Absolute Encoder Design: Magnetic or Optical?

The angle resolution and accuracy of magnetic position encoders with a diametric magnet and central scanning Hall sensor IC are limited by the feasible depth of interpolation and available field quality. By scanning many sine periods per revolution, the resolution of optical position encoders is much higher. If magnetic pole wheels are used, this approach can also be applied to magnetic systems, but which system is better?

This White Paper describes the key parameters of a magnetic and an optical one-chip encoder, the tradeoffs for both solutions and compares the performance of both encoder designs.

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1) Introduction

The demands made of today's absolute position sensors with regard to measurement accuracy, size, and cost are often extremely diverse. Benefits are only forthcoming where an appropriate system solution can be found that suits the task on hand. Solving the problem is time consuming, as not just the sensor's mechanical construction, but also individual characteristics not reflected in the component datasheet must be accounted for. In turn, the chip development of integrated sensors must be based on a given measurement target, or provide suitable possibilities for adaptation.

Structured masks are generally available for optical scanners to geometrically trim the photodiode array. However, there is no comparable option available for magnetic Hall encoders; these have to either provide a suitable sensor array within the chip or, the other way round, determine the magnet target by the chip layout. In both cases, small dimensions and top performance constitute the usual and challenging design targets [1]. This white paper compares the **iC-MU**, 18-bit, magnetic single-chip Hall encoder in a 16-pin DFN package to the **iC-LNB**, 18-bit, optical encoder in an optoQFN package.

2) Two sensors, two systems

Multichannel, optoelectronic scanner **iC-LNB** captures absolute position data for linear displacement measuring systems or rotary encoders (Figure 1). The synchronized scanning of a 10-bit binary code, in addition to an analog signal track which is evaluated using real-time interpolation, permits high angle resolutions with a small code width. The desired absolute and incremental output resolution is calculated using internal FlexCount® arithmetic allowing any number of pulses between 1 and 65,536 to be selected.

The code width is just 5.2 mm enabling smaller code disks or larger hollow shaft diameters to be used. The accompanying energy-efficient **iC-SN85** LED acts as a compact light source and the iC-LNB monitors and controls the level of illumination. Runtime-critical logic processing also takes place within iC-LNB and more complex tasks can also be performed by an external microcontroller.

Offset and amplitude compensation features have been integrated for the correction of the analog track signals which are also output as differential sine and cosine signals at 1,024 cycles via four output port pins. The interpolation error can be reduced by signal correction to gain more precise position data.

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Position data can be output in parallel (up to 16 bits) or serial using a fast shift register. Clock rates of up to 16 MHz are possible for cycle times of less than 1 µs. The 3.3 V-compatible SPI port allows for device configuration and can also be used to scan position data and diagnostic information (e.g., for when the parity bits on storage monitoring indicate an error). The maximum permissible speed is resolution dependent; 6,000 rpm can be obtained with a resolution of 17 bits (Table 1).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Opto Encoder iC-UNB</th>
<th>Hall Encoder iC-MU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>16/17/18 bit</td>
<td>18/19/20 bit</td>
</tr>
<tr>
<td>Commutation signals</td>
<td>(by MCU)</td>
<td>UVW</td>
</tr>
<tr>
<td>Pole pair supported</td>
<td>(any)</td>
<td>1 to 16</td>
</tr>
<tr>
<td>Max. motor speed [RPM]</td>
<td>12,000/6,000/3,000</td>
<td>24,000/12,000/6,000</td>
</tr>
<tr>
<td>Interpolation</td>
<td>8-bit vector (80 ns)</td>
<td>2x 12-bit vector (160 ns)</td>
</tr>
<tr>
<td>ABZ output [CPR]</td>
<td>1 to 16/3/2768/6/536</td>
<td>1 to 65536</td>
</tr>
<tr>
<td>A/B edge rate</td>
<td>80 ns</td>
<td>FlexCount®</td>
</tr>
<tr>
<td>Serial output</td>
<td>Shift reg., SSI, SPI</td>
<td>BiSS, SSI, SPI</td>
</tr>
<tr>
<td>Sine/cosine output [CPR]</td>
<td>1024</td>
<td>16/32/64</td>
</tr>
<tr>
<td>Parallel output</td>
<td>16 bit</td>
<td>No</td>
</tr>
<tr>
<td>Controller interface</td>
<td>SPI</td>
<td>SPI</td>
</tr>
<tr>
<td>Configuration</td>
<td>by MCU</td>
<td>external EEPROM (I2C)</td>
</tr>
<tr>
<td>Supply</td>
<td>4 bits 5.5 V (15 mA)</td>
<td>5 V (50 mA)</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>-40 to 110 °C</td>
<td>-40 to 110 °C</td>
</tr>
</tbody>
</table>

Table 1: Electrical device characteristics

Hall encoder iC-MU, a fully integrated, single-chip device, is ideal for the scanning of magnetic pole disks, pole wheels, and tapes for motion control applications. Typical applications include absolute position encoders, incremental encoders, and commutation encoders for brushless motors (Figure 2). Position data is captured in real time and is transmitted both through serial interfaces (BiSS, SSI, and SPI) and as an incremental signal. Any number of pulses can again be selected here using internal FlexCount® arithmetic.

A suitable magnetic measurement target has two incremental tracks with pole widths of approximately 1.28 mm, where the number of pole pairs differs by one pole pair across the measurement distance. Two synchronous sine-to-digital converters are used to digitize the Hall sensor signals; these vector tracking converters track field changes at a rate of 8 MSPS with practically no delay.

As there is a phase difference between the two track signals, the integrated mask-programmed signal processor calculates the absolute position based on the Nonius principle. With this principle, movement is not necessary for obtaining absolute position. In rotary applications, a resolution of 19 bits (equivalent to 2.5 arc seconds) is obtained when pole disk MU2S 30-32 is used and allows speeds of up to 12,000 rpm.

By arranging the pole pairs on a magnetic polymer above a flat disk, compact systems can be created which are ideal for direct assembly on the motor flange. The operating distance for parallel plane scanning is approximately 0.4 mm.

Designed as a 16-pin DFN package, iC-MU integrates all of the required encoder functions in the smallest possible space of just 5 x 5 mm. Off-center or off-axis placement permits hollow shafts to be used for high-resolution, magnetic absolute encoders. With a pole disk diameter of 30 mm, hollow shafts of up to 10 mm can be used.
The digital angle position can be output through the A/B/Z interface at any resolution required and with an interpolation factor of 1 to 65,536. Thanks to the internal FlexCount® arithmetic, an entire range of specifications can be catered to by using just one sensor. This allows one design to suit various types of encoder resolutions without varying the measurement target. Fully mounted position encoders can also be programmed on delivery for a minimum time to market. Furthermore, the zero position can also be programmed after assembly.

The **iC-MU** can generate three commutation signals (U, V, and W) to operate brushless DC motors [1], suitable for motors with 1 to 16 pole pairs. This provides a key advantage as the precise electronic adjustment of the U/V/W signals can be made according to the rotor position, making Hall switches common to such systems no longer needed.

As hollow shaft applications can be served, resolvers can be replaced with a compatible assembly. Seen as part of the overall system, this can result in a much cheaper revolver replacement being found, which with its high resolution, permits more precise motor control.

Available interfaces are SPI for direct connection to a microcontroller, BiSS for bidirectional and CRC secured control communication along longer connecting cables, and the SSI as a standard encoder interface. All interfaces permit clock frequencies of up to 10 MHz.

With its data input, **iC-MU** supports multi-slave applications under BiSS for the chain connection of several position encoders with clock-synchronized data capture. If a reference encoder is connected up for installation and startup, the absolute accuracy could be recorded at the highest speed, evaluated, and corrected by a microcontroller, provided the microcontroller can be allowed in the system as an alternative output interface.
3) Linear applications

The **iC-MU** takes absolute measurements of linear distances of 40, 80, or 160 mm at a position resolution of around 160 nm. Two devices can be cascaded for larger distances making the maximum possible absolute distance lengthened by a factor of 2 to 64 (Figure 3). This makes absolute measuring systems for distances of several meters possible at traversing rates of up to 16 m/s.

**Figure 3: Cascading devices for linear measuring systems and larger hollow shaft**

For example, the multi-turn device in Figure 3 determines the absolute position from the middle track with 1,024 cycles and from the upper track with 1,023 cycles. The phase difference is defined across the entire measurement length of 2.6 meters. The lower iC-MU(1) device computes the phase difference between the middle track with 1,024 cycles and the lower track with 992 cycles. This device thus generates position values which are repeated 32 times across the entire measurement length. The multi-turn information from iC-MU(2) is used to differentiate between these 32 segments.

Besides cascading two iC-MU Hall encoders, other multi-turn sensors (e.g., gear stage scanners) can also be used to supply their multi-turn data to iC-MU. The multi-turn data is read in automatically once the supply voltage has been applied and cyclically checked during metering mode.
4) Comparison of both systems for rotary encoder applications

Sensor structures have been chosen for both encoders that allow a small and therefore cost-effective device to be created without sacrificing any measurement accuracy (Figure 4). Although the devices adopt different circuit design approaches, they share similar features regarding performance (Table 1); high absolute resolution in real time and incremental signals with any number of programmable pulses.

![Figure 4: Principal assembly and comparison of size](image)

Other deciding factors must be taken into account when selecting the basic system layout, such as the field of application and required measurement accuracy. Table 2 compares the major sensor-specific parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Optical Sensor Characteristics</th>
<th>Magnetic Hall Sensor Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Principle</td>
<td>coded disc/scale, through beam arrangement</td>
<td>magnet/tape/polewheel opposed to sensor</td>
</tr>
<tr>
<td>Incremental accuracy of target</td>
<td>100 nm ... 1 μm (lithography process)</td>
<td>5 μm ... 30 μm (magnetization process)</td>
</tr>
<tr>
<td>Energizing</td>
<td>by external LED (Ptot 20 mW)</td>
<td>by target (Br &gt;220 mT)</td>
</tr>
<tr>
<td>Typ. Signal Level</td>
<td>30 nA ... 1 μA</td>
<td>2 mV @ 20 kA/m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 mV @ 50 kA/m</td>
</tr>
<tr>
<td>Typ. Signal Level Temp. Co.</td>
<td>-40 ... -80 % @ +100 K degradation of LED efficiency</td>
<td>-60 % @ +100 K</td>
</tr>
<tr>
<td>Typ. Signal Offset (referred to signal ampl.)</td>
<td>50 %</td>
<td>25 ... 250 %</td>
</tr>
<tr>
<td>Signal Frequency</td>
<td>&gt; 1 MHz possible</td>
<td>generally limited to &lt; 50 kHz</td>
</tr>
<tr>
<td>Benefits</td>
<td>high code density, high code accuracy</td>
<td>robust</td>
</tr>
<tr>
<td>Disadvantages</td>
<td>sensitive to contamination, high alignment require</td>
<td>raw code density, medium code accuracy</td>
</tr>
</tbody>
</table>

Table 2: Comparison of optical and magnetic sensor characteristics
With faultless electronic evaluation measurement, target pitch errors are shown as absolute measurement errors. For example, if a typical magnetism accuracy of 15 µm is compared with an optical code disk line accuracy of 300 nm, the difference is obvious. With the help of the scanning radius (Table 3), this value can be converted into the angle error; in theory, this is approximately 0.07° (252 arc seconds) for the magnetic system and approximately 0.0018° (6.4 arc seconds) for the optical system. Other sources of error dominate the optical system which gives a total error of 0.011° (40 arc seconds).

Users opt for a specific system according to its key advantages and disadvantages. For instance, the magnetic system has multiple strengths including its immunity to environmental influences, such as dust, oil, and moisture. It also allows a high operating distance which can allow axial play and generous mounting tolerances for ease of assembly. A flat design is also possible as the system has no need for LEDs or optics.

For the chip designer, the sensor signal plays a major role when developing the circuit. The optical sensor reads the shaft angle with the light distribution and intensity generated by the optical code disk. Imaging errors must be avoided for good signal contrast. To combat this, special encoder LEDs that provide homogenous, collimated light are suitable here (iC-SN85). This provides photocurrents of approximately 200 nA to be generated, which at a transimpedance of 1 MΩ, produces signal voltages of 200 mV.

For the magnetic sensor, the field components vertical to the chip are of interest. The Hall Effect provides a directed voltage of typically a few mV depending on the magnetic field strength towards Z. As one single Hall element only senses the distance to the magnet, several elements record the Z field at various positions so that the angle information can be determined by evaluating local gradients. The Hall sensor must practically ‘feel’ the bended near field of the magnetic measurement target. As the polarity of the Hall voltage follows the field direction, the magnetic north pole can be distinguished from the south pole, making it possible to determine the absolute angle within a pole pair.

At best, the Hall elements can only generate 10 mV from the magnetic pole wheel's magnetic field. In order to reach the resolution of the optical system, the signal bandwidth must be restricted. For the purpose of signal conditioning, the Hall elements are evaluated with a fixed scanning frequency and filtering. The Hall sensor acts as an analog low pass with a cutoff frequency of approximately 20 kHz. However, in practice, the longer signal propagation delay is irrelevant.

### 4.1) Assembly tolerances and compensation features

Both systems use fast real-time interpolation circuitry as vector tracking converters with arc tangent conversion. Regarding offset, amplitude matching, phase accuracy, and harmonic-free waveforms, the converters are reliant on the quality of the analog sine/cosine sensor signals. However, deviations from the ideal mounting position cause signal errors which reduce the interpolation accuracy. So that measurement accuracy is ensured, both systems permit the static correction of mounting-induced signal errors and correctively adjust the analog signal path through several integrated D/A converters.

Electronic signal calibration increases the degree of mechanical freedom (Table 3). The iC-MU also allows the sine/cosine phase shift to be corrected which can also compensate for a radial alignment error. Once installed and calibrated, the selected operating point is maintained by automatic functions. For the optical encoder, the integrated LED power control compensates for the drop in
LED efficiency caused by a rise in temperature. The Hall encoder has a gain control to compensate for changes in field strength when the distance to the magnetic pole disk varies.

4.2 Possible sources of error

As a matter of principle, errors should be taken into consideration. Here, fundamental observations have been made taking the Hall encoder as an example. If the relevant code geometry of the measurement target is taken into account, these observations also apply to the optical system as well.

Should the Hall encoder not be aligned on the ideal scanning radius, it will distort the sine signals. If there is a radial shift ($\Delta R$) the device does not detect the measurement target or the segmented poles at the correct pitch (Figure 5B). Here a constant shift error between the sine and cosine signal from the Hall scanning then occurs. However, it is possible to compensate for this using the integrated signal correction facility.

![Figure 5: Typical alignment errors](image)

**Formula 1:** Measurement error due to radial alignment error.

\[
ERR_{RAD} = 90^\circ \cdot \left( \frac{D + \Delta R}{D} - 1 \right)
\]

Formula 1 gives the electrical phase error of the sensor signals with $D$ as the scanning diameter and $\Delta R$ as the radial shift. For example, referenced to the electrical sine periods, a Hall encoder radial
shift of 0.1 mm produces a phase error of 0.35° at a scanning diameter of 26 mm. If the mechanical angle error is then to be calculated per rotation, the result must be divided by the number of pole pairs. A standard disk has 32 pole pairs; this amounts to a mechanical angle error of 0.01°.

On the other hand, a device with a tangential shift (\(\Delta X\)) has a more or less identical influence on the electrical phase angle of both track signals (Figure 5A). The pitch changes only slightly and the phase difference for the calculation of the absolute value remains practically unchanged.

However, an eccentrically mounted measurement target (\(\Delta E\)) causes the device to wobble (Figure 5C). The smaller the diameter, the more the pitch of the measurement target changes. A long-wave error occurs that reduces the absolute measurement accuracy.

\[
ERR_{WOB} = 360° \times \frac{\Delta E}{2 \times p}
\]

Formula 2: Measurement error due to eccentricity.

The eccentricity error is accrued from the shift of the measurement target \(\Delta E\) to the rotation axis and the pole width of the measurement target \(p\). Accordingly, an eccentricity error of 10 µm leads to a phase error of 1.4° referenced to the sine period, or to an angle error of 0.05° referenced to the mechanical rotation (for dimensions, see Table 3; calculation for the standard disk with a scanning diameter of 26 mm, a pole width of 1.28 mm, and 32 pole pairs). When determining the phase difference for the Nonius calculation[2], the eccentricity error plays only a minor role as it influences both signal tracks to the same degree.

Over a complete mechanical rotation of 360°, the achieved angle accuracy is better than +/-0.1°. The accuracy of the magnetization has systematic limitations; if individual poles vary, slight shifts are the result. This effect is visible at around 45° and 90° in the given measurement (Figure 6). The mechanical axis connection to the reference encoder can also introduce a centering error which can become visible as a slight long-wave deviation through one rotation.

![Figure 6: Angle accuracy of an iC-MU magnet system](image-url)
Figure 6 shows the measured angle accuracy of an iC-MU magnet system with magnetic pole wheel MU2S 30-32; the magnetic period is equal to an angle of 11.25°. Here, the math and graphic functions in the BiSS reader software ease comparison of the measurement data.

5) Conclusion: Which is better?

There are many benefits that speak for magnetic sensor technology: excellent reliability, a high resistance to shock and vibration, a lack of breakable parts, and insensitivity to dirt and moisture. Single-chip Hall encoder iC-MU permits hollow through shafts to be used and achieves a position resolution, which to date, was only achieved by optical encoders. However, if the application demands top measurement accuracy, optical sensors such as the iC-LNB have the advantage, but do require more costly assembly space. But, given their small, enclosed optoQFN and optoBGA assemblies, single-chip optical encoders are a viable alternative. To these points, defining which is better must be determined by the design requirements of the application itself.

6) Literature

[1] Boost Performance in Motion Control Systems with One-Chip Encoder, White Paper iC-Haus

Introducing iC-Haus

iC-Haus GmbH is one of the leading independent German manufacturers of standard iCs (ASSP) and customized ASIC semiconductor solutions. The company has been active in the design, production, and sales of application-specific iCs for industrial, automotive, and medical technology for over 25 years and is represented worldwide. The iC-Haus cell libraries in CMOS, bipolar, and BCD technologies are fully equipped to realize the design of sensor and actuator iCs, laser/opto iCs, magnetic Hall and optical encoder iCs, driver iCs, and other mixed-signal components. The iCs are assembled either in standard plastic packages or using iC-Haus chip-on-board technology to manufacture complete microsystems, multichip modules, and optoBGA™, the latter in conjunction with sensors.

Additional information is available at http://www.ichaus.com.