Application Note

Linear Hall-Effect Sensor Array Design

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ABSTRACT

Position sensing in mechanical systems using Hall-effect magnetic sensors allows precise control while also providing contact free feedback. This increases overall reliability and durability. Since magnetic fields are able to permeate most materials, the sensor can be placed so that it is protected and isolated from other moving parts of the system. This allows for a great deal of flexibility of design. Hall sensors can be used in detecting angular position, angular rotation speed and direction, proximity, and even absolute position. When moving a magnet along a path, some applications require determination of absolute position. This application note covers how to implement this type of design for long stroke movement where it is necessary to use multiple sensors in a linear array.

Table of Contents

List of Figures

List of Tables

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1 Introduction

The best Hall-effect sensor for any given application depends on the type of motion being detected and the various mechanical limitations of the system. Latches and switches operate relative to a fixed threshold. When the sufficient magnetic field is present, the outputs state of these devices changes. Linear sensors however produce a variable output relative to the input magnetic field. Latches and switches are primarily useful where discrete fixed operating positions are used. For example, you might detect the closure of a lid or setting of a 3 position switch using a single DRV5032. Linear Hall-effect sensors are typically needed where absolute position or fine control is required, such as tracking the fluid level in a tank, dial or slider state, or seat adjustment setting.

Selecting a linear Hall-effect sensor depends on system constraints. In the case of long stroke linear transit, the following devices offer design flexibility to suit the application each can provide an appropriate solution.

Table 1-1. Comparison of Linear Hall Sensors

Device	Axis of Sensitivity	Output Mode	Package Options	Automotive Grade Available
DRV5055	Z	Analog	SOT-23, TO-92	✓
DRV5057	Z	PWM	SOT-23, TO-92	✓
TMAG5170, TMAG5170D-Q1	X, Y, Z	SPI	VSSOP	✓

For simple applications, DRV5055 and DRV5057 can be quickly implemented, and their outputs update immediately upon change in magnetic flux density. However, both of these devices are constrained mechanically due to only having sensitivity along a single axis. TMAG5170 offers three integrated sensors with each sensor oriented along a different axis. This allows the greatest flexibility in system design, and allows the user to observe the entire magnetic flux density. Upon completing each conversion TMAG5170 transmits the resulting digital code over SPI, which eliminates the need for an ADC to convert the output signal.

In every case, the number of sensors required to implement a linear transit solution is primarily dictated by magnet length and the total travel distance. Magnet strength and distance from the sensor also impact the quality of measurement. Fortunately, there is a simple algorithm that scales easily in this application that can be used to determine position of a magnet with an array of sensors.

This discussion demonstrates a basic design procedure focused around DRV5055. The observations and principles discussed apply equally to the DRV5057 and TMAG5170. The TMAG5170D-Q1 is a dual-die version of the TMAG5170 that can be used in a system where redundancy is required.

2 Linear Transit Position Sensing

When the transit of a magnet is being monitored, we can determine position most accurately using linear Hall sensors. Total observable range for a single sensor is maximized by orienting the magnet as shown in DRV5055 Magnet Orientation for Linear Stroke Detection and by using a bipolar linear Hall Effect sensor which is capable of detecting both North and South poles of the magnet.

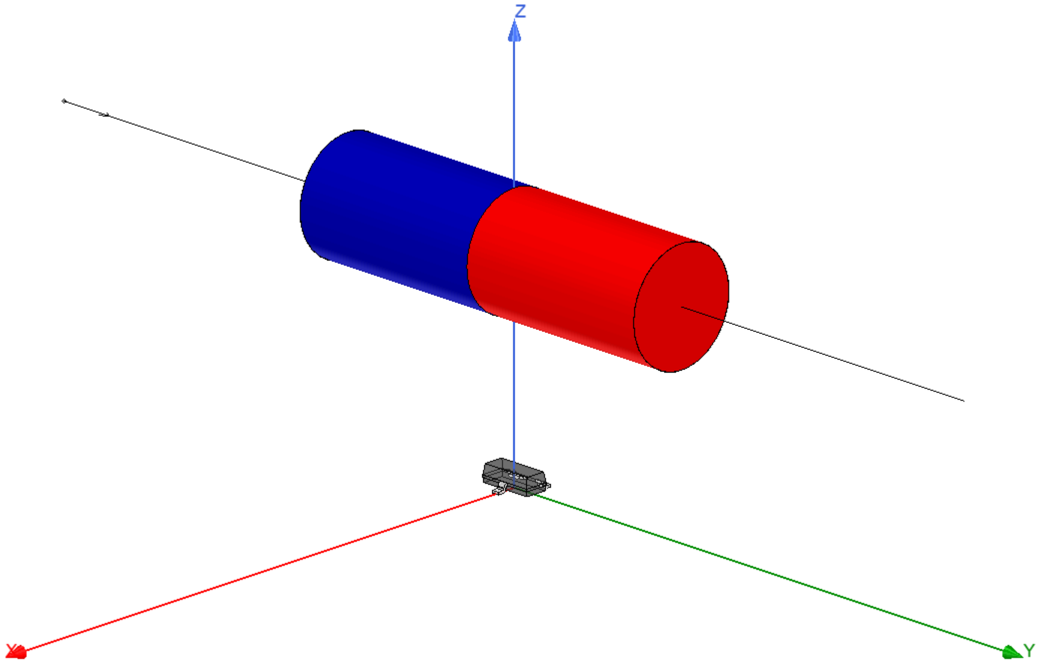

Figure 2-1. DRV5055 Magnet Orientation for Linear Stroke Detection

In the example shown in DRV5055 Magnet Orientation for Linear Stroke Detection , we have a N42 type Neodymium magnet traveling along a 60 mm path parallel to the y-axis. The center of the magnet is separated from the sensor by an air gap of 8 mm. The magnet has a diameter of 6.3 mm (0.25 in) and a length of 22.2 mm (0.875 in). Observed DRV5055 Magnetic Flux Density shows the expected input that DRV5055 would experience during the transit of the magnet. Here we see that the maximum z-component detected by the sensor is about 24.9 mT.

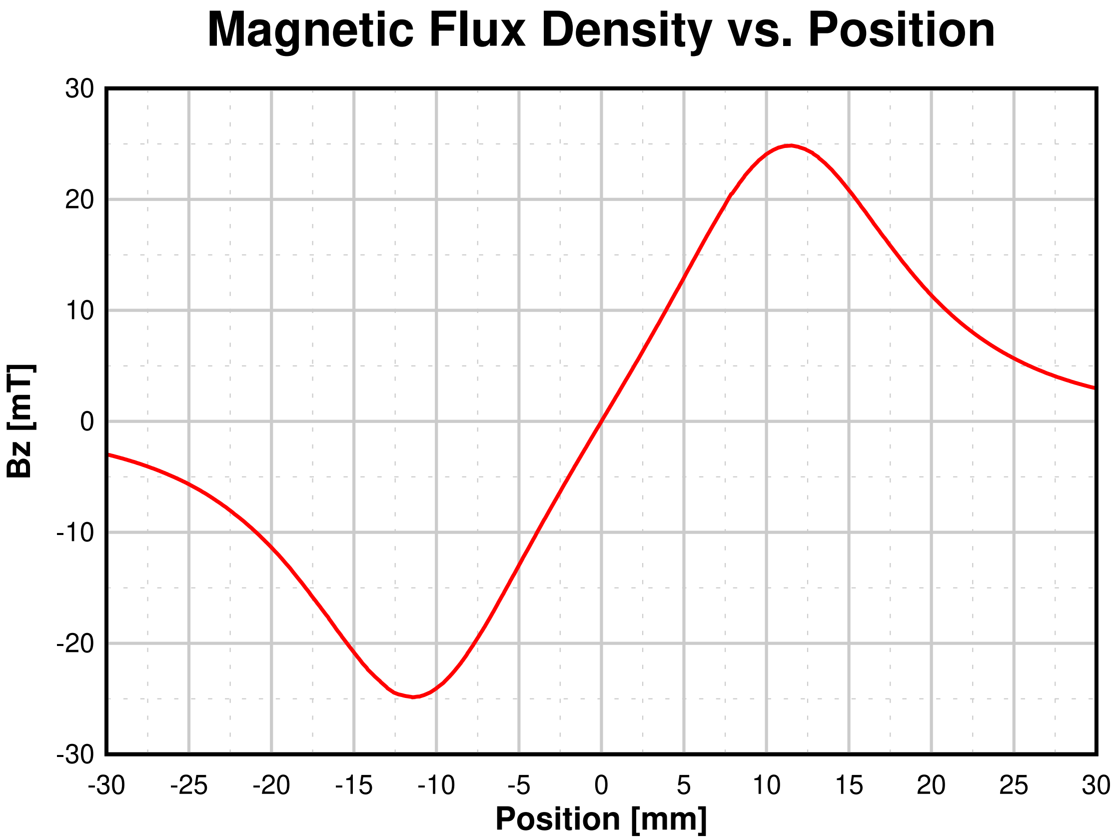

Figure 2-2. Observed DRV5055 Magnetic Flux Density

A linear Hall sensor such as DRV5055 works well in this application. For this device there are four sensitivity ranges available:

Table 2-1. DRV5055 Sensitivity Variations

Package Variant	Sensitivity (Vcc = 5 V)	Sensitivity (Vcc= 3.3 V)
A1	100 mV/mT	60 mV/mT
A2	50 mV/mT	30 mV/mT
A3	25 mV/mT	15 mV/mT
A4	12.5 mV/mT	7.5 mV/mT

When selecting the best sensor for the application we want to utilize as much of the linear output swing of the device as possible. In every case, 0 mT input produces an output at Vcc/2. For this example, select A1 at a sensitivity of 60 mV/mT, which generates a maximum output swing of ±1.49 V.

The peak field observed by the sensor can be adjusted by a number of factors:

Table 2-2. Table of Magnet Variables

Magnet Variation	**Peak B-Field**	**Detection Range**	**Other Effects**
Air Gap	Reducing the air gap between the magnet and sensor results in an increase in peak B-Field.	Decreases in Air Gap produce minor increases to detection range, primarily in the non-linear region of the input.	As the air gap is reduced, a non-linear region becomes more pronounced across magnet transit.
Magnet Length	An increase to magnet size results in an increase in peak B-Field.	Magnet length is the governing factor in determining the detectable range for the sensor.	Physically larger magnets costs more to use in production.
Magnet Radius	An increase to magnet size results in an increase in peak B-Field.	Increases to magnet radius produce minor increases to detection range, primarily in the non-linear region of the input.	Physically larger magnets costs more to use in production.
Magnet Material	Increasing the strength of the magnetic material likewise causes an increase in peak observed B-Field	Stronger magnetic materials produce minor increases to detection range, primarily in the non-linear region of the input.	Stronger magnetic materials costs more to use in production

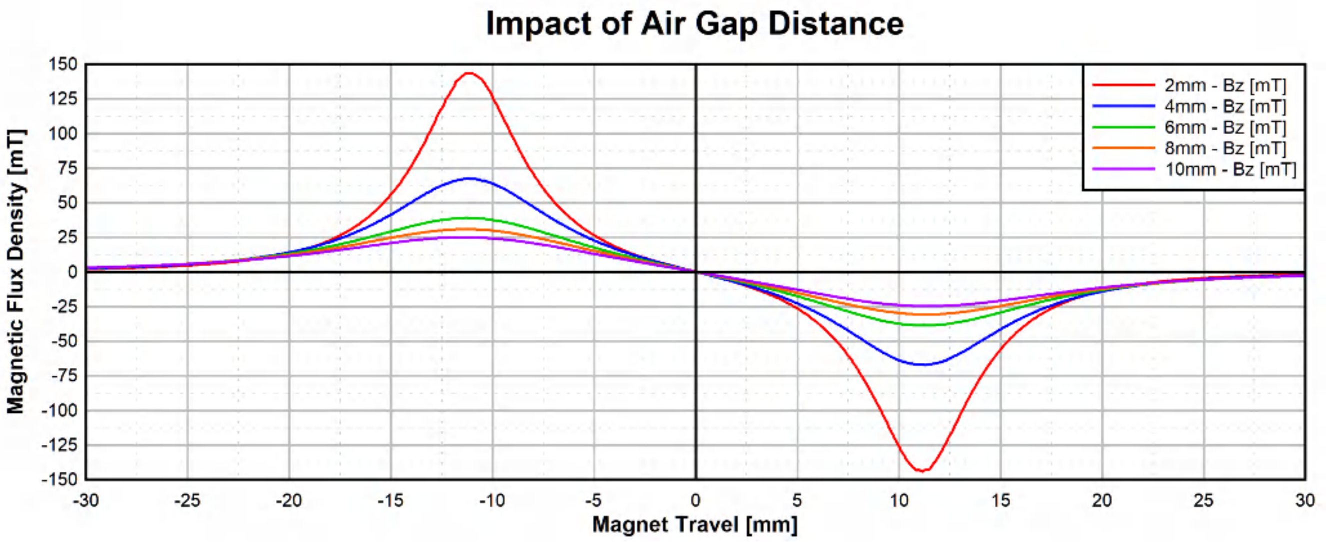

Figure 2-3. Impact of Magnet Variables

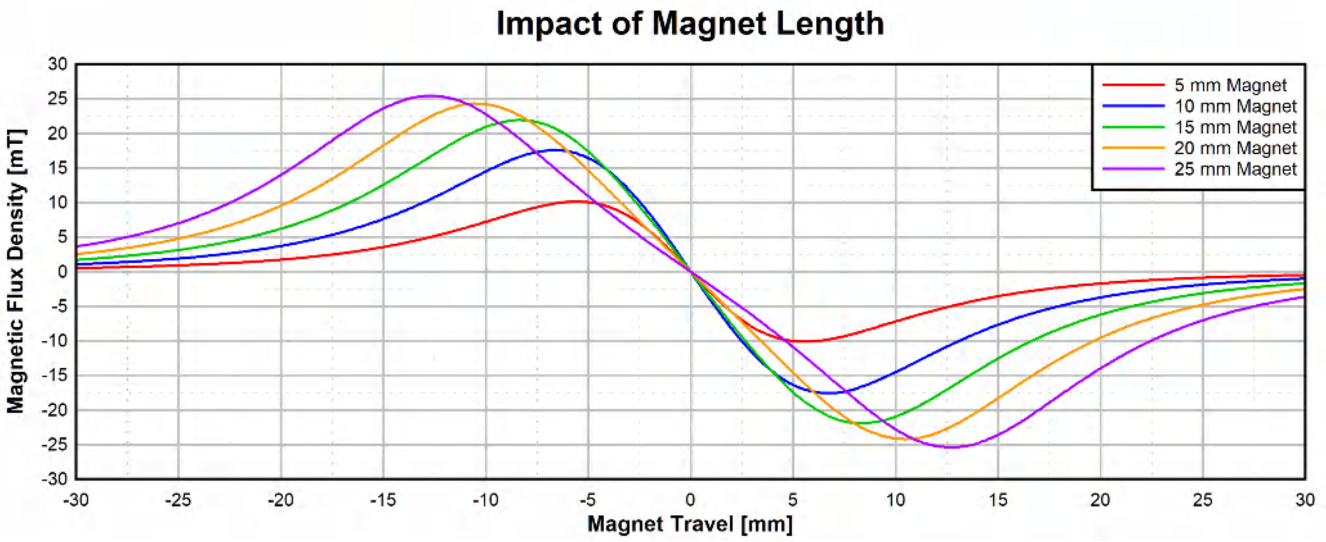

Figure 2-4. Impact of Magnet Length

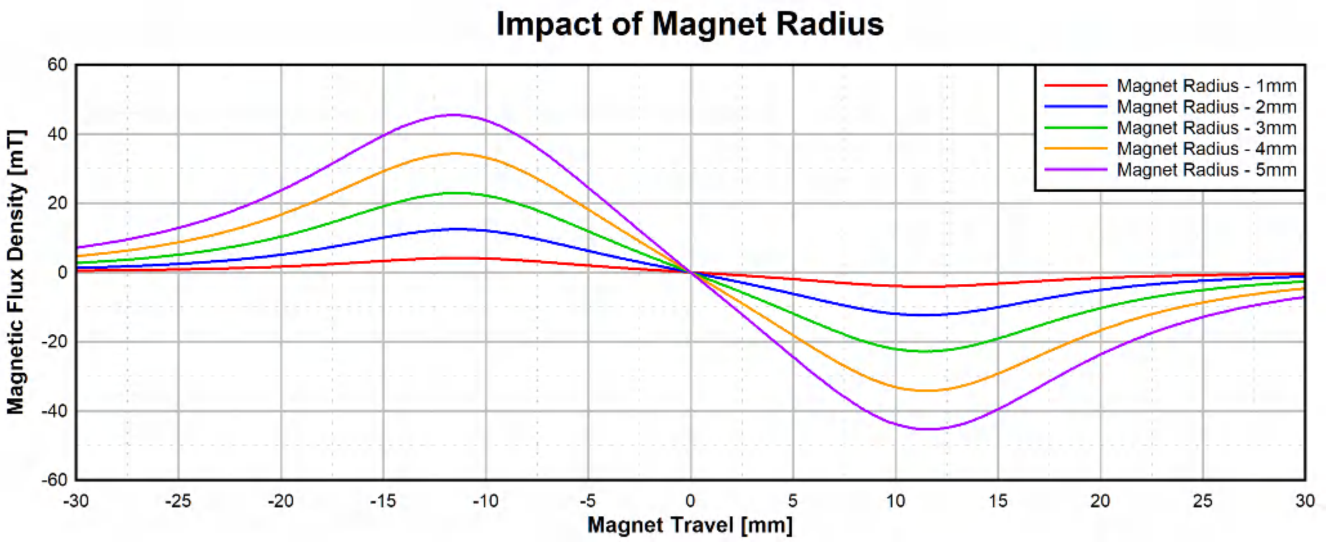

Figure 2-5. Impact of Magnet Radius

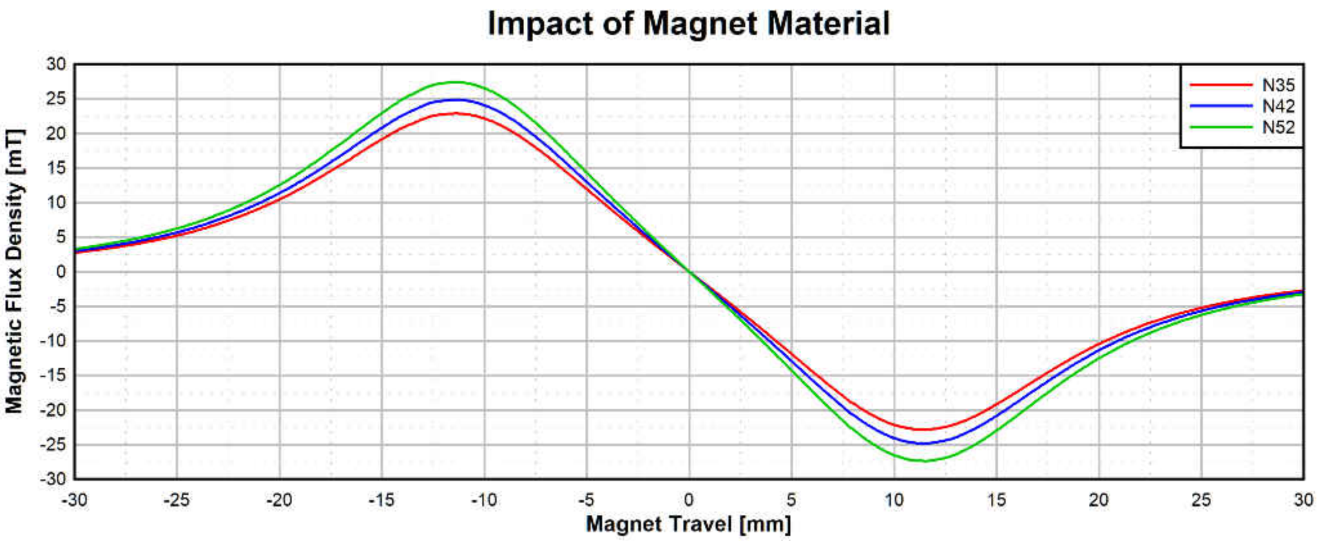

Figure 2-6. Impact of Magnet Material

Reviewing Observed DRV5055 Magnetic Flux Density shows that for each value of Bz,there are two possible magnet positions. To resolve ambiguity, measurements should be based solely on the region of the plot immediately between the maximum and minimum values. Excluding the portion nearest the extremes, this part of the output response is typically very linear.

This means that for the total travel distance in this example we can distinguish positions ranging from about ±10 mm. Notice that this range from peak to peak is approximately the length of the magnet, 22 mm.

In fact, the B-Field produced by the magnet in this orientation is governed by the length of the magnet. Thus, to expand the range of a single sensor it is necessary to increase the length of the magnet. Using stronger magnetic materials may add minute increases to the total range, but this is mainly only effective to increase the available air gap between the sensor and the magnet.

Cost can often be a limiting factor for implementing solutions with long magnets. If the range of a single magnet/sensor combination is inadequate, then the most practical approach is to expand the design by using additional sensors in a linear array.

3 Linear Array Design

Based on the results from the preceding simulation, we can expect that the maximum appropriate sensor spacing is roughly the magnet length of 22 mm. This aligns with the maximum of one sensor with the minimum of the following device. In practice this presents a few challenges. Firstly, air gap, alignment, or sensitivity of the DRV5055 may vary enough to produce measurement gaps. Secondly, the output voltage is nonlinear near the extremes. This makes interpreting the final position difficult. As a result, it is recommended to have overlap between sensors.

Let us expand the previous setup and consider a linear array of 5 sensors with approximately 20 mm spacing between each sensor.

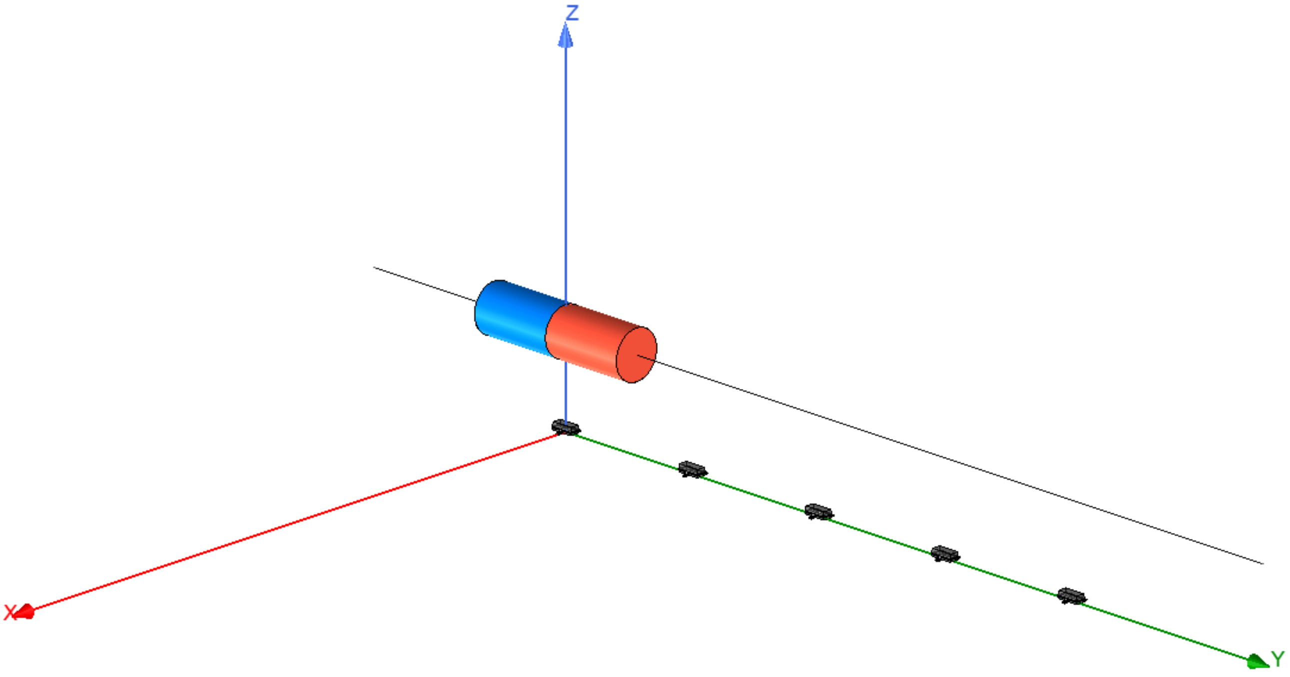

Figure 3-1. DRV5055 Linear Array

This spacing aligns the peak of one sensor with the linear output region of the adjacent sensor and gives us a total usable range of about 100 mm as shown in DRV5055 Output Response.

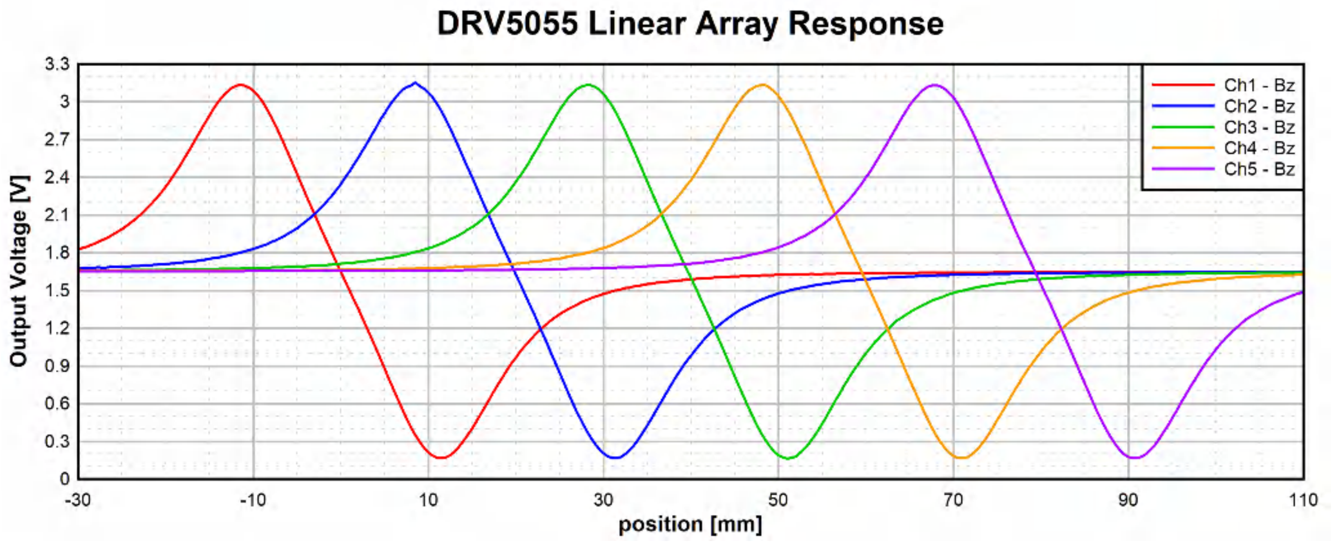

Figure 3-2. DRV5055 Output Response

For the output data to be useful, it must be decoded. The system must decide which sensor output is most relevant at any given time to use for position calculations. An easy algorithm to determine which output should be monitored is as follows:

1. Check the output of each device and select the device with the greatest absolute magnitude.
    a. Note: In this case the output should be shifted down by 1.65V as this is the mid-range output value for DRV5055 and corresponds to 0 mT B-field.
2. If the value from the step above is negative, use the signal from the sensor to the right. If the output is positive, use the signal from the sensor to the left. If the device is the first in the array and positive, then use the signal of that device. Similarly, use the signal from the last device when it is negative.
    a. For example, consider the position at 0 displacement which is directly centered over the first sensor. Here the output from the blue trace has the greatest magnitude and is positive. Use the red trace (to the left) to determine location.
    b. We might also consider the case of 51 mm. The maximum negative output value for the green trace is observed, and calculations should therefore be made using the value from the orange trace (to the right).
3. Calculate position based on selection in step 2. This may require obtaining calibration points from each sensor to achieve the highest accuracy. Knowing the start position for each sensor and the slope of the output voltage vs. distance allows the system to stitch the outputs together to produce a final position measurement.

4 Absolute Rotational Position

This same linear arrangement for this application may be transformed into a rotational measurement as well. For example, now consider a cylindrical magnet with a radius of 1/32” and a thickness of ¼” made of N52 material. The magnet is placed such that there is approximately a 2-mm gap between the magnet and sensor. The magnet rotates about the z axis at 20 mm from center. Again, the selected sensor is DRV5055A1 with a sensitivity of 60 mV/mT.

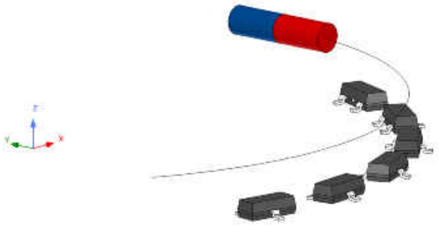

Figure 4-1. DRV5055 Circular Array

In this scenario we find a spacing of about 16° from sensor to sensor provides a continuous gradient output. With six sensors in this format we are able to accurately monitor about 99° (10° to 109°) .

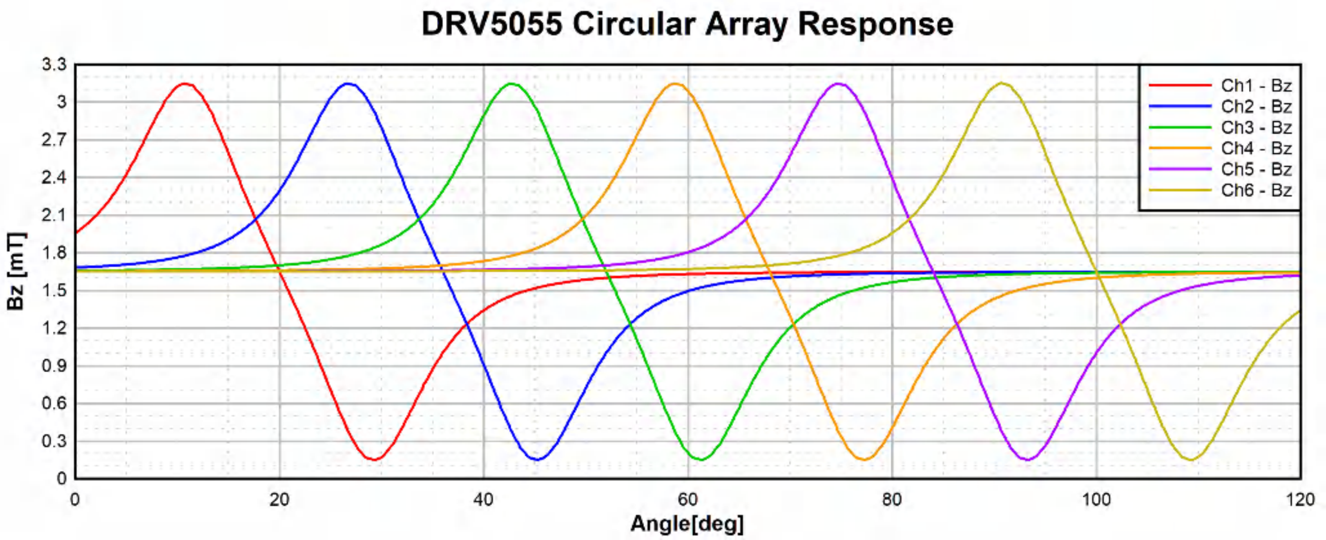

Figure 4-2. DRV5055 Circular Array Output

With this implementation of the linear Hall sensor array, we are now able to track movement along a circumference. Typically angle calculations can be done with 2 sensors installed adjacent to a rotating cylindrical magnet. A rotational array configuration allows for flexibility of magnet placement and is useful in cases where it is not practical to place a magnet or sensors on or near the axis of rotation.

5 Identifying Sources of Error

To explore the solution further, the DRV5055EVM was modified to use all four sensors with the A1 sensitivity option. A magnet matching the geometry and material in Linear Transit Position Sensing was selected for consistency.

Absolute position of the magnet was driven using a motorized motion controller along a single axis of motion, and the PCB was positioned such that the 8 mm air gap to the magnet was maintained for the full transit.

The captured data helps show the impact of various sources of error which may be present in a design.

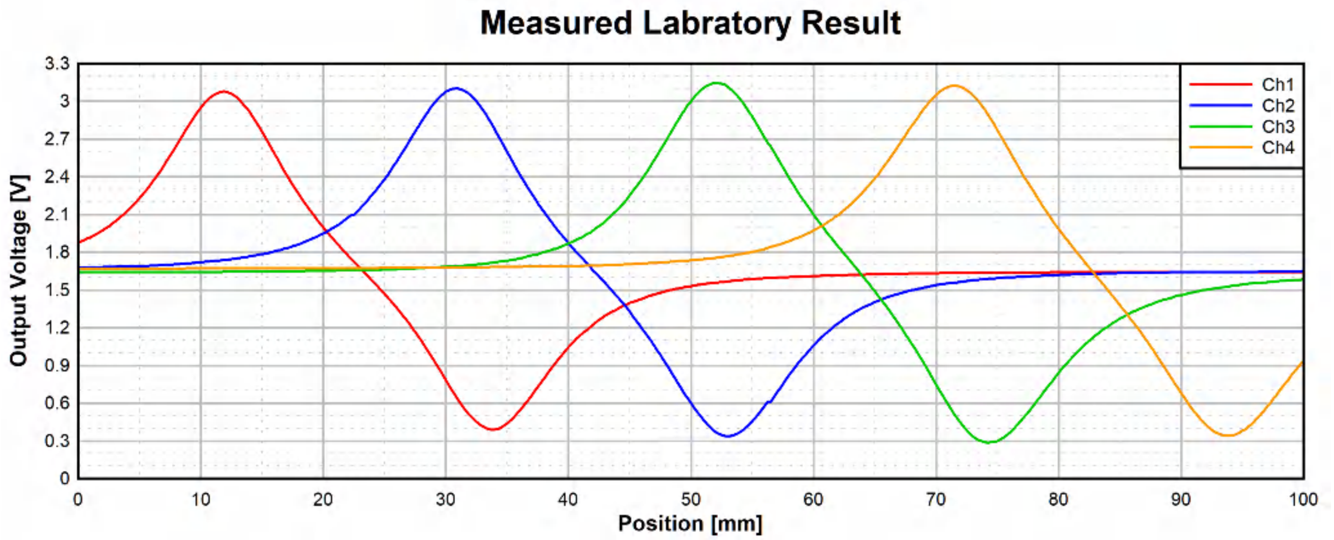

Figure 5-1. Measured DRV5055 Array Output

At an initial glance, the output data closely resembles the simulation data, and the peak values correlate very well. In this case, however, the through-hole package variant (TO-92) was used in order to be compatible with the EVM. Alignment was variable during soldering and each device will have a slightly different sensitivity. Both of these errors will cause that each device will detect a slightly different peak amplitude.

Careful review of the data also shows that the output is not perfectly linear during the optimal region for each sensor. The magnet should be traveling parallel to the axis of polarization. However, a slight rotation of the magnet from parallel produces a slightly non-linear output.

To see the total impact of these errors, we must continue the effort by calculating the estimated position of the magnet. Two calibration points, 8 total, were taken at the upper and lower end of each sensor's linear region. These points were used to calculate dY/dB and define the zero location for each sensor. Using this along with the outlined algorithm in Linear Array Design produces a plot representing the entire transit of the magnet.

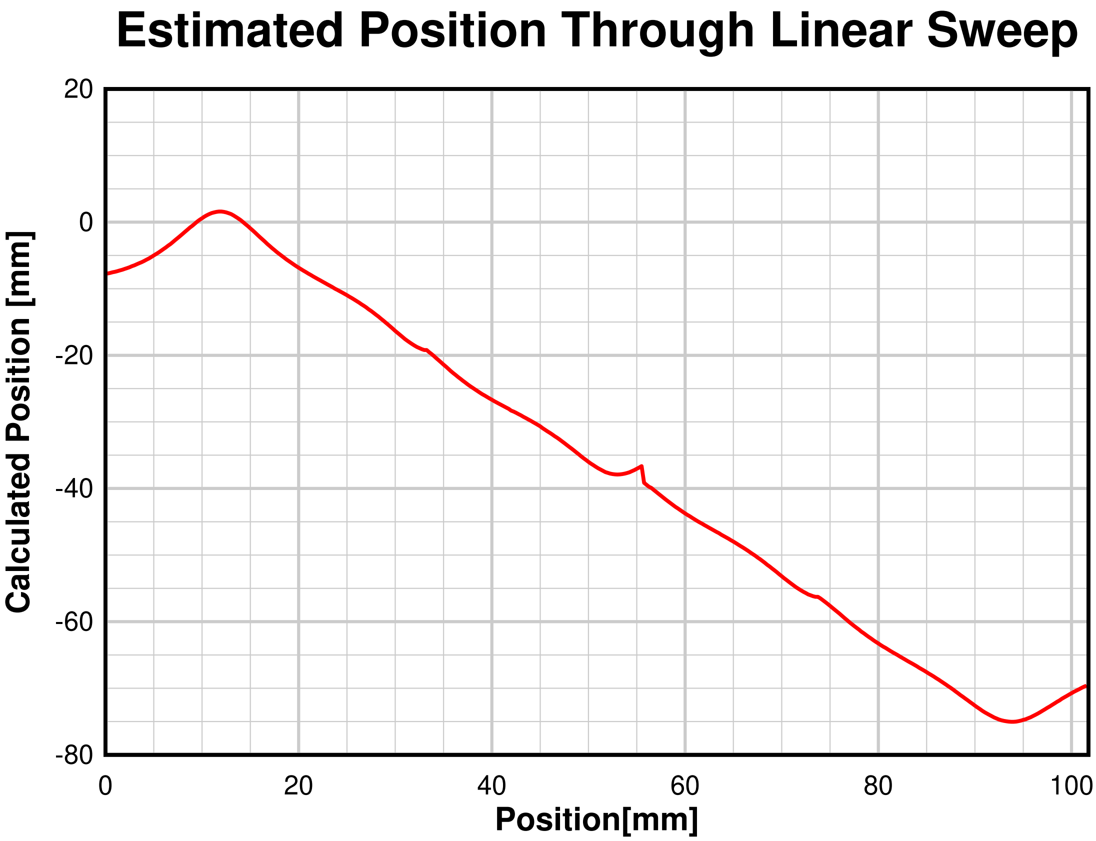

Figure 5-2. Estimated Magnet Position

Using the entire data set results with a clearly defined region where a 1:1 linear response is evident.

If we allow the magnet to travel beyond the linear region for either the first or final sensor, we observe uncertainty in absolute position. The non-linear portion of the output maps into the expected value for the linear region and provides a result the does not reflect the actual stroke position of the magnet. We actually calculate it has moved the opposite direction.

There is also a very clear up-tick that is observed in this data set at about 55 mm. This is the result of unequal spacing between the sensors on the PCB. In the transition from device 2 to device 3 the device spacing is slightly larger than the measurable length of the magnet. As a result, the output of the second device is still selected until the linear region of sensor 3 is realized. Had the sensors been placed closer, this error would not have occurred, but the total measurable length would also be reduced. To achieve this same distance without this error, it would be better to add another sensor along the path and to have each sensor spaced evenly.

6 Summary

Linear Hall sensors are powerful devices to enable robust position tracking by providing critical mechanical feedback via contactless sensing. This can be particularly helpful in increasing overall system reliability. As magnet size increases, cost and availability can limit manufacturability. In these cases, it is often more practical to use linear arrays of sensors. When a linear array is implemented correctly, a modestly sized magnet allows for an accurate working solution.

The linear Hall sensor array has a practical use in any scenario that requires continuous granularity across distances larger than the length of the magnet. The simple algorithm scales easily so long as there is means to accumulate all the output data. With an understanding of the errors that can be present, a high degree of accuracy can be achieved.

This can be applied to track the position of an actuator or other type of mechanical plunger, control a knob such as a cordless drill torque selector, monitor an object sliding along either a straight or curved track, and so forth. By adding additional sensors the measurable transit of a magnet becomes multiplied and allows for a wide range of creativity in design.

7 References

- Texas Instruments, *DRV5055 Ratiometric Linear Hall-Effect Sensor Data Sheet*
- Texas Instruments, *DRV5055 Evaluation Module*
- Texas Instruments, *Linear Hall-effect sensor portfolio*
- Texas Instruments, *E2E™ Hall-Effect Sensor Forum*
- Texas Instruments, *DRV5057-Q1 Automotive Linear Hall-Effect Sensor With PWM Output Data Sheet*
- Texas Instruments, *TMAG5170-Q1 High-Precision 3D Linear Hall-Effect Sensor With SPI Data Sheet*
- Texas Instruments, *TMAG5170D-Q1 Dual-Die High-Precision 3D Linear Hall-Effect Sensor With SPI*

8 Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Revision * (October 2020) to Revision A (April 2023)	Page
• Updating application note to include TMAG5170D	2
• Updated References section	14

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