DESIGN CONSIDERATIONS FOR TWO-WHEELER ACCELERATOR POSITION SENSOR

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INTRODUCTION

In a two-wheeler, the accelerator—or throttle—is typically implemented as a twist-grip on the handlebar. To measure movements of this twist-grip, both electric bikes (e-bikes) and ride-by-wire internal-combustion-engine (ICE) bikes use an accelerator position sensor (APS). The APS accurately and reliably translates the physical action of the rider (the twist of the grip) into an electrical signal. This signal indicates to the electronic control unit (ECU) precisely how much power the rider requests.

The system architecture of a generic APS for both e-bikes and ICE bikes is shown in Figure 1. In a traditional APS, a mechanical sensor, such as a potentiometer, senses the position of the twist-grip; however, frequent and repetitive twisting of the grip quickly results in wear and damage. For durability and reliability, modern two-wheelers employ noncontact magnetic sensors for this application.

This application note provides an overview of the design considerations for an APS. This discussion includes:

- Physical configurations for setup:
  - On-axis arrangement.
  - Off-axis arrangement.
- Advantages of an angle sensor *versus* a linear sensor.
- Critical system-level decisions for:
  - Interface options like analog, pulse-width modulation (PWM), and single-edge nibble transmission (SENT).
  - Implementation of single or redundant sensor architectures to meet functional safety requirements.
  - Definition of custom output profiles.
  - Optimal magnet selection.
- Magnetic field simulation results demonstrate sensor and magnet interactions.
- Recommendations to achieve Automotive Safety Integrity Level D (ASIL D) requirements with a ride-by-wire system, which eliminates the mechanical cable between the throttle body and the accelerator. In the ride-by-wire solution, the APS continuously reads the position of the handle grip and provides electric signals to the ECU. The ECU with electronic-fuel-injection (EFI) capability controls the air-fuel supply: It controls a butterfly valve in the throttle body based on inputs from the APS and various other sensors, such as engine speed, exhaust sensor, temperature, etc. This improves safety and fuel efficiency and reduces hazardous emissions. In an electric two-wheeler, the ECU controls the motor speed and the optimal direction. As a safety-critical component, a ride-by-wire solution is recommended to meet ASIL C or ASIL D requirements.

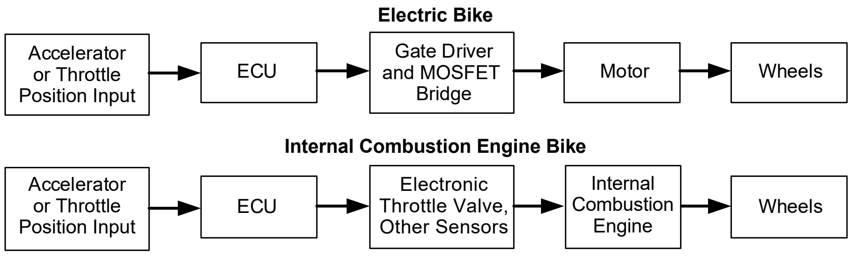

Figure 1: System Architectures of E-Bikes and ICE Bikes

SYSTEM DESIGN METHODOLOGY AND SENSOR SELECTION

A successful APS implementation requires a synchronized approach to mechanical geometry, magnetic field behavior, and electronic signal processing. The design process typically follows a hierarchy where mechanical constraints drive the selection of the magnetic sensing technology and the subsequent calibration strategy.

- Mechanical geometry and magnetic mapping: The physical mounting—whether on-axis or off-axis—determines the linearity of the magnetic field vector. On-axis setups provide a naturally linear relationship between mechanical rotation and magnetic angle, whereas off-axis setups introduce geometric nonlinearities (S-curves) that require electronic compensation.
- Sensor capability and linearization: Allegro MicroSystems provides a tiered portfolio to address these varying geometric challenges. While basic 2D sensors like the A1330[1] serve linear on-axis applications through simple two-point calibration, advanced 3D sensors like the A31315[2] use sophisticated on-chip linearization (up to 33 points) to correct the complex nonlinearities inherent in off-axis designs.
- Signal integrity and protocol selection: Once the angular position is accurately captured and linearized, the system must communicate this data to the ECU. The choice between Analog, PWM, or SENT protocols involves a balance of system cost, required resolution, and the safety requirements of the vehicle.
- Functional safety and redundancy: For ride-by-wire systems targeting ASIL D compliance, the sensing architecture must include redundancy. This is often achieved through dual-die sensors that provide two independent electrical channels within a single package, supporting various output profiles (same, criss-cross, or half-gain) for real-time cross-checking by the ECU.

By understanding these dependencies, designers can select the optimal combination of magnet material, mounting arrangement, and sensor functionality to meet the stringent accuracy and safety demands of modern two-wheeler applications.

MOUNTING ARRANGEMENTS

In an APS, the primary arrangements for sensor and magnet placement are on-axis and off-axis mounting.

On-Axis Arrangement

In an on-axis mounting arrangement, a small, circular, diametrically magnetized disc magnet is mounted at the center of the rotating twist-grip, as shown in Figure 2. The sensor integrated circuit (IC) is positioned directly over the center of this rotating disc magnet. The diametric magnet has a north pole on one half of the flat surface and a south pole on the other half, which creates a magnetic field that points straight across the diameter of the disc, as shown in Figure 2.

When the accelerator is in the idle position, the sensor witnesses only the magnetic field that points in a specific direction. As the accelerator rotates, the attached disc magnet also rotates axially in front of the stationary magnetic sensor. As the magnet rotates, a Hall sensor detects the change in the angle of the magnetic-field vector and the sensor IC provides a proportional output signal. The Hall sensor can be programmed for the idle position with the desired output profile. This allows flexible placement of the sensor.

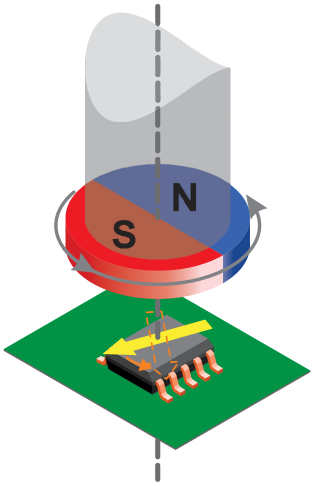

Figure 2: On-Axis Arrangement

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[1] https://www.allegromicro.com/-/media/files/datasheets/a1330-datasheet.pdf
[2] https://www.allegromicro.com/-/media/files/datasheets/a31315-datasheet.pdf?sc_lang=en

Off-Axis Arrangement

An off-axis arrangement offers a more-flexible arrangement than an on-axis arrangement. In an off-axis arrangement, the Hall sensor is placed to the side of the rotating magnet mounted on the handlebar, as shown in Figure 3. An arc-shaped magnet (a segment of a ring) is attached to the rotating handlebar grip. The arc-shaped magnet is typically magnetized either radially or axially. The Hall sensor is mounted in a fixed position above, below, or to the side of the magnet. As the handlebar grip rotates, the arc magnet moves past the stationary sensor. As the magnet moves, the Hall elements of the sensor detect the change in the magnetic field. Depending on sensor type, the sensor measures either the change in the strength of the field or the angle of the field.

The greatest advantage of off-axis mounting is mechanical flexibility: Off-axis mounting does not require access to the end of the shaft and easily integrates into a wide variety of housing designs, which makes it a very popular arrangement option.

However, off-axis mounting does not provide a direct one-to-one correlation between the mechanical input angle and the magnetic angle, so multipoint calibration is always required. To compensate for the inherently nonlinear geometries that result from off-axis mounting, modern programmable sensors typically include on-chip linearization.

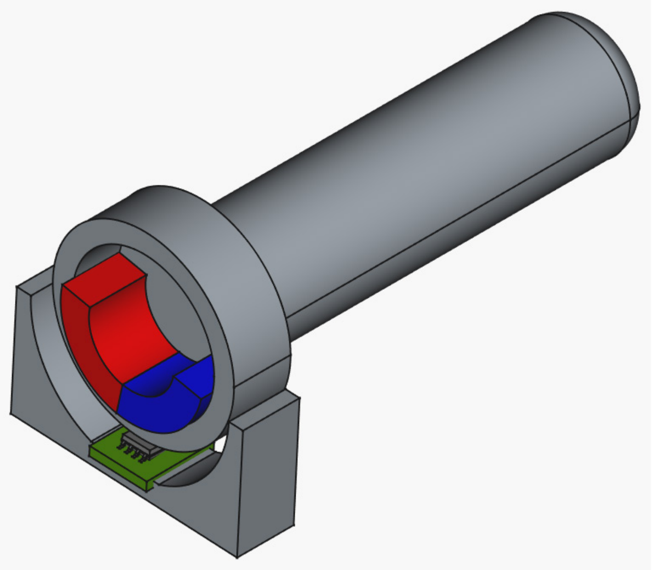


Figure 3: Off-Axis Arrangement

On-Axis versus Off-Axis

The on-axis and off-axis arrangements each have advantages and disadvantages. In the on-axis design, the mechanical input angle is a direct one-to-one representation of the magnetic angle, so multipoint calibration is unnecessary; in the off-axis arrangement, angle correlation is not direct, so multipoint calibration is required. However, the off-axis arrangement eases mechanical placement compared to the on-axis arrangement.

OUTPUT PROTOCOL

Different APS applications use different types of output protocols, including ratiometric analog, PWM, and single-edge nibble transmission (SENT). The choice of output type is a critical system-level decision that imposes tradeoffs associated with simplicity, cost, robustness to electrical noise, and compatibility with legacy designs.

Analog Output

For a sensor equipped with analog output, the sensor IC measures the angle of the throttle and converts that angle into a corresponding voltage level. This creates a simple linear relationship. For example, at 0% throttle, the sensor provides a 0.5 V output; and, at 100% throttle, the sensor provides a 4.5 V output. The ECU uses an analog-to-digital converter (ADC) pin to read this voltage and instantly translate this voltage into a known throttle position.

The advantage of the analog output is simplicity in implementation: The microcontroller unit (MCU) requires only a standard ADC pin, which is available on nearly all MCUs; and, when an ADC is used, the ratiometric analog outputs enable system-level error cancellation of supply-voltage variation.

The disadvantage of the analog output is susceptibility to electrical noise and signal degradation, and limited fault-reporting capability: A fault is only reported as high (>4.5 V) or low (<0.5 V), and detailed information about the fault cannot be obtained.

PWM Output

A pulse-width-modulation (PWM) output is a digital square wave that switches between a low voltage (e.g., 0 V) and a high voltage (e.g., 5 V). The angle datapoint is encoded in the duty cycle, which is the percentage of time the signal remains in the high state during one cycle. The sensor can be programmed to have a duty cycle of 10% at 0% throttle angle and a duty cycle of 90% at 100% throttle angle.

Because the signal is digital, small voltage fluctuations caused by electrical noise do not affect the data of the PWM output. Compared to an analog output, the benefit of a PWM output is its ability to provide detailed fault data at different frequencies and duty cycles; however, the PWM output updates at a slightly slower rate.

SENT Output

The single-edge nibble transmission (SENT) output mode converts the calculated angle to a binary value mapped to the full-scale output (FSO) range of 0 to 4095 (for a 12-bit output). The SENT protocol is a commonly accepted automotive protocol for highly efficient transfer of sensor data along intravehicular communications networks and is standardized by the Society of Automotive Engineering in publication SAE J2716.

SENT output provides several advantages, including:

- Noise immunity: Data are encoded in the time between the falling edges (digital timing) rather than in the voltage levels.
- High resolution: SENT typically transmits 12-bit to 16-bit data.
- Functional safety: SENT frames include a dedicated status nibble and a cyclic redundancy check (CRC) that together enable the ECU to verify the integrity of the data and the health of the sensor in real time. In SENT output mode, internal faults are able to be read.

SENSOR CALIBRATION TECHNIQUES

An angle sensor measures the absolute angle of the magnetic-field vector. Allegro MicroSystems offers a wide portfolio of angle sensors that satisfy the requirements of the APS application, including:

- A1330, a 360-degree-angle sensor IC that provides contactless high-resolution angular position data based on magnetic circular vertical Hall (CVH) technology.
- A31315 3DMAG^{TM}, a position sensor that integrates vertical and planar Hall-effect elements with precision temperature-compensation circuitry to detect two out of three magnetic-field components (X, Y, and Z).

The A1330 and A31315 are compared in Table 1.

The APS application demands accuracy better than 1% to 2% of the V_{CC}. To achieve this accuracy, a programmable sensor is required. For the on-axis arrangement, short-stroke (travel angle < 360°) and two-point calibration can often suffice. However, to achieve similar performance with the off-axis arrangement, multipoint calibration is required.

After assembly of the APS, sensor calibration must be performed. Calibration techniques include:

- Two-point calibration: Calibration is performed at the two angles to correct for offset and gain errors and to set the zero-angle position. This ensures the transfer function matches the application requirements, where a closed throttle corresponds to the minimum output (typically 0.5 V) and a wide-open throttle corresponds to the maximum output (typically 4.5 V). The A1330 architecture supports this calibration method and allows for accurate endpoint configuration, even in cost-sensitive applications.
- Multipoint calibration: This is a more-advanced, fine-tuning step. After two-point calibration, the output might exhibit imperfections in the linearity between the start and end points. To fix these residual nonlinearities, a piecewise correction (such as a lookup table) is applied to linearize the data to ensure that, for example, a 50% twist of the throttle results in exactly a 50% output signal. In an advanced sensor like the A31315, this capability is built into the sensor to allow for a highly customized and accurate throttle with a highly responsive feel.

Table 1: Comparison of A1330 and A31315 Angle Sensor

Feature	**A1330**	**A31315**
Sensing Technology	2D circular vertical Hall (CVH)	3D Hall-effect (planar and vertical Hall plates)
Output Interfaces	Analog, PWM	Analog, PWM and SENT
Mounting Arrangements	On-axis (XY)	On-axis (X-Y) and off-axis (X-Z)
Response Time	120 µs	600 µs
Maximum Operating Field Range	1200 G	1000 G
On-Chip Linearization	Two-point (offset and gain)	2 to 33 fixed points, 2 to 22 movable points, or binning-mode point
ASIL Support Level	–	ASIL B (single-die) ASIL D (dual-die)
Programmability	End-of-line programming of offset, gain, clamping, polarity, and zero angle	Highly user-programmable for gain, offset, clamping, polarity, zero angle, and advanced linearization
Angle Error over Temperature	±1.5 degrees	±1.2 degrees
Package	TSSOP-8 (single-die or dual-die)	SOIC-8 (single-die) TSSOP-14 (dual-die)

SAFETY CONSTRAINTS

Because accelerator position sensing is a safety-critical application, the APS module must comply with safety requirements. To assist with decomposition of safety requirements, some angle sensors, such as the Allegro A31315, are ASIL rated. An ASIL-rated device includes diagnostics to detect faults and to provide fault data to the ECU. Some of these devices, such as the Allegro A31315 dual-die device, also employ redundancy to achieve higher ASIL ratings.

Redundancy

Redundancy means there is more than one way to perform a critical function. If one method fails, another method either takes over or indicates that the first method is incorrect. A dual-die architecture is the modern, highly integrated solution used in the sensors: Two completely independent sensor circuits, one for each die, are integrated into a single physical package. Each die has its own power, ground, sensing element, and processing logic. Each die functions as an independent sensor. The dual-die architecture thus provides full electrical redundancy (when integrated and used in the manner prescribed in the applicable safety manual and datasheet) in a compact, cost-effective package that simplifies design.

Diagnostics

For safety-critical applications like an accelerator position sensor (APS), modern sensors like the A31315 are equipped with a suite of internal monitors. These diagnostics are used to ensure the sensor fault operates correctly.

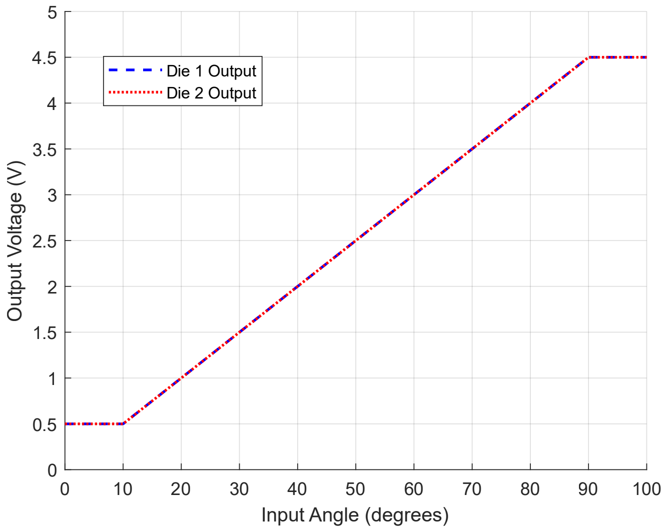
VARIOUS DUAL-DIE OUTPUT PROFILES

The output profile required for an APS application is based on the ECU requirements of the original equipment manufacturer (OEM), so the output profile required for one APS application is often different for another. Common solutions employ two signals, where the output of one signal is: 1) the same as the other (same output); 2) the inverse of the other (criss-cross output); or 3) half that of the other (half the output). These profiles are typically implemented using a dual-die sensor, where two independent Hall sensor circuits are integrated into a single package. The goal is to create two distinct signals that can be compared to detect any faults.

Same Output

This is the most-intuitive redundant configuration. Both sensors are programmed to have the exact same output profile. As the throttle is twisted, both outputs rise and fall together, tracking each other perfectly, as shown in Figure 4.

The main ECU continuously verifies that the output of one die (OUTPUT_DIE1) is equal to (within a small tolerance of) the output of the other die (OUTPUT_DIE2). If OUTPUT_DIE1 does not equal OUTPUT_DIE2, a fault is detected, and the ECU takes appropriate safety steps.



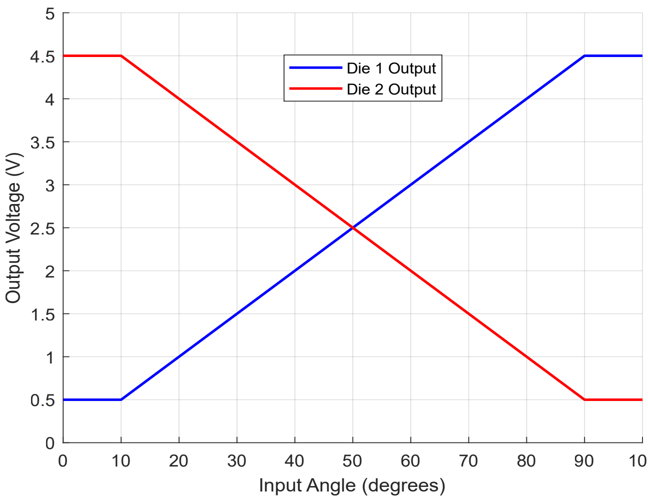
Die 1 Output: 0.5 V at 0% throttle → 4.5 V at 100% throttle.
Die 2 Output: 0.5 V at 0% throttle → 4.5 V at 100% throttle.

Figure 4: Same-Output-Level Configuration

Criss-Cross Output

The criss-cross output method is a very common and highly robust fault-detection method. The two Hall sensor dies are programmed to have outputs with opposite slopes. As the angle increases, one output transitions from low to high, whereas the other output transitions from high to low, as shown in Figure 5.

The primary check of the ECU is to verify that the sum of the two outputs is always a constant value. For example, OUTPUT_DIE1 + OUTPUT_DIE2 = 5 V. If OUTPUT_DIE1 + OUTPUT_DIE2 ≠ 5 V, a fault is detected, and the ECU takes appropriate safety steps.



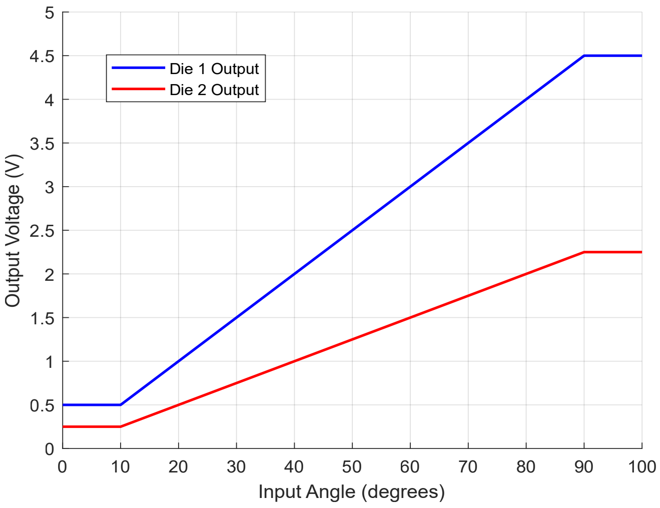
Die 1 Output: 0.5 V at 0% throttle → 4.5 V at 100% throttle.
Die 2 Output: 4.5 V at 0% throttle → 0.5 V at 100% throttle.

Figure 5: Criss-Cross-Output Configuration

Half Output

The half output method is a common strategy that uses different gains for each channel. One die is programmed to have an output range (span) that is exactly half that of the other die, as shown in Figure 6.

The ECU performs a check based on the linear relationship of the two signals. If the relationship is not linear, a fault is detected, and the ECU takes appropriate safety steps.



Die 1 Output: 0.5 V at 0% throttle → 4.5 V at 100% throttle.
Die 2 Output: 0.25 V at 0% throttle → 2.25 V at 100% throttle.

Figure 6: Half-the-Output Configuration

MAGNET SELECTION

Magnet selection is a critical factor in application performance. The choice primarily involves a tradeoff between magnetic strength, stability, cost, and availability. For an APS application, a rare-earth or ferrite material is suitable for the magnet.

- Rare-earth magnets offer the highest magnetic field strength for their size. The high strength allows for a compact design. The strong magnetic field allows use of this magnet with a larger air gap between the magnet and sensor, which provides greater flexibility in mechanical design and tolerance.

  A neodymium (NdFeB) rare-earth magnet is costlier than a ferrite magnets. An NdFeB magnet is also highly susceptible to rust, so it requires a protective coating. A scratch or crack in this coating can lead to magnet degradation.
- Ferrite magnets are made from abundant, inexpensive materials like iron oxide and strontium carbonate. Because it is essentially ceramic, a ferrite magnet does not rust and does not require a protective coating, so they are inherently robust. Ferrite magnet have less magnetic-field strength and derate significantly over temperature. Therefore, to create the strength of magnetic field required by the sensor, the design might require a larger magnet or a smaller air gap.

The shape of a magnet is determined by the mechanical construction of the throttle and the sensing arrangement (on-axis versus off-axis). Disc and arc forms are suitable for the APS application. A small, diametrically magnetized round magnet is attached to the end of the handle grip. This configuration is optimal for an angle sensor because the average magnetic field is constant throughout the 0° to 360° angle.

In off-axis sensing, an arc-shaped magnet is used. The arc magnet is attached to the throttle grip. As the grip is twisted, the magnet moves past a stationary sensor. This is a very common and mechanically flexible design. NdFeB magnets are suited for this form due to their higher magnetic strength compact size, and ability to allow a larger air gap. A similar output with a ferrite magnet requires a much larger magnet.

The choice of magnet size is restricted by the requirements of the APS application. For example, the APS might be required to have a defined operational range of movement for the throttle, such as 100 degrees. The same APS might be required to have a functional safeguard where, if the throttle grip is quickly hard-forced through its full range of motion and the sensor detects the magnetic field on the opposite side of the magnet (assuming the arc length of the magnet is the same as the working range), the sensor output drops from 4.5 V to 0.5 V, and the ECU produces a fault output. Therefore, the arc length of the magnet should be at least 20% larger than the desired angle, and a 10% buffer should be included on the starting and finishing sides of the desired angle.

FEM ANALYSIS

A detailed analysis of an APS that uses the A31315 angle sensor was conducted. The analysis uses the finite element method (FEM) to simulate the magnetic field produced in different arrangements. The magnetic fields were further post-processed in MATLAB to emulate the performance of the Allegro angle sensor for the simulated magnetic input.

The requirements considered for the APS are:

- Accelerator stroke range: 5° to 95°
- Supply voltage (V_{CC}): 5 V
- Desired output 1: 0.5 V to 4.5 V
- Dead band: 0° to 5° = 0.5 V; and 95° to 100° = 4.5 V
- Typical air gap: 4 mm
- Desired accuracy: ±2% of V_{CC}

The simulation results for the two mounting arrangement (on-axis and off-axis) are detailed in the Appendix. The analysis reveals that the on-axis arrangement with the disc magnet provides a more-accurate angle measurement with only a two-point calibration. In contrast, to achieve comparable accuracy with an off-axis arrangement that uses an arc magnet, multipoint calibration is required; however, this tradeoff allows for significantly greater flexibility in the mechanical arrangement.

CONCLUSION

This application note details the design and implementation of an APS for a two-wheeler application. It covers critical topics including output signal types, custom output profiles, magnet material selection, and various mechanical setup configurations. Additionally, it addresses functional safety constraints and demonstrates how end-of-line calibration significantly enhances system performance. The Allegro A31315 3D angle sensor is highlighted as a comprehensive solution that satisfies the requirements of APS applications.

APPENDIX—SIMULATION DATA

On-Axis with Disc Magnet

The simulation takes into account an on-axis arrangement with disc magnet made of NdFeB (10 mm diameter × 2.95 mm thickness) with diametric magnetization. A plot of the magnetic-flux lines induced by a diametric disc magnet is shown in Figure 7. The magnet center aligns with the sensor center.

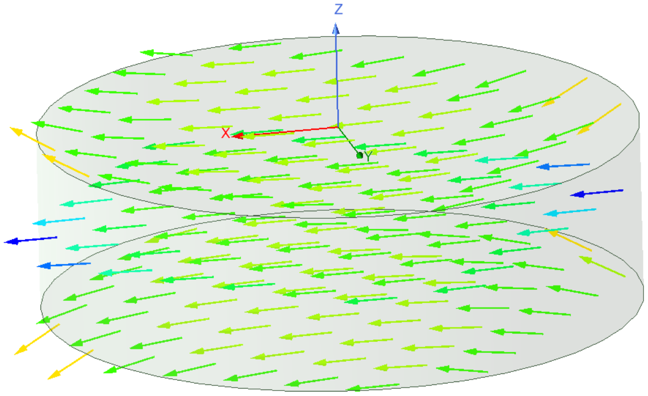


Figure 7. Magnetic-Flux Lines of Disc Magnet

Magnetic Field Sensed by X-Axis and Y-Axis

The magnetic field simulated by the diametric disc magnet at a 4 mm air gap is shown in Figure 8. The magnetic-flux density in the on-axis arrangement remains constant over a 360-degree angle. At a 4 mm air gap, the average magnetic-flux density is approximately 925 G.

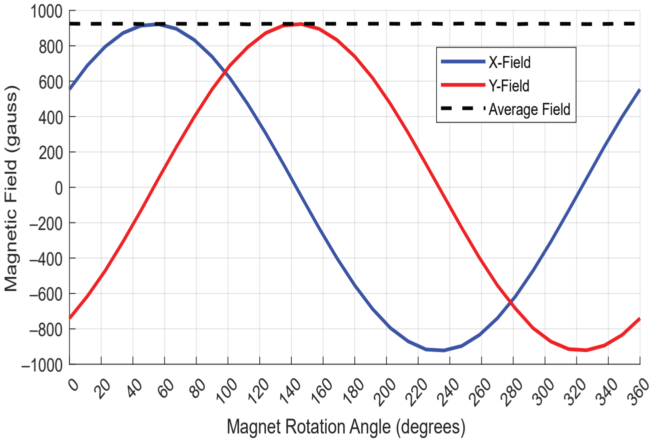


Figure 8: X-Field, Y-Field, and Average Magnetic-Field Data

Measured Data versus Desired Output

In the on-axis arrangement, the magnetic-flux density remains constant throughout the 360-degree angle, and the sensor produces a linear output throughout the accelerator position angle when the magnet center aligns with the sensor center. This approach improves results with only two-point programming, as shown in Figure 9.

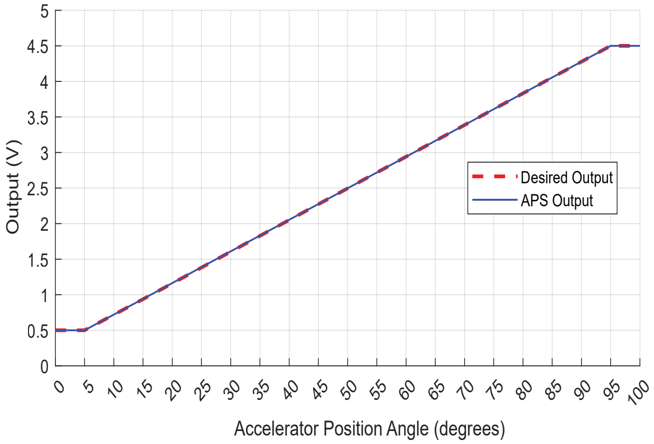


Figure 9: Two-Point Programming Output vs. Desired Output

Two-Point Programming: Angle Error

When the centers of the magnet and the sensor align, the output error is less than 10 mV (which is 0.225 degree of angle error, 1 degree = 44.44 mV) with only two-point programming, as shown in Figure 10. If the application allows the sensor and magnet to fit in the on-axis arrangement, to achieve the desired output, the customer must program the sensor at the end of the production line. Two-point programming is faster than multipoint programming. As a general note, simulations assume that magnetization is ideal. Dynamic and placement tolerances are not considered.

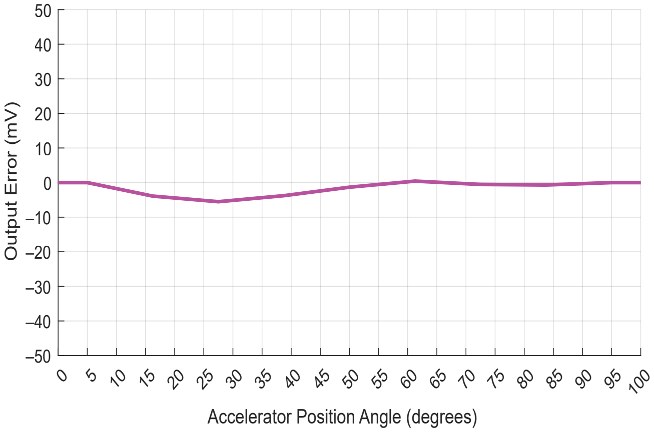


Figure 10: Output Error after Two-Point Programming

Off-Axis with Arc Magnet

The simulation takes into account an off-axis arrangement with an arc magnet made of NdFeB (110-degree arc length × 3.95 mm width × 2.95 mm thickness) with through-width magnetization. A plot of the magnetic-flux lines induced by an arc magnet is shown in Figure 11.

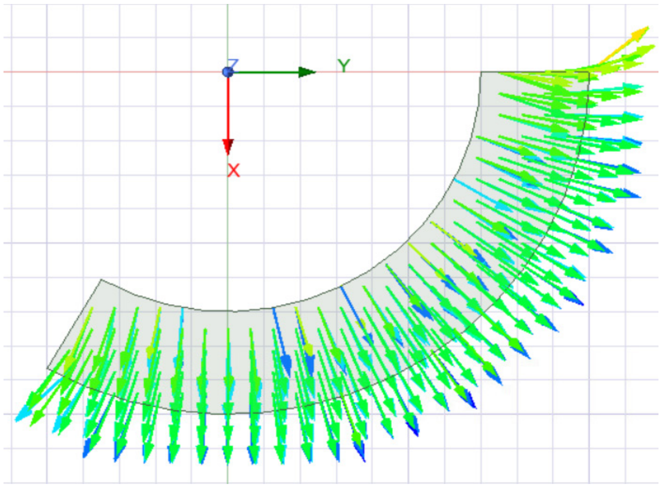


Figure 11: Magnetic-Flux Lines for Arc Magnet

Magnetic Field Sensed by X-Axis and Z-Axis

The magnetic field produced by an arc magnet at a 4 mm air gap is shown in Figure 12. Due to the nonlinearity between the magnetic vector and the mechanical angle, the field of the arc magnet is nonlinear (i.e., S-shaped). To obtain the desired output, multipoint programming is required. At a 4 mm air gap, the average magnetic-flux density is approximately 380 G.

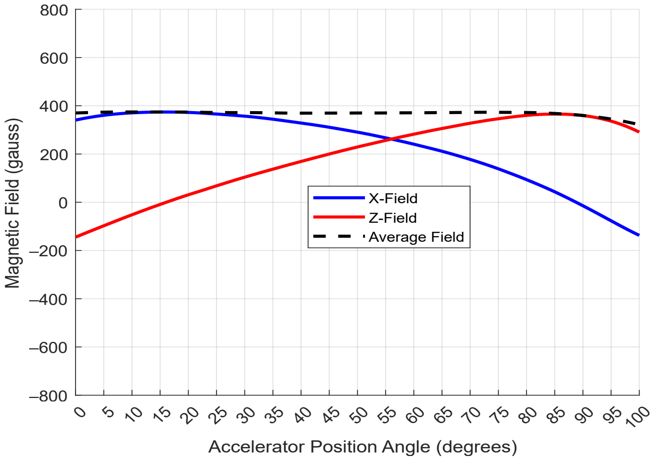


Figure 12: X-Field, Z-Field, and Average Magnetic-Field Data

Measured Data versus Desired Output

As the magnetic-flux density in the off-axes arrangement is not linear for the accelerator position angle, the output after two-point programming is non-linear and results in a large inaccuracy in the accelerator position angle with respect to the desired output, as shown in Figure 13.

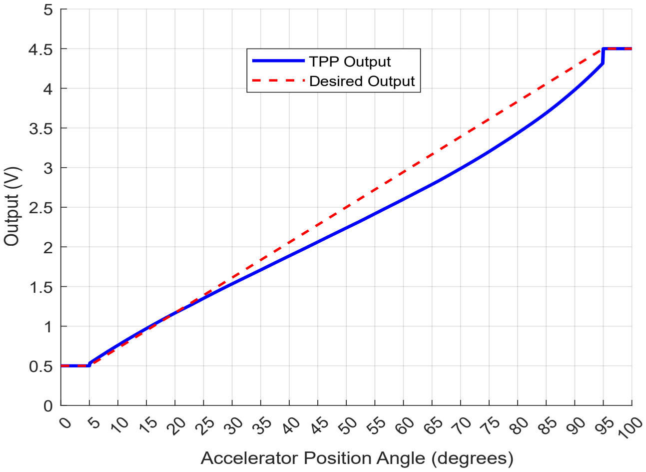


Figure 13: Two-Point Programming vs. Desired Output

Two-Point Programming Error

In the off-axes arrangement, following two-point programming, the sensor output error reaches a maximum of 400 mV (which is 9 degrees of angle error; 1 degree = 44.44 mV) in the accelerator position angle range, as shown in Figure 14. Therefore, to reduce output error, multipoint programming is required to reduce error to achieve the desired results. As a general note, simulations assume that the magnetization is ideal. Dynamic and placement tolerances are not considered.

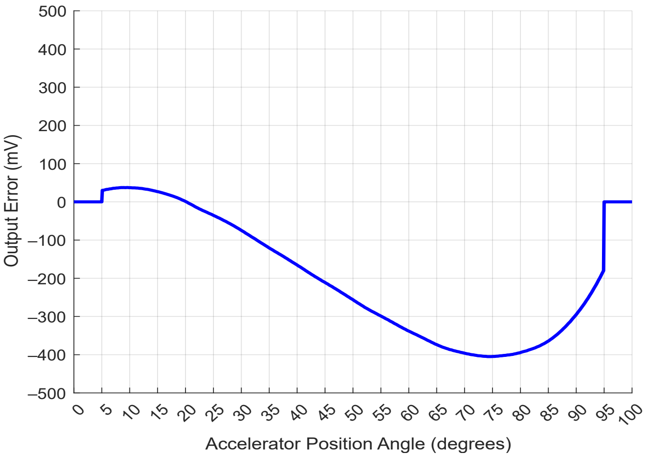


Figure 14: Output Error after Two-Point Programming

Linearize Output versus Desired Output

The A31315 angle sensor includes a linearization feature to eliminate application nonlinearity and obtain the desired results. In post-processing, linearization can be performed using 10 variable points. For an accelerator position angle of 90 degrees, with linearization points set at 5, 15, 25, 35, 45, 55, 65, 75, 85, and 95, the desired results can be achieved, as shown in Figure 15.

Figure 15: Linearized Output vs. Desired Output

Error after Linearization

An arc magnet configuration requires multipoint programming to obtain the same effects as an on-axis arrangement. After multipoint programming, the output error is less than 15 mV (which is 0.34 degree of angle error; 1 degree = 44.44 mV).

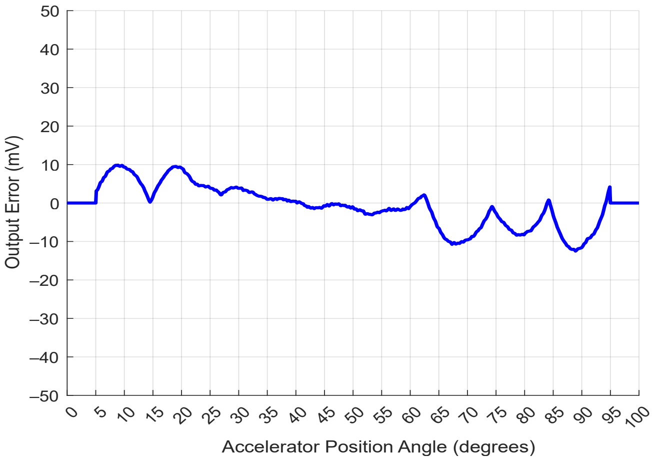


Figure 16: Output Error after Linearization

Revision History

Number	Date	Description	Responsibility
–	June 12, 2026	Initial release	R. Farakate