequently the air gap further reduced [11]. This requires very accurate mechanical adjustment of the sensor and magnet and it bears the risk of destruction of the magnetic scale by mechanical contact with the sensor if slightly misaligned. In our approach, we intentionally break the link between sensing element distance and pole size by introducing multi-axis sensing enabled by 3D Hall magnetic field sensors.

<table>
<thead>
<tr>
<th>Device</th>
<th>Technology</th>
<th>Accuracy</th>
<th>Resolution*</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>[5]</td>
<td>Magnetic</td>
<td>10 bit</td>
<td>14 bit</td>
<td>50 mW</td>
</tr>
<tr>
<td>[7]</td>
<td>Magnetic</td>
<td>12 bit</td>
<td>18 bit</td>
<td>265 mW</td>
</tr>
<tr>
<td>[4]</td>
<td>Inductive</td>
<td>15 bit</td>
<td>20 bit</td>
<td>425 mW</td>
</tr>
<tr>
<td>[12]</td>
<td>Optical</td>
<td>14.5 bit</td>
<td>23 bit</td>
<td>650 mW</td>
</tr>
<tr>
<td>This work</td>
<td>Magnetic</td>
<td>13 bit</td>
<td>17 bit</td>
<td>100 mW</td>
</tr>
</tbody>
</table>

*Resolution is the RMS noise in a bandwidth of 500 Hz

II. SENSING CONCEPT

A. Single sensing spot per track

Instead of using two sensing spots per track measuring the same component of the magnetic field in two separate locations, we use a single sensing spot measuring two orthogonal magnetic field components e.g. one axial $B_a$ and one tangential $B_t$ [Fig.1]. With an appropriate magnet design where the axial component has a sine shape and the radial component is about zero, the tangential component automatically shows the behavior of a cosine function when the magnet rotates.

B. The link between pole size, air-gap and tolerances

The “single spot - two components” feature allows the use of the same sensing device in combination with a large range of magnet pole sizes. We can therefore work with pole dimensions that are significantly larger than the sensor chip. Bigger poles are naturally stronger so that we can increase the distance between the magnetic scale and the sensor significantly. Using a 24mm diameter magnetic scale with 8 pole pairs where each pole is more than 4mm long, we work with a nominal air gap of 2mm. A larger air gap bears two distinct advantages:
The change of the air gap with temperature or with lifetime wear-out has a relatively smaller impact on measured magnetic field components.

The mutual positioning of the magnetic scale and the sensor chip allows for much larger assembly tolerances.

III. FROM MAGNET TO ANGLE

In this concept, the four signals measured by the sensor are:

$$B_{t,M} = B_m \cos 8\phi + c_1 B_m \cos 7\phi$$

$$B_{a,M} = B_m (1 + \alpha_1) \sin (8\phi + \theta_1) + c_2 B_m \sin (7\phi + \theta_2)$$

$$B_{t,N} = B_n \cos 7\phi + c_3 B_m \cos 8\phi$$

$$B_{a,N} = B_n (1 + \alpha_2) \sin (7\phi + \theta_2) + c_4 B_m \sin (8\phi + \theta_1)$$

where $\phi$ is the mechanical rotation angle, $B_m$ and $B_n$ are the field amplitudes of the Master and the Nonius track, $\alpha_1$ and $\alpha_2$ describe the amplitude mismatch, $\theta_1$ and $\theta_2$ the phase mismatch and $c_1$, $c_2$, $c_3$, $c_4$ denote the cross-talk between the two magnetic tracks. On top of this, we observe errors arising from magnet imperfections like inaccurate pole separations and non-homogeneous magnetization. In the following sections, we will guide the reader by a step-wise approach to how each of those effects is compensated [Fig.3]. The data used in those steps had prior been generated by a referenced calibration, i.e. registering the four sensor outputs versus a high-accuracy reference system.

A. Nonius angle reconstruction

As the Nonius track is very weak, the sensor measuring its components suffers from heavy crosstalk from the strong Master track. Therefore, it is required to reconstitute the Nonius signal by a linear combination of all four sensor signals.

$$\hat{B}_{a,N} = d_1 B_{t,M} + d_2 B_{a,M} + d_3 B_{t,N} + d_4 B_{a,N}$$

$$\hat{B}_{t,N} = d_5 B_{t,M} + d_6 B_{a,M} + d_7 B_{t,N} + d_8 B_{a,N}$$

where $d_1, ..., d_8$ are coefficients that have been extracted during the calibration procedure by a least square fit. $\hat{B}_{a,N}$ and $\hat{B}_{t,N}$ are the reconstructed Nonius signals. We can now extract the Nonius angle:

$$7\phi_{LC} = \arctan \left( \frac{\hat{B}_{a,N}}{\hat{B}_{t,N}} \right)$$

7$\phi_{LC}$ is required to assign a unique sector number ranging from 0 to 7 to each pole pair of the Master track, making the system a true power-on absolute encoder.

B. Amplitude and Phase Correction

In this step, we match the amplitude and the phase for the Master source signals. Such mismatch causes the presence of a 16th harmonic in the error [Fig. 2(a)]. The following equation shows the correction function that needs to be applied to $\hat{B}_{a,M}$ [13]:

$$\hat{B}_{a,M} = \frac{(A_0 B_{a,M} + \sin A_1 B_{t,M})}{\cos A_1}$$

$A_0$ and $A_1$ are the coefficients compensating for amplitude and phase mismatching. They are determined during the calibration procedure by solving a least square problem minimizing the 16th harmonic content in the angle error.

C. Fine angle reconstruction

After the amplitude and phase correction, equations (1) and (2) are written as follows:

$$B_{t,M} = B_m (\cos (8\phi) + k_1 \cos (7\phi))$$

$$\tilde{B}_{a,M} = B_m (\sin (8\phi) + k_2 \sin (7\phi))$$

The main error contribution is the crosstalk between the Master track and the Nonius track which will be treated in section III-D. We can now extract the angle from the Master track signals:

$$8\phi_{ct} = \arctan \left( \frac{\tilde{B}_{a,M}}{\tilde{B}_{t,M}} \right) = 8\phi + \epsilon_{ct}$$

where $\epsilon_{ct}$ is the angular error due to the crosstalk. The mechanical angle is retrieved by the following expression:

$$\phi_{mech} = 8\phi_{ct} - 7\phi_{LC} = \phi + \epsilon_{coarse}$$

$\epsilon_{coarse}$ is the error in the discrimination of the Master sector. Since we are using 8 pole pairs this error needs to be lower than $\pm 22.5^\circ$. Using $\phi_{mech}$, we are able to assign to each...
Master pole pair a unique Master Pole Pair Number (MPPN) from 0 to 7. At this point, we are able to extract the fine angle which will be equal to:

$$\phi_{\text{fine}} = \text{MPPN} \times 45^\circ + (8\phi_{\text{ct}} \mod 360^\circ)/8 = \phi + \epsilon_{\text{ct}}/8$$

(13)

We recognize that in (13) the error of the angle measured is reduced by a factor 8.

D. Harmonic correction and linearization

After dealing with the Amplitude and Phase mismatching, we address the challenge arising from cross-talk between Master and Nonius magnet due to their close distance. After some mathematical manipulations, we can express the angle error due to cross-talk for the Master track as:

$$\epsilon_{\text{ct}} = (k_1 + k_2) \sin(\phi)/2 + (k_1 - k_2) \sin(15\phi)/2$$

(14)

This equation is valid if $k_1, k_2 \ll 1$.

We can identify in (14) the presence of a 1st harmonic and a 15th harmonic in the error curve. In experimental data, we measured $k_1 = 2\%$ and $k_2 = 3\%$ and we observe these harmonics in Figure 2(b). To reduce the contribution of these harmonics we need to solve a minimization problem in the form of:

$$\phi_{\text{har}} = \phi_{\text{fine}} - \sum_{h \in \{1,15\}} j_h \sin(h\phi_{\text{line}} + p_h)$$

(15)

After finding the coefficients $j_h$ and $p_h$ we are left with the non-linearity due to the imperfections of the magnet [Fig.2(c)]. To compensate for this we use a Look-Up-Table (LUT) to store the reference angle information for certain measured angle positions. Then the corrective value is found through interpolation of the LUT points according to the measured position[Fig.2(d)].

$$\phi_{\text{cal}} = \phi_{\text{har}} - f_{\text{LUT}}(\phi_{\text{har}})$$

(16)

IV. REALIZATION OF THE NOVEL ROTARY ENCODER

The realized encoder prototype is shown in Fig. 4. The sensor chip contains two configurable 3-axis magnetic field sensor devices assembled together side-by-side inside a TSSOP16 package. The distance between the sensitive spots of the two dies is 1.9mm. The sensor chip is mounted on a PCB and fixed at a 2mm distance from the magnetic scale surface. The magnetic scale with two tracks, a first external Master track with 8 pole pairs and a second internal Nonius track with 7 pole pairs. Its outside diameter is 24mm with an inner through-shaft opening of 14mm. The scale is mounted on the axis of a commercial stepping motor with reduction gear. We use a separate high-accuracy magnetic sensor with its own magnet and sensor chip as a reference encoder [11]. Both systems are calibrated after assembly to eliminate the impact of manufacturing and assembly tolerances on the angle position output. The angular performance is assessed by the output difference between our system and the reference system with the motor stepping through the full $360^\circ$ circle. As shown in [Fig.2(d)], this difference is lower than $\pm 0.03^\circ$ over the full magnet rotation. The amplitude of the magnetic field captured at a 2mm distance is large enough to deliver 18-bit RMS resolution for 1 ms integration time.

V. CONCLUSION

In this paper, we explain and demonstrate a novel high-accuracy sensing concept based on a multi-axis magnetic sensor combined with a novel dual-track magnet with large and thus strong magnetic poles. With a 2mm nominal air gap between sensor and magnet the system outperforms the current state of the art technologies on the initial placement tolerances and on lifetime wear-out. The system accuracy is better than $0.03^\circ$ over the full $360^\circ$ rotation. This angular encoder is a general-purpose sensing device and may be used in a broad range of angle positioning and motor driver applications.
REFERENCES


