Choosing a position sensor in motor control

Introduction

Are there still position sensors in motors, since the trend is to go “sensorless”? The full answer to this question is rather convoluted, but basically, position sensors are here to stay. There are applications such as power tools where a sensorless design with a brushless-DC motor block commutation or a field-oriented-control (FOC) brushless-AC motor works without any rotary angle sensor. But the reality is that end equipment such as industrial and humanoid robots, autonomous mobile robots, and linear motor transport systems absolutely need rotary angle or linear position sensors.

Using a position sensor with brushless motor control

Position sensors are not just used for the commutation of stator currents with brushless-DC or brushless-AC motors, but also for speed and position control. Industrial multiaxis robots often include a gear between the motor shaft and robot axis. A rotary angle sensor coupled with the motor shaft not only needs to sense the rotor angle, but also count the turns of the motor shaft to control the equivalent absolute angle position of the corresponding robot axis. Depending on the application, the type of encoder will vary.

Incremental and absolute encoders

Incremental encoders typically use ABZ digital or analog unidirectional interfaces, where two quadrature-encoded digital pulse train signals (A and B) or two analog Sin/Cos signals (A and B), allow for a low latency relative angle measurement with high resolution from approximately 10 bits up to 28 bits. An optional index (Z or I) enables absolute mechanical angle information. Incremental encoders do not provide an absolute angle at startup, and need to turn up to one revolution before the index occurs. Therefore, these encoders fit well in speed-variable applications that need very low latency (<1µs) but do not need an absolute angle at startup.

Conversely, absolute single- or multiturn rotary encoders offer an absolute angle position at startup. They offer a bidirectional **RS-485** interface with vendor-specific protocols, and enable time-triggered angle measurement as well as information such as rotary speed and number of rotary turns. The angle resolution typically goes from 10 bits to >30 bits, with a latency as low as 10µs to meet a wide range of industrial applications. The position resolution is typically the data format, which transmits through the digital interface. For example, an angle with a 20-bit integer format has a resolution of $360/2^{20}$; 0h = 0 degrees and 0xFFFFF = 360 degrees-$360/2^{20}$. Overall system noise is significantly higher than quantization noise; the effective number of bits (ENOB) characterizes this effect.

Equation 1 calculates the ENOB of the angle with the standard deviation of the angle measured in degree:

$$\text{ENOB [bit]} = (20 \times \log10(360/\text{stdev(angle)}) - 1.76)/6.02 \quad (1)$$

The root mean square of the angle noise signal equals the standard deviation (1 sigma). **Figure 1** illustrates the angle accuracy; the related angular error is larger than the standard deviation. The angle accuracy not only depends on the peak noise, which often uses the 6-sigma value, but also the nonlinearity over one revolution.

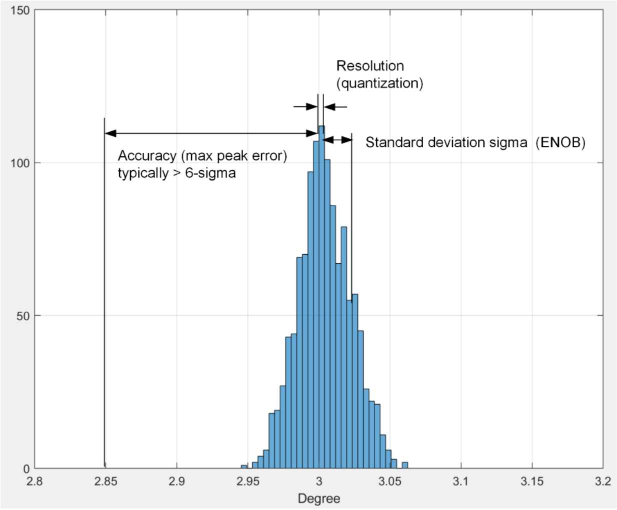

Figure 1. *Static angle distribution.*

FOC motor-control techniques and requirements for encoders

The FOC method shown in **Figure 2** is a high-performance technique that controls the resulting stator current vector according to the rotor magnetic flux angle to maximize torque with permanent-magnet synchronous motors. FOC enables smooth torque with fast transient response from standstill to high-speed operation. Accurate and low-latency measurement of the rotor magnet field angle will decompose the three stator-phase currents (i_U, i_V and i_W) into a rotor magnetic field-oriented coordinate system, with i_q equal to the torque-generating current and i_d equal to the field-weakening current.

In end equipment such as humanoid robots, the absolute rotary angle is typically measured at an accuracy from 1 degree to 0.1 degrees, an ENOB from 12 bits to 15 bits, and sample rates from 8kHz to 32kHz. The rotary angle is sensed simultaneously with the motor-phase currents. A low-latency angle measurement of <20µs enables enough time for the microcontroller (MCU) to run the control algorithms and update the pulse-width modulator (PWM) for the next PWM cycle.

It is possible to integrate rotary angle sensors into the motor housing, as in most humanoid robots, or in separate housing for mounting onto the motor shaft. Both cases require operation at high temperatures – often up to 125C ambient. In humanoid robots, where the control MCU is located close to the rotary encoder, 360-degree angle sensors such as TI's TMAG6180-Q1 anisotropic magnetoresistive (AMR) sensor offer a cost-efficient and low-latency interface.

Unlike rotary motors, linear motor-based transport systems require absolute linear position sensing, but still apply FOC for maximum torque. A 12-bit position resolution with <100µs latency is often sufficient.

In addition, achieving International Electrotechnical Commission 62061 or International Organization for Standardization (ISO) 13849 functional safety in industrial machinery requires safety-certified encoders determined by the safety integrity level or performance level, as well as additional diagnostics with the position sensor to detect random hardware faults. In automotive applications, systems designed according to ISO 26262 run diagnostics during system startup, whereas industrial systems require continuous diagnostics during normal operation, since they often run 24/7.

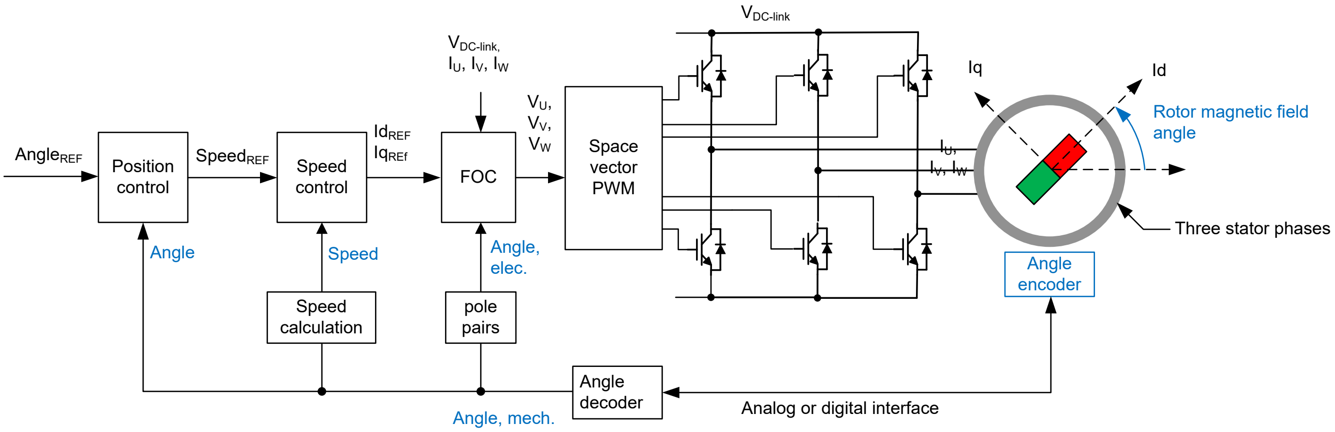

Figure 2. *Cascaded position, speed and FOC.*

Position sensor technologies

The predominant types of position sensors are optical, magnetic, inductive or capacitive. Optical sensors typically offer the highest resolution (although magnetic and inductive sensors are more reliable), and may offer a lower total system cost. In industrial or automotive systems, large current flows in nearby wiring necessitate a sensor technology such as inductive that is immune to magnetic stray fields. Capacitive sensors typically have lower resolution than inductive and magnetic sensors and are not as common.

For cost-sensitive systems in harsh environments (for example, high temperatures caused by motor integration), TI offers magnetic and inductive position sensors.

Magnetic position sensors

Magnetic encoders enable a cost-efficient method to detect rotary or linear movement while providing immunity in harsh environments that may include dust, oil and water. Magnetic position sensors detect magnetic field changes, convert them into electrical signals, and generate output signals. There are a variety of magnetic position sensor technologies, including Hall-effect, AMR, tunneling magnetoresistance (TMR) and giant magnetoresistance (GMR). **Table 1** lists each sensor's benefits and drawbacks.

Parameter	Hall Effect (without a magnetic flux concentrator)	Hall Effect (with a magnetic flux concentrator)	AMR	GMR	TMR
Operation region	–	–	Saturation	Saturation	Saturation
Cost	Least expensive	>Hall	>Hall	>Hall and AMR	Most expensive
Angles measured	XYZ	XYZ	XY	XY	XY
Angle range (degrees)	0-360	0-360	0-180 (the TMAG6180-Q1 extends to 360)	0-360	0-360
Latency	High	High	Low	Low	Low
Angle error (degrees)	<1.2 [1]	<1 [1]	<0.6 [1]	>1 [2]	<0.6 [2]
Magnetic flux density range (limits magnetic air-gap distances) (in milliTeslas)	0-300	0-70	>20-unlimited (the TMAG6180-Q1 tolerates up to 1,000)	20-120	20-120

Table 1. *Comparison of magnetic sensor technologies: Key features and specs.*

1. After gain and offset calibration.
2. After gain, offset and orthogonality calibration

Linear position example with a 3D Hall-effect linear sensor

In linear motor transport systems with fast-moving payload carriers zipping by at 5m/s to 15 m/s, a 12-bit position resolution with latency <100µs and sample rates ≤8kHz is often sufficient, while multiple position sensors connect to a single MCU through a high-speed Serial Peripheral Interface (SPI) bus, as shown in Figure 3.

The TMAG5170 3D Hall-effect sensor provides three main advantages – accuracy, low latency and board placement flexibility. The sensitivity error drift across the full temperature range is less than 2.8%. A 10MHz SPI enables low latency. Additionally, onboard 3D sensing elements enable configurable XY, YZ or XZ sensing directions, enhancing flexibility when placing the sensor in relation to the magnet.

The Accurate Low-Latency Linear Position Sense Reference Design with Quad 3D Hall-Effect Sensors uses the TMAG5170 placed at 25mm intervals for precise, low-latency linear position sensing. A C2000™ MCU reads out the magnetic Z and X field data from all four TMAG5170 sensors for sample rates ≥8kHz, and calculates the moving magnet position with an error <0.15mm and latency <57.5µs.

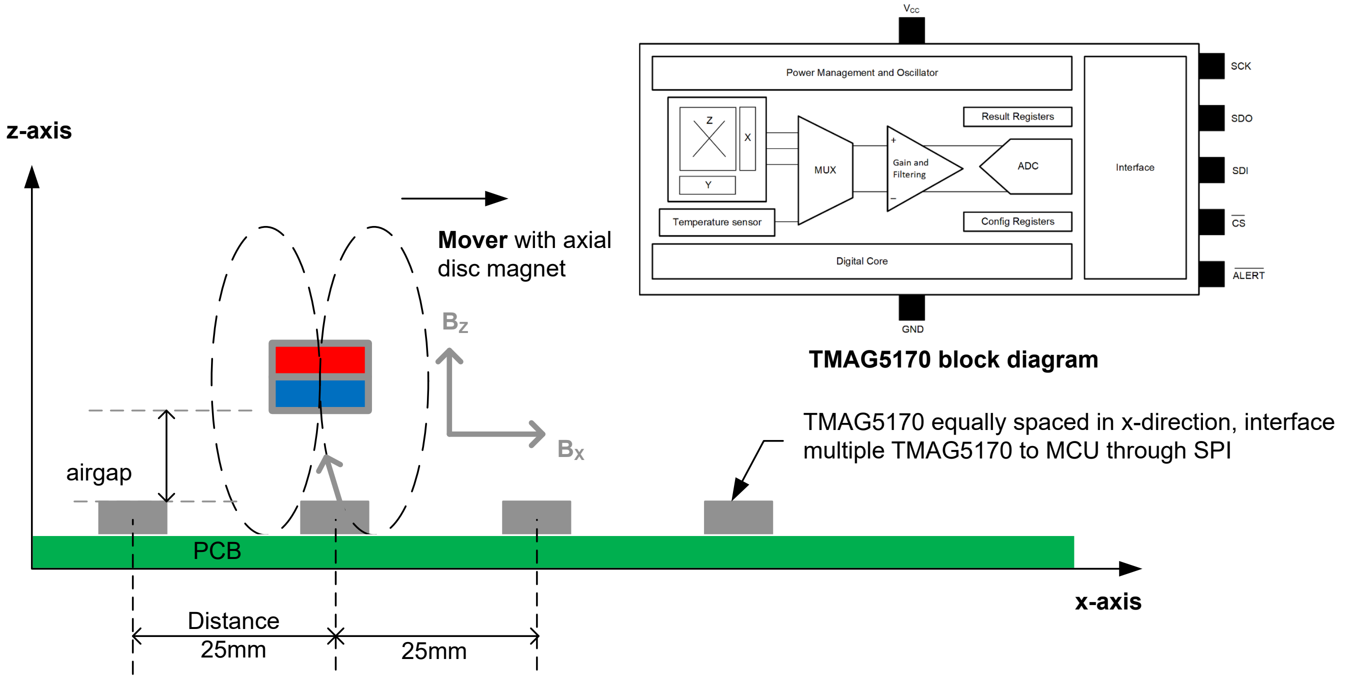

Figure 3. *The TMAG5170 in a linear motor transport system.*

Rotary angle example with an AMR sensor

The AMR sensor comprises four magnetoresistance Wheatstone bridges, where the voltage differences of two bridges' output terminals will reflect the external magnetic field magnitude.

Compared to Hall-effect sensors, AMR sensors have higher frequency operation and a higher signal-to-noise ratio (SNR). Compared to GMR and TMR sensors, AMR sensors have a relatively negligible orthogonality error. In applications such as servo drives that need a high-accuracy encoder, AMR sensors are often preferable given their higher magnetic field tolerance, yielding overall better immunity.

The TMAG6180-Q1 2D AMR angle sensor measures magnetic fields and produces two differential (or single-ended) voltage outputs proportional to those magnetic fields. The <2µs latency of the TMAG6180-Q1 also minimizes angle errors caused by high-speed movement. Integrated Hall-effect switches produce two digital quadrant outputs (Q0 and Q1), thus extending the angle detection range to 360 degrees. Together with the sine and cosine waveforms, the Q0 and Q1 digital outputs are enough to determine the absolute rotary angle. **Figure 4** is a functional block diagram of the TMAG6180-Q1, while **Figure 5** shows the output waveforms.

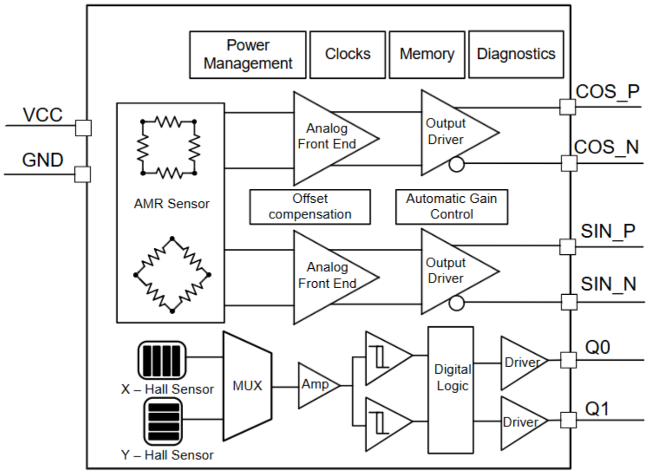

Figure 4. *TMAG6180-Q1 block diagram.*

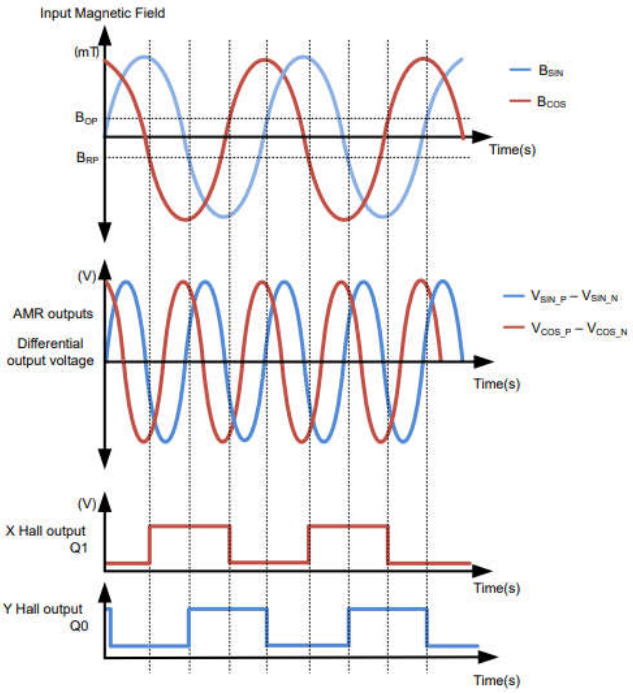

Figure 5. *TMAG6180-Q1 output waveforms.*

For better accuracy, the MCU should integrate a high-speed, high-ENOB analog-to-digital converter, be able to run a digital filter such as a finite impulse response filter to eliminate signal-chain noise, and have an additional compensation algorithm to eliminate errors caused by mechanical tolerances and the signal chain's gain and offset mismatch. The **High-Resolution, Low-Latency, Compact Absolute Angle Encoder Reference Design with AMR Sensor** is a small-form-factor (3cm diameter) reference design with the TMAG6180-Q1 and **MSPM0G3507** MCU, with integrated dual 12-bit ADCs up to 128X oversampling and a math accelerator to help improve efficiency and reduce system cost. The system achieves an angle measurement with a 94.7dB SNR equivalent to 15.4 ENOB and an angle error below 0.05°, as shown in **Figure 6**.

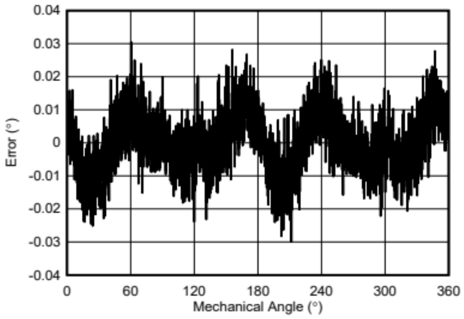

Figure 6. *Angle error over one revolution with offset calibration at 25°C.*

Inductive position sensing

Inductive angle sensors offer some advantages over magnetic sensors. Their main advantage is inherent magnetic immunity to external DC fields. Additionally, inductive technology requires only a conductive metal target – and no magnet – to be in proximity with the sense coils in order to determine the metal target position as it spins about the shaft.

Figure 7 shows an absolute encoder using two **LDC5072-Q1** inductive sensors, one for each sense coil. Nonius encoding requires two sense coils: the outer sensor target may have 16 metal positions; the inner target, 15. Evenly spacing both targets forces a unique pattern across a complete rotation, providing the ability to know the absolute angle with high precision.

Mechanical resolvers perform the same function as absolute inductive encoders, but have size and weight disadvantages. It is possible to build inductive encoding solutions directly on a printed circuit board, while resolvers are built on thick steel laminations with copper-wire-wound teeth. Resolvers are also expensive to build because of their mechanical structure. Finally, power consumption can be an issue, as resolvers easily consume 500mW of power (assuming 70mA at $7V_{RMS}$).

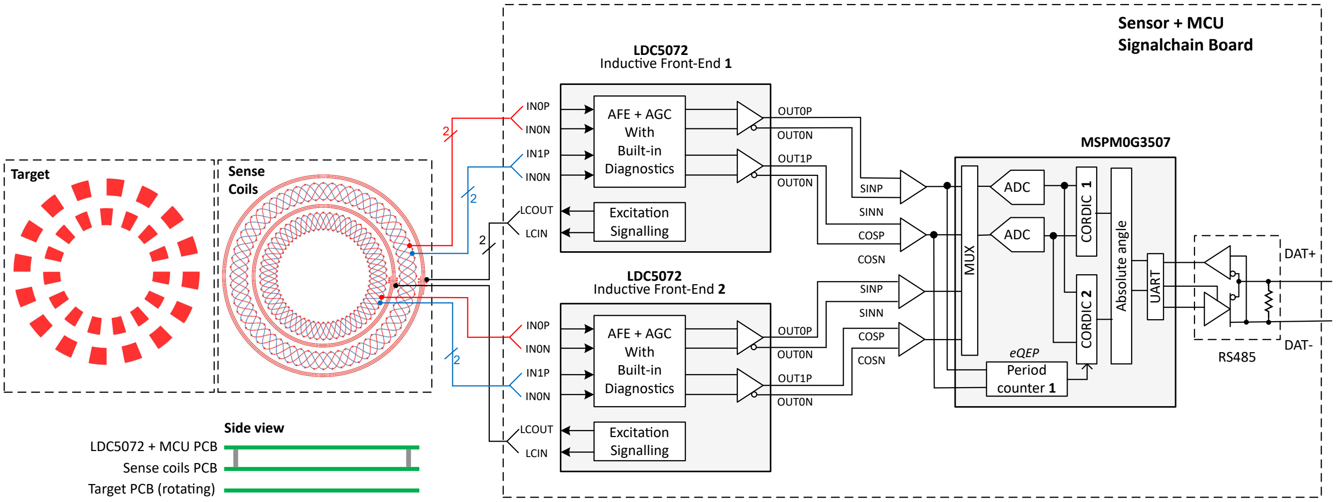

Figure 7. Absolute encoder with the LDC5072-Q1.

Conclusion

Selecting the most appropriate position sensor depends on motor-drive system requirements, with cost, performance, operating temperature and size the most important trade-offs to consider. Another aspect is whether to add additional diagnostics or functional safety to an industrial or automotive solution. Each motor and encoder type have their own requirements, so it's important to choose the best sensor type for the application.

Additional resources

- Read the application brief, **Motor Control in Humanoid Robots**.
- Check out the **Absolute Angle Encoder Reference Design with Hall-Effect Sensors for Precise Motor Position Control**.

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