How Position Sensors Enable Innovation in Automotive and Industrial Applications

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This paper examines trends in position sensing and associated design challenges and solutions in automotive and industrial applications.

At a glance

1 Trend No. 1: The electrification of systems

Position sensors measure complex angles with high accuracy throughout evolving automotive systems, including electric motors and electric power steering (EPS) systems.

2 Trend No. 2: The need for increased reliability and safety

Shifting from mechanical systems to magnetic sensors reduces wear and tear while increasing the need for functional safety.

3 Trend No. 3: The miniaturization of overall end-product form factors

High-sensitivity magnets and greater integration address trade-offs of miniaturization, including lower accuracy and resolution.

4 Trend No. 4: The transition from rare earth materials to ferrites

Ferrite is an abundant and cost-efficient alternative to rare earth materials in magnetic sensors but requires features to compensate for its reduced magnetic field and temperature drift.

Even if you have been behind the wheel for a while, you probably have not noticed much difference in the steering wheel or even the braking system from one vehicle to another. This is by design. Handling improvements make it easier for drivers, but in general, the feel of these systems has remained relatively the same, in order to ensure that the user experience also remains the same regardless of model year.

The technologies used in these systems have evolved over time, however, and position sensors have been a big part of this evolution.

Many types of position sensors are available today, including ultrasonic, optical, magnetic, capacitive and inductive. Position-sensing integrated circuits (ICs) detect the movement of an object and transduce the input signal into an electrical signal suitable for microcontroller (MCU) processing and control. In the context of this paper, when referring to a position sensor, you can assume that the IC sensor uses Hall-effect, anisotropic magnetoresistor (AMR) or inductive technology. Figure 1 illustrates the basic functionality of these three sensor types.

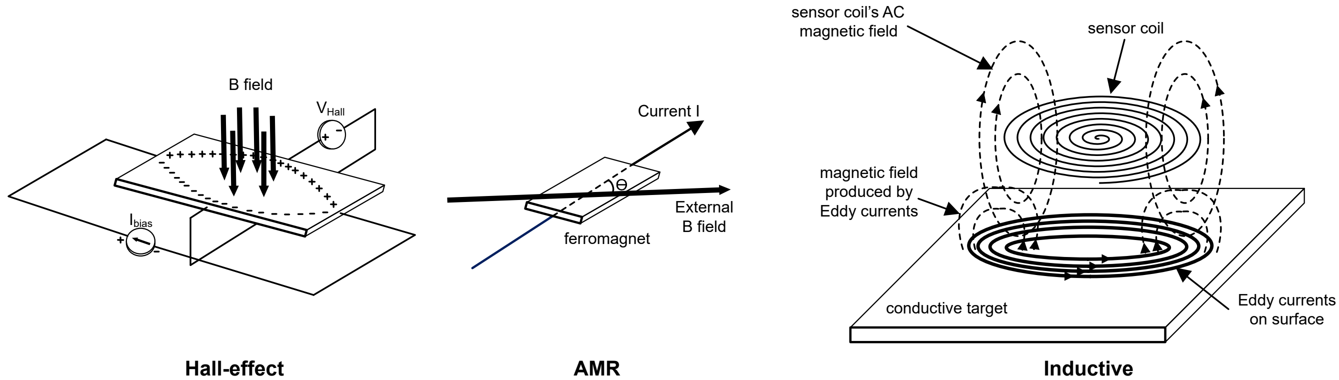

Figure 1. *Hall-effect, AMR and inductor sensor functionality.*

In the Hall-effect technology, a current is induced into a ferromagnetic material. Applying a magnetic field (labeled a B field, see **Figure 1**) produces a Hall voltage perpendicular to the current flow.

An AMR sensor's resistance decreases with the applied magnetic field. Additionally, the anisotropic aspect means that the AMR sensor is dependent on the direction of the magnetic field applied.

Inductive sensors use sensor coils (inductors) to produce magnetic fields of their own, which couple with the magnetic fields produced by eddy currents developed on metal targets.

This white paper discusses four current trends in position sensing: the electrification of systems, the need for increased reliability and safety, the miniaturization of overall end-product form factors, and the transition from rare earth materials to ferrites. Designers can benefit from understanding the latest in IC sensor improvements, which are now far more accurate and sensitive; able to provide higher resolution and more functionality; and consume less power than before, while being available in ever-smaller packages.

Trend No. 1: The electrification of systems

Autonomous driving, demand for a better user experience, and the push to reduce greenhouse gas emissions have led to the increased electrification of vehicles, necessitating the inclusion of more semiconductor devices in automobiles, including position sensors. This is our first trend.

Thermal efficiency is of the utmost importance for electric vehicles (EVs). Electric pumps circulate coolants such as oil and water glycol throughout the vehicle, keeping various system-level temperatures in check. Multiple electronic control units (ECUs) control these systems. Once the EV is on, an MCU can determine if enough coolant has been pumped to a specific system by monitoring the temperature. High-resolution Hall-effect sensors used in electric pump incremental rotary encoders enable the microprocessor to respond to thermal events much more efficiently. Devices such as the high-bandwidth **TMAG5110-Q1** offer low-latency outputs while also providing high sensitivity capabilities, giving designers more flexibility in sensor placement.

Steering column designs vary from one original equipment manufacturer (OEM) to another, but the most popular implementation connects multiple control modules and manages several switch and button control functions such as blinkers, headlights, wipers, cruise control and scroll wheels. Previously mechanically implemented for autonomous driving or comfort reasons, these features have become electrical solutions that also incorporate magnetic functionality. For most applications, the **TMAG5170D-Q1** and **TMAG5173-Q1** have the ability to measure complex angles with high accuracy, allowing Automotive Safety Integrity Level (ASIL) B or even ASIL D system-level compliance.

Figure 2 shows an OEM steering column control module retrofitted to replace mechanical contacts with 3D Hall-effect sensor development boards.

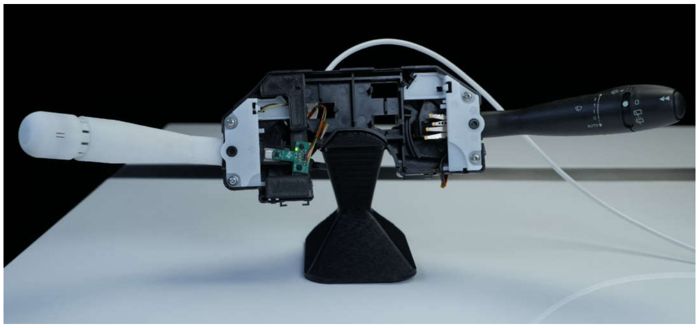

Figure 2. *Steering column retrofitted with TI 3D sensor evaluation modules.*

Motor position sensing is a fundamental aspect of an electric motor design to ensure that it is running at optimal efficiency. As power efficiency requirements increase, so have the performance expectations of the position sensors that monitor with high precision the exact rotational position of the motor shaft. By knowing the position of the motor, the microprocessor and power stage within a traction inverter can provide the exact amount of current to the motor coils to manage torque more efficiently. The challenge is to measure the angle with the highest accuracy possible (approximately 0.5°) across the full rated temperature range while the motor is running at full speed (100,000 rpm or higher). The LDC5072-Q1 inductive sensor (also known as an inductive resolver) is appropriate for this task given its inherent immunity to stray magnetic fields. Another bonus for this technology is that there is no need for magnets. Figure 3 shows an electric motor with a traction inverter mounted on top.

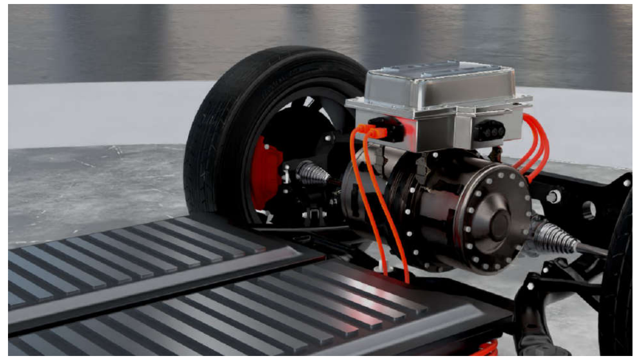

Figure 3. *Electric motor and traction inverter.*

Vehicle electrification has created many use cases for position sensors, with electric power steering (EPS) arguably the most prevalent. As EPS continues to evolve, the accuracy and resolution requirements have increased for motor position sensors as well as for wheel position sensors. In an EPS system, the TMAG6181-Q1 can provide the motor rotor position with a minimal angle error of 0.4° and support up to 100,000rpm with latency less than 2µs, while the TMAG5170D-Q1 can help determine the 3D position of the steering wheel. The steering wheel angle sensor sends data to the ECU for optimal vehicle operation and control.

Electrification involves not only automobiles but also transportation systems such as e-bikes, pedal electric cycles and e-scooters. While these products have been around for a number of years, there are new advancements in motor commutation, cadence and wheel speed sensing that require position sensors. There are a couple of new trends in e-bikes worth noting:

- Motor commutation previously occurred with a three-latch brushless-DC motor implementation, but most e-bike motor providers now monitor the motor with high-speed, high-precision angle sensors. The TMAG6180-Q1 AMR sensor is great for this application because of its high-accuracy angle measurement (0.1° at room temperature).

- Using a Hall-effect latch such as the **TMAG5115** for wheel speed and cadence monitoring provides low jitter and fast response times, enabling higher-precision speed and direction measurements. In the past, Hall-effect switches were predominantly used for wheel speed detection.

Trend No. 2: The need for increased reliability and safety

While developing industrial, personal electronics and automotive systems, designers are concurrently thinking of how to make their designs more reliable in order to increase their product's life span. A rather recent trend for position sensing involves a couple of different methods to achieve this goal – moving from mechanical systems to magnetic sensors and the acceleration of functional safety compliance.

Magnetic sensors eliminate constant mechanical wear and tear caused by friction. In cordless power tools, for example, the mechanical trigger design is the most prevalent failure mode, and manufacturers typically have a target of >200,000 cycles over the life of the product. The lifetime cycle targets vary by end product, but the expectation is that a magnetic-based solution has the potential to extend product life. **Table 1** summarizes a few of these examples.

Application	Existing technology	Benefit of using a position sensor over a mechanical sensor	Recommended technologies
Triggers for cordless power tools and medical power drills	Mechanical potentiometer designs	• Increased life cycle of the trigger mechanism. • You can place the sensor directly on the main circuit board without the need for an external module.	Hall effect and inductive
Refrigerator door open-and-close detection	Microswitches	• Provides an aesthetically looking door interface with no visible switch.	Hall effect
Gaming controllers and keyboards	Mechanical designs	• Provides the ability to detect the amount of force being used on a specific button or trigger. • In gaming controllers, helps prevent drift over time.	Hall effect and inductive
Steering systems: steering stalk shifters, steering columns, knobs and e-shifters	Mechanical designs	• Provides a steer-by-wire method using electrical position signals with no wear and tear.	Hall effect, inductive and AMR
Braking systems	Mechanical hydraulic designs	• Electronic brake-by-wire provides greater safety with fast response times.	Hall effect and inductive

Table 1. *Examples of industrial, personal electronics and automotive system applications moving to contactless methods.*

The advent of vehicle electrification and the addition of more electronics into almost every electrically powered product has accelerated the need for functional safety. The automotive industry follows International Organization for Standardization 26262 for automotive products, while the industrial sector follows International Electrotechnical Commission 61508. Functional safety aims to protect users by eliminating unreasonable risk caused by the malfunctioning of electronic systems. If the system fails, it should default to a predictable and known state.

There are several categories of automotive and industrial functional safety standards based on severity or consequence (how much injury could occur), exposure or likelihood (how likely it is), and controllability (how much control does the user have). A couple of examples in automotive systems that require the highest functional safety rating are EPS or shifter systems (e-shifters). Both systems often require the highest automotive rating (ASIL D) given the risks associated with their failure.

To comply with ASIL D requirements, system developers typically use redundant sensors or solutions that have two identical but independent sensors that are internally isolated from each other. There is a very low probability that both sensors will fail. These types of high-performance systems also need high-accuracy angle detection. The **TMAG5170-Q1** 3D sensor and its dual-die equivalent, the **TMAG5170D-Q1**, have built-in diagnostics features for both device and system levels.

Trend No. 3: The miniaturization of overall end-product form factors

The third trend relates to the miniaturization of magnetic system designs. The reasons to reduce the size of a product are many – cost, better user experience, sleeker look and feel – and doing so often involves reducing the magnet size or using multiaxis sensors. Another approach with little risk is to reduce board size by migrating to the smallest and most integrated components that the manufacturing flow will allow. To address these concerns, Texas Instruments offers small-size solutions in extra-small outline no-lead (X2SON) ($1.1mm^2$ by $1.4mm^2$) and wafer chip-scale packaging (WCSP) ($0.8mm^2$ by $0.8mm^2$). One example of high integration in a small package is the **TMAG3001**, which is a 3D linear solution available in WCSP.

Reducing magnet size poses a problem because it means a weaker magnetic field, therefore requiring magnetic sensors with high sensitivity. High-sensitivity solutions such as the **TMAG5231** make it possible to use smaller magnets. Alternatively, you could place the magnet closer to the sensor to get an accurate measurement without a high-sensitivity solution. For weaker magnetic fields, devices with a high signal-to-noise ratio (SNR) can help ensure the most accurate measurement possible. The **DRV5055** and **TMAG5253** may provide as much as 70dB of SNR.

The general trend in the size reduction of end equipment is challenging for any position sensor, regardless of technology. Inductive sensors use metal targets to detect the position or presence of an object and, by meeting the guidelines as specified in data sheets, make it possible to achieve form factors as small as the side button on a fitness wristband. The main system-level requirements for inductive sensors are to have the sense coil the same size as the target, and to be within 10% to 20% of the diameter of the coil. Examples of applications trending toward smaller sizes include medical insulin pumps, surgery endoscopic tools and pneumatic cylinders in factory automation.

It is also possible to achieve miniaturization by reducing the number of components. For example, the implementation of tamper detection in an e-meter (or smart e-locks and door and window sensors) involves the use of a single 3D linear sensor instead of three Hall-effect switches or linear devices to detect tampering from large external magnets that render the e-meter incapable of accurately measuring electricity usage. Designers are using 3D magnetic sensors to improve their e-meter designs with lower power operation and adjustable external magnetic field detection devices such as the **TMAG5273**. With such devices there are other benefits of miniaturization with fewer components, including a single digital interface instead of multiple outputs, lower printed circuit board assembly costs and higher configurability in magnetic sensitivity.

When miniaturizing a system with fewer components, one challenge that incremental and absolute encoder designers have is how to improve the resolution of their products, which includes choosing between digital or analog output solutions. An incremental encoder monitors the speed or rate at which the magnet is moving, and also the direction. An absolute encoder can do this and know its exact position at all times with high resolution.

When incremental encoder designers use digital output Hall-effect latches, the resolution strictly depends on the number of magnetic poles in the system.

Achieving higher resolution requires higher-pole-count ring magnets, and as pole dimensions get smaller, the magnetic fields produced by the magnet are inherently weaker, forcing designers to place the sensor even closer to the magnet or to use a sensor with higher sensitivity. At this point, most designers switch over to a single-chip solution with dual integrated latches such as the **TMAG5111**. It is important to make sure that the dual-latch solution has built-in 2D latches, which allows for the greatest flexibility in monitoring any two axes in a 3D space. Higher-resolution designs require absolute encoders with linear sensors. A single 3D linear sensor with angle measurement capability is the final migration step for high-resolution absolute encoders. Note that this implementation measures only two axes, but most 3D linear sensors have the flexibility to configure any two axes. An added bonus to using a 3D sensor is having the capability to detect a push function. **Figure 4** shows trends in encoder designs.

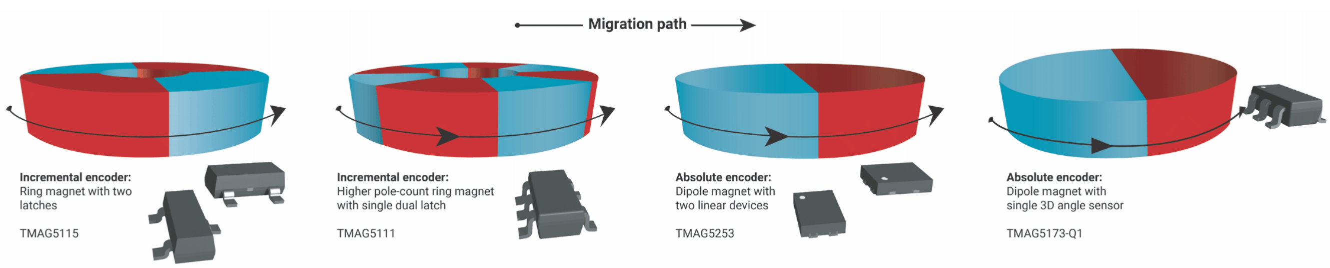

Figure 4. *Higher-resolution trends in encoders.*

Trend No. 4: The transition from rare earth materials to ferrites

Rare earth materials production is concentrated among a short list of countries worldwide. These materials are not inexhaustible and, at the rate of current consumption with no recycling, it is expected that world reserves likely will be exhausted during the second half of the 21st century [1].

Some companies have started to reduce their dependence and geopolitical risk by shifting some of their magnet consumption over to ferrite materials. Ferrite magnets cost a fraction of rare earth magnets such as neodymium ferrite boron and also have stable pricing, given the abundance of ferrite materials. The downside to using ferrite magnets is that the magnetic fields produced are greatly reduced – as much as 10 times lower – and have a temperature drift of 0.2%/°C.

Texas Instruments' **TMAG5170** and **TMAG5273** magnetic sensors operate with ceramic ferrite or rare earth magnets and have temperature drift compensation features specific for these magnet types.

Conclusion

Innovation is an integral part of industrial and automotive systems, and position sensors are vital to applications that require precise measurements of linear or rotational motion. As industries adopt the latest technologies, market demand for advancements in safety and user experience will continue to grow, and in turn the need for accurate sensing technology. Texas Instruments' position sensors are helping enable these four trends, and the company will be developing position sensors well into the future to support the next wave.

References

1. Britannica. n.d. "**Abundance, Occurrence, and Reserves**." Accessed Oct. 24, 2023.

Additional resources

1. Read the white paper, ***Using Hall-Effect Sensors for Contactless Rotary Encoding and Knob Applications***.
2. Read the design guide, ***1° Dial Using the LDC1314 Inductance-to-Digital Converter Design Guide***.
3. Read the technical article, ***Meter Anti-Tampering: Stopping Those Pesky Meter Tamperers***.
4. Read the application note, ***Reducing Quadrature Error for Incremental Rotary Encoding Using 2D Hall-Effect Sensors***.
5. Check out the ***TMAG5115 Evaluation Module User's Guide***.

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