Application Note

Hall Sensor and Magnet Selection for Auto Body Motor Module Design

TEXAS INSTRUMENTS

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Position Sensing

ABSTRACT

Auto body motor modules enable many of the luxuries found in modern automobiles. Motor modules consists of a gear train and an electric motor, usually packaged in a shared housing, and are used to drive a geared lever or pulley system that in turn moves a mechanical accessory, like a window, car seat, or sun-roof. This application note uses a window regulator to illustrate the interaction between the mechanical assemblies of the regulator and their impact on the magnet and Hall-effect sensors used to monitor the motor in the regulator.

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1 Introduction

While formerly considered a luxury, motor-driven windows, sunroofs, seats, and other accessories are common-place in modern vehicles. Some applications - like a window regulator - need only a single motor module to support movement through a single dimension. Other applications, like an adjustable seat can require three or more distinct modules to support movement in multiple planes.

At a high level, automotive body modules are composed of a tri-state human machine interface (HMI) switch that translates user-mechanical input into an electrical stimulus that is then processed by a microcontroller that initiates a bridge circuit to spin a motor. The spinning motor connects to a gear box that trades speed for torque to move the window. Depending on whether the window is engaged by the driver or the passenger, window movement can be transitory and occur while the tri-state switch is engaged. Or a transitory press is sufficient to make the window completely open or closed. Such behavior as the latter, requires yet another circuit block of feedback.

Figure 1-1 illustrates a high-level view of the intended system operation. Section 2 and Section 3 provide some insight on the electromechanical chain between the motor and window and the Hall-effect feedback system that controls the window.
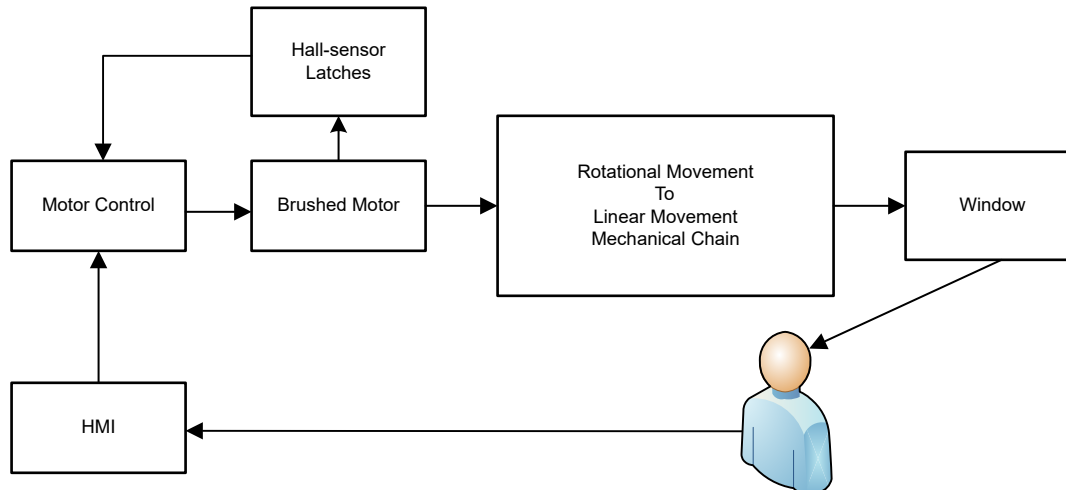

Figure 1-1. System Block Diagram

Introduction

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A motor-driven accessory, like a power window, uses a lever or belt-driven actuator driven by a motor module which in turn contains a motor, gear train, external electrical connections, and mechanical couplings, all integrated into a rugged housing. The example in this application note focuses on a window regulator that uses a geared lever in a scissor-arm assembly to move a window glass pane vertically, as shown in Figure 1-2.
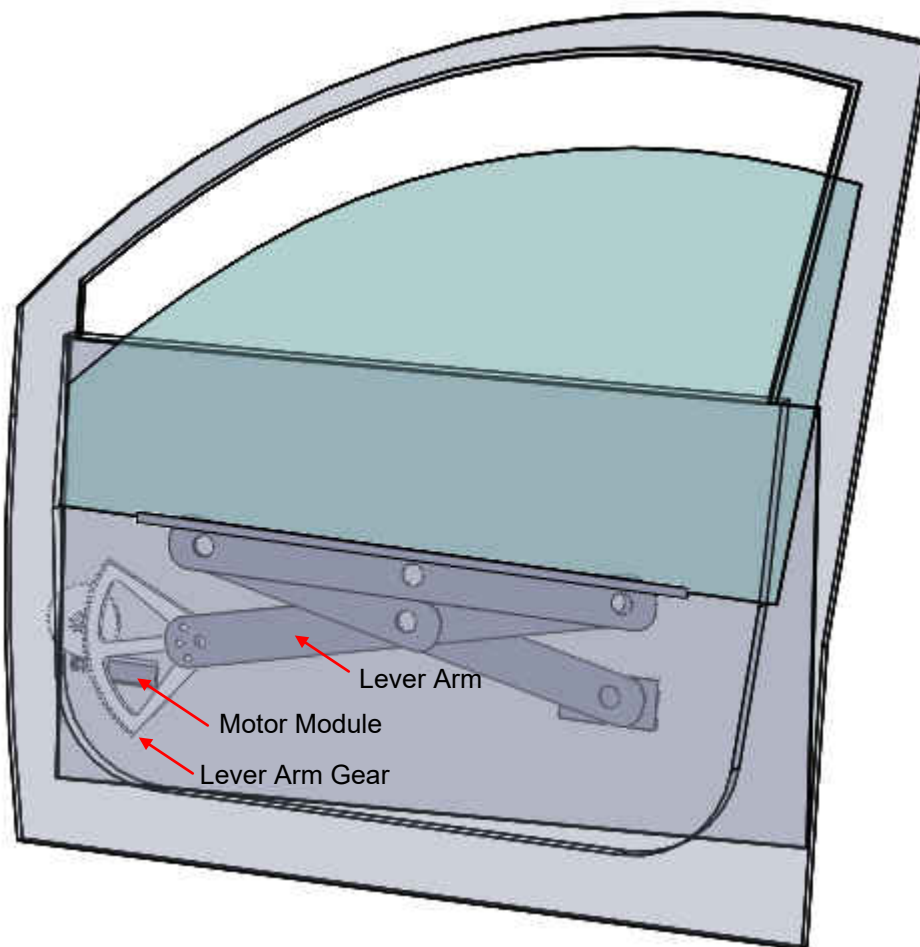

Figure 1-2. Window Regulator

The most common motor choice is a low-cost, brushed DC motor which, unlike brushless motors, has no built-in sensors. As a result, some kind of external monitoring is needed for estimating the position, speed, and direction of a motor. For example, monitoring the window position informs the system if a window is 25%, 50%, or 100% closed. Monitoring the window can also allow the control system to balance a desired open or close speed requirement with motor efficiency. In either case, estimating window position, speed, and direction is best accomplished by directly monitoring the motor rotation and direction.

One way to estimate motor position, direction, and speed is to monitor the motor supply voltage, current, or both, and then count ripple axis crossings that occur as the motor revolves. While seeming like a useful approach, this method bases the estimates on an indirect metric – power supply ripple – and does not directly monitor the actual turning of the motor, and the physical movement of the accessory. Excess ripple caused by poor electrical connections, aging components, or EMI can result in unreliable estimates of direction, speed, and position.

An efficient and accurate method to directly monitor the turning motor is by mounting a multipole ring magnet on the motor shaft and using Hall-effect sensors and latches to monitor the magnetic field variations as the shaft spins, as illustrated in Figure 1-3. While this approach uses a magnet, the method has the advantage of directly monitoring the turning motor shaft and providing accurate estimates of motor position, speed, and direction.
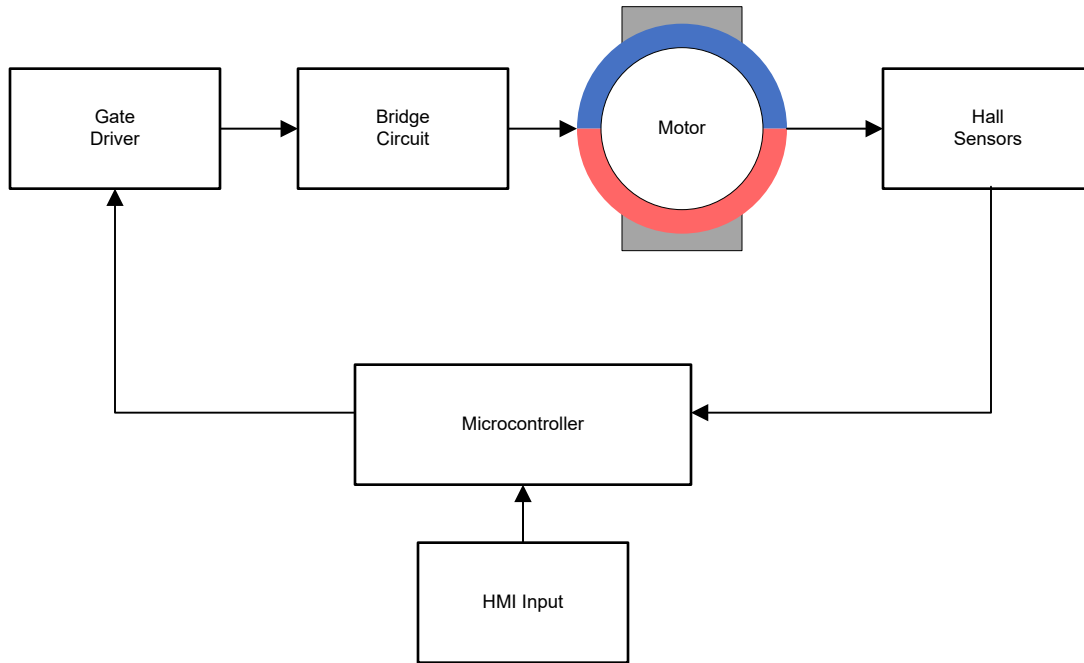
Figure 1-3. Circuit Block Diagram

Figure 1-4 shows a more detailed view of the motor-monitoring devices and the early stage of the regulator gear train. The multipole ring magnet on the turning motor shaft is monitored by Hall-effect sensors mounted on a nearby PC board. As the spinning ring magnet moves through successive changes in north and south polarity, the Hall sensors provide output signals based on the time-varying magnetic fields.

Figure 1-4. Motor Monitoring With a Ring Magnet and Hall-Effect Sensor

The Hall sensors recommended for this application are latches, with output behavior illustrated in Figure 1-5. These devices have *high* or *low* binary outputs that are functions of the detected field relative to the internal threshold of that device. These thresholds are typically symmetric about zero (0 mT) with the B_{OP} trigger corresponding to a positive, magnetic-south fiel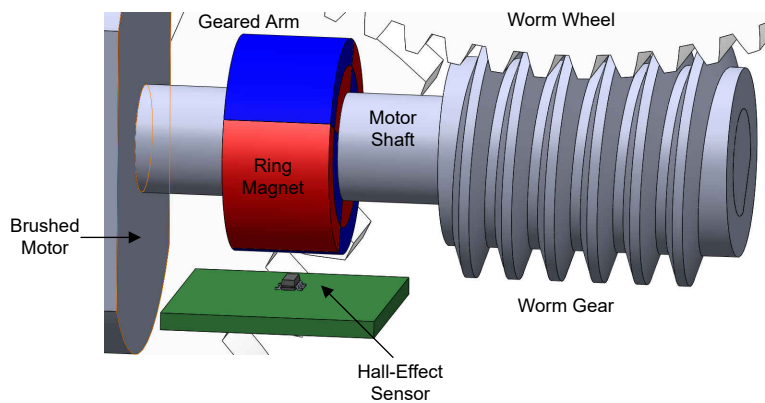d passing through the Hall-element of the device and the B_{RP} trigger corresponding to a positive, magnetic-north field passing through the Hall-element of the device.
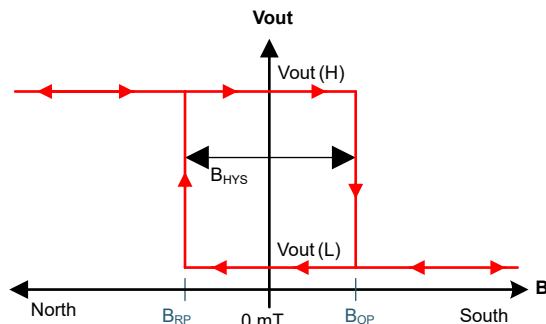
Figure 1-5. Latch B-Field Response

Figure 1-6 illustrates how the alternating polarity of the magnetic field causes the output of the Hall sensor to change as the motor shaft rotates. Each polarity flip of the magnetic field causes an output state change for a Hall element and every two polarity flips results in a pulse on the output of a single Hall-element latch. Considering a device with orthogonal Hall elements, it is possible with additional logic circuitry to get an output pulse every time a pole moves past the Hall sensor. A rotating motor shaft and magnet results in a train of pulses that can be monitored and counted by a microcontroller for customized feedback control. For more details, see the *TMAG511x 2D Latch Benefits* application note.
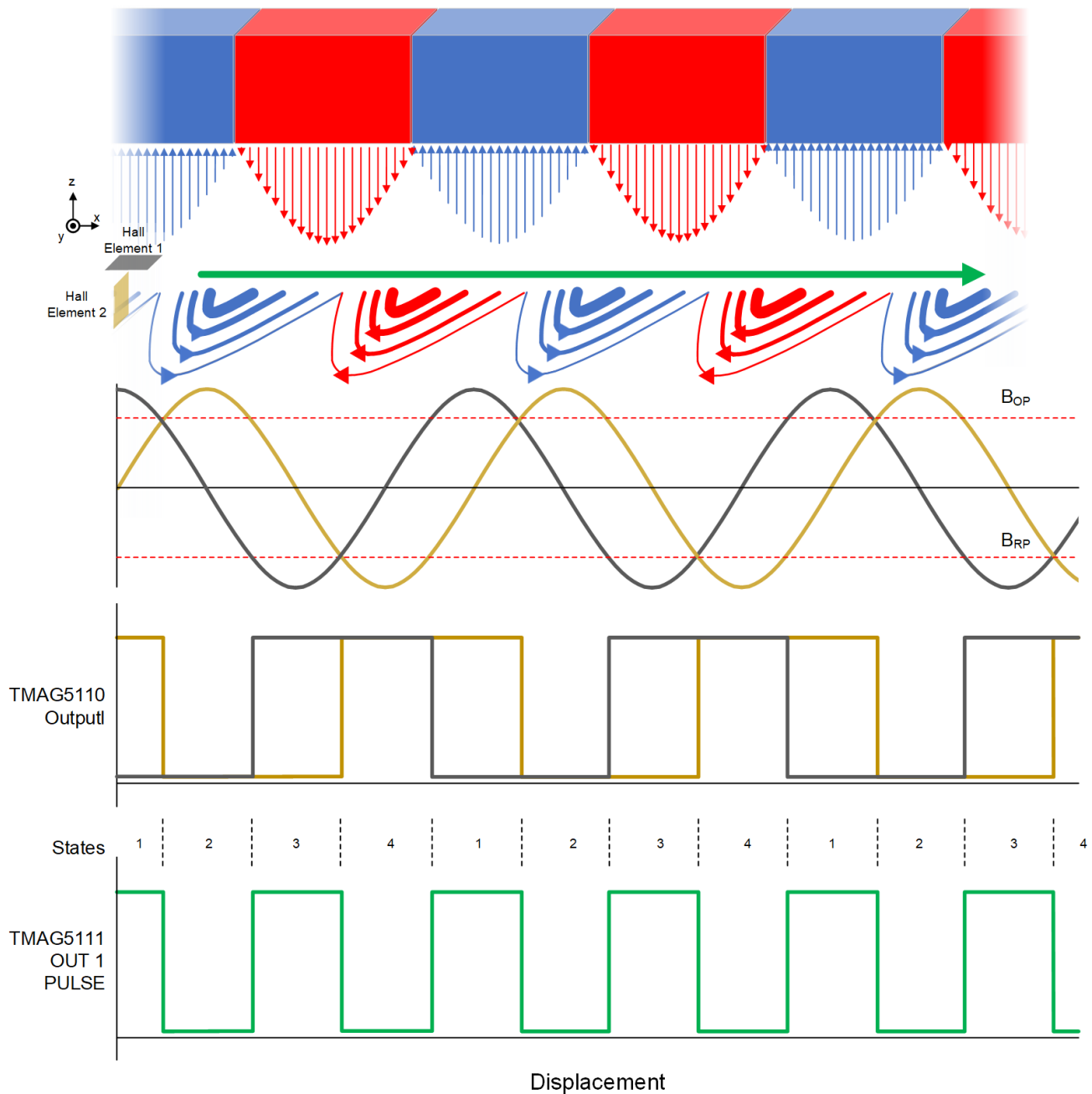
Figure 1-6. TMAG5111 Operation

The goal of this application note is to examine the impact of the mechanical assemblies - levers, gears, and so forth - on the choices for the magnet and Hall sensors, which are in turn used to track position, speed, and direction of the window, sunroof, or seat. The remainder of this document is divided into several sections. Section 2 provides a high-level description of a lever-based window regulator as well as some basic parameters used in the example developed in this paper. Section 2.2 provides a description of the mechanical parts (levers, gears, and so forth) of the window regulator that serve as part of the electromechanical signal chain. Section 3 gives an overview of Hall-effect latches and their parameters that most readily impact this application. The Analysis and Results section provides simulation results of the magnet and Hall sensors that reflect the underlying requirements and gives some recommendations for design and selection of the magnet and Hall device.

2 Window Regulator Description and Example

While auto motor modules provide movement in many different applications this document focuses on a window regulator that uses a geared lever to move the glass pane vertically up-and-down. Figure 2-1 shows a conceptual diagram of the window and regulator in a car door. The motor module that powers the regulator is positioned on the lower left of the regulator diagram, and moves the end of the geared lever arm. The end of the other arm on the lower right side of the door moves about a sliding pivot point. As the motor module pinion gear turns, it drives the geared lever arm, moving the overall scissor assembly up or down – closing or opening the window.

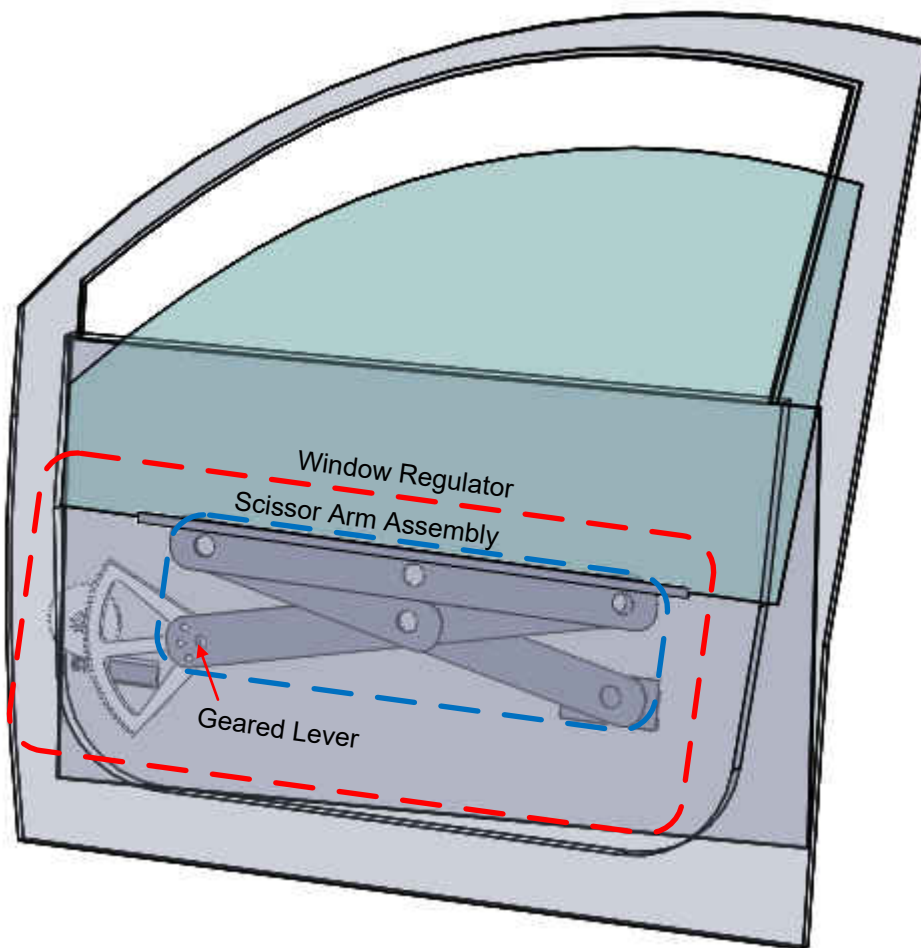**Figure 2-1. Window Regulator**

The motor module is comprised of the brushed DC motor as well as multiple gears including the pinion, the worm-wheel, and the worm gears. Figure 2-2 shows how the pinion gear of the module drives the geared lever arm regulator. The pinion gear shares a shaft with a worm-wheel gear (internal to the motor module) that is, in turn, driven by a worm gear on the shaft of the motor.
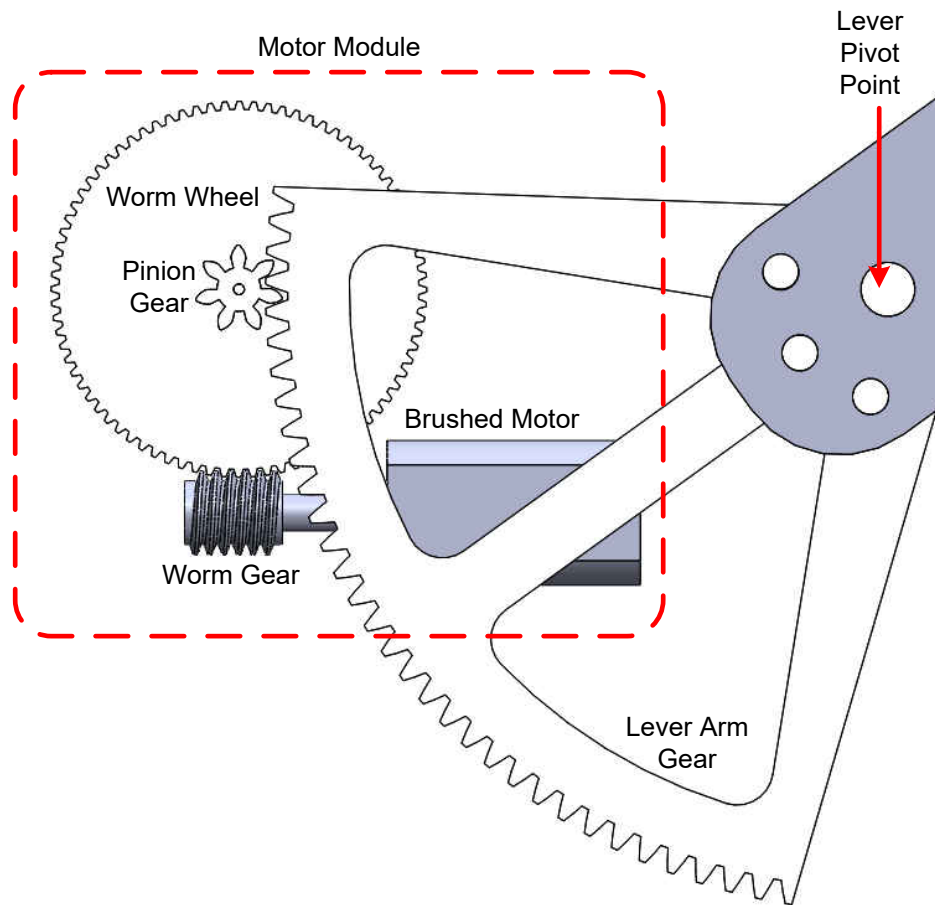
Figure 2-2. Gear Chain

2.1 Design Requirements

The basics of window operation include opening and closing, and for the basis of this design, the position and movement of the window needs to be known. The *Regulator Requirements* table shows some parameters for window travel distance and open and close time taken from a popular car model. These requirements are used to develop the example demonstrated in this document.

Section 4 shows how these parameters ultimately affect the choice of the magnet and Hall-sensors that are used to monitor the motor. System space constraints, materials, and mechanical torque also are important factors, but they are not considered in this application note.

Table 2-1. Regulator Requirements

Specification	Value
Full window movement range	18 in = 457 mm
Completely open to completely closed duration	4 s

2.2 Mechanical Chain - Window Lever

A comprehensive treatment of mechanical behavior is beyond the scope of this paper. However, understanding the impact of the salient mechanical specifications on the magnet, Hall sensor and motor, and also knowing the device pairings and design margins is necessary. By using a model of the mechanical assembly (gear train coupled with the window lever), we will determine the motor speed needed to support the window open and close velocity and the resolution (accuracy) of the window position. We will also determine the Hall sensor bandwidth needed to meet the mechanical requirements.

The first stage of the mechanical chain is the window lever. In this approach, the window movement is symmetric about the lever gear x-axis. As an example, assuming an arm length of 12 in (304.8 mm), calculate the angle of rotation. The end of the arm travels in an arc and the angle for half the window vertical travel distance is found using Equation 1.

$$\text{lever terminal angle} = \arcsin\left(\frac{\frac{\text{Full Wndow Displacement}}{2}}{\text{lever length}}\right) = \arcsin\left(\frac{\frac{457 \text{ mm}}{2}}{304 \text{ mm}}\right) = 48° \tag{1}$$

The movement of the window regulator can be surprisingly linear, in spite of the nonlinear functions in the lever equation. The plot in Figure 2-3 shows the near-linear window movement - from the example regulator - versus the number of gear rotations.
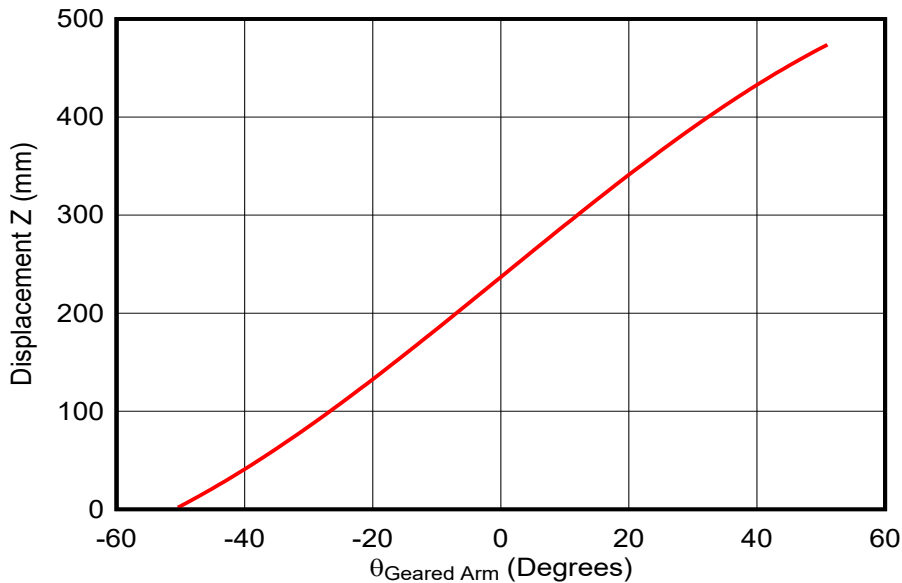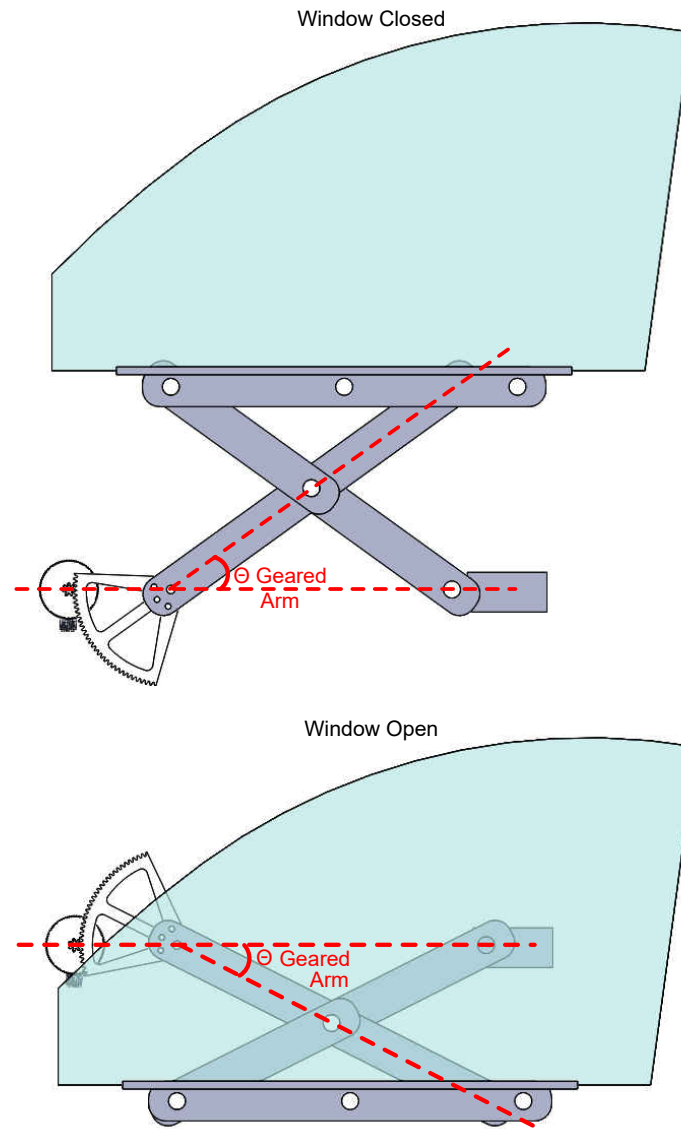

Figure 2-3. Window Movement

Figure 2-4. Window States

For the purposes of the developing example based on a window regulator for a popular car model, assume the mechanical requirements of the regulator are equivalent to a 120 tooth spur gear to be used on the arm. Based on the angles calculated in Section 2.2, only a fraction of the total spur is needed for the geared window lever. In other words, the lever gear does not make a full 360 degree rotation, so the gear does not need a full complement of 120 teeth . Recall Equation 1 is for a rotation equivalent to half of the total window movement, which defines the partial rotation of the lever gear. Now the minimum number of window lever gear teeth, N_{GL}, can be calculated.

$$\frac{2 \times 48°}{360°} = \frac{N_{GL} \text{teeth}}{120 \text{ teeth}} \tag{2}$$

$$N_{GL} = 120° \times \frac{2 \times 48°}{360°} = 32 \text{ teeth} \tag{3}$$

The next step is to consider individual points in the gear train and then create an overall model. The gear model - coupled with the window open and close time - helps develop an understanding of the speed requirements for the motor and, in turn, the magnet selection and the Hall sensors.

The individual points in the gear train use the gear parameters in the developing example. The 32-tooth lever gear interfaces with a 7 tooth pinion gear. The number of pinion gear rotations that occur as the lever arm raises or lowers the window is found using Equation 4.

$$\text{pinion rotations} = \left(\frac{\text{lever gear teeth}}{\frac{\text{pinion teeth}}{\text{pinion rotation}}} \right) = \left(\frac{32 \text{ teeth}}{7 \frac{\text{teeth}}{\text{rotation}}} \right) = 4.57 \text{ rotations} \tag{4}$$

The pinion shares the same axle as a worm wheel gear - which is internal to the motor module - and therefore the worm wheel gear rotates at the same speed as the pinion gear.

$$\text{pinion rotations} = \text{worm wheel rotations} \tag{5}$$

The worm wheel gear is driven by a worm gear that is on the motor shaft. Worm gears are considered 1 tooth gears, which means 1 tooth is used per motor shaft rotation. Benefits of the worm gear are that the gear trades speed for torque, which implies a powered motor is unnecessary to keep a window in position or prevent someone from trying to pull down the window.

$$\text{worm gear rotations} = \left(\text{worm wheel rotations} \times \frac{\text{worm wheel teeth}}{\text{worm gear teeth}} \right) = 4.57 \text{ rotations} \times \frac{80 \text{ teeth}}{1 \text{ tooth}} = 365.7 \text{ rotations} \tag{6}$$

$$\text{worm gear rotations} = \text{motor shaft revolutions} \tag{7}$$

Thus far, the points in the gear train have been detailed. Now the total gear ratio (from the motor to the lever gear) can be calculated, which allows the motor speed to be determined. Beginning at the motor and then moving along the mechanical path formed by the worm gear, worm wheel gear, pinion gear and finally the geared lever:

$$R_{REG} = \left(\frac{N_{GL}}{N_{PG}} \right) \times \left(\frac{N_{WW}}{N_{WG}} \right) \tag{8}$$

where

- N_{GL} = Number of teeth on the geared lever
- N_{PG} = Number of teeth on the external pinion gear of the motor module
- N_{WW} = Number of (internal) worm wheel gear teeth
- N_{WG} = Number of (internal) worm gear teeth driving the worm wheel = 1

A "revolution" of the geared lever (with N_{GL} teeth) represents the window going from fully closed to fully open, or vice-versa as shown in Figure 2-4. As a result, the total gear ratio R_{REG} is interpreted as the number of motor revolutions needed to open or close the window.

The motor speed needed to support a window going from fully closed to fully open or vice-versa is found using Equation 9.

$$S_M = \frac{R_{REG}}{T_{WIN}} \tag{9}$$

where

- T_{WIN} = period of window open or close

The ongoing example is developed further in the Analysis and Results section.

3 Hall Devices and Magnet for Motor Monitoring

So far, this application note has focused on how the mechanical chain of the system translates the rotational movement of the motor into vertical window movement. The next step is to look at the magnet and Hall sensors used to monitor motor speed as illustrated previously in Figure 1-4, which shows a multipole ring magnet on the motor shaft and the Hall sensor positioned just below the magnet. As the magnet spins, the resulting time-varying magnetic field is monitored by the Hall-effect latch. For more information on magnet selection, see the TI E2E™ FAQ TMAG5170: How does Magnet Selection Impact Hall-Effect Angle Measurements? as well as the references shown in the bibliography.

Monitoring motor speed and direction requires two appropriately placed Hall-effect latches. For more information, see the *TMAG511x 2D Latch Benefits* application note. Orient and space the Hall-effect latches such that the flux density from the magnet is sufficient for triggering the latch thresholds in response to magnet rotation. Additionally, space the two sensors of the latch such that there is delay between their latching behavior. Figure 3-1 shows one possible ring magnet – device configuration in which either a 2D latch or dual planar latch can be used. The red squares in both devices indicate the two sensing Hall-elements that are needed for this application. Other magnet – device orientations that can be considered are listed in Figure 3-2 through Figure 3-13; however, the *TMAG511x 2D Latch Benefits* application note discusses how dual planar might not be suitable for some of the configurations.
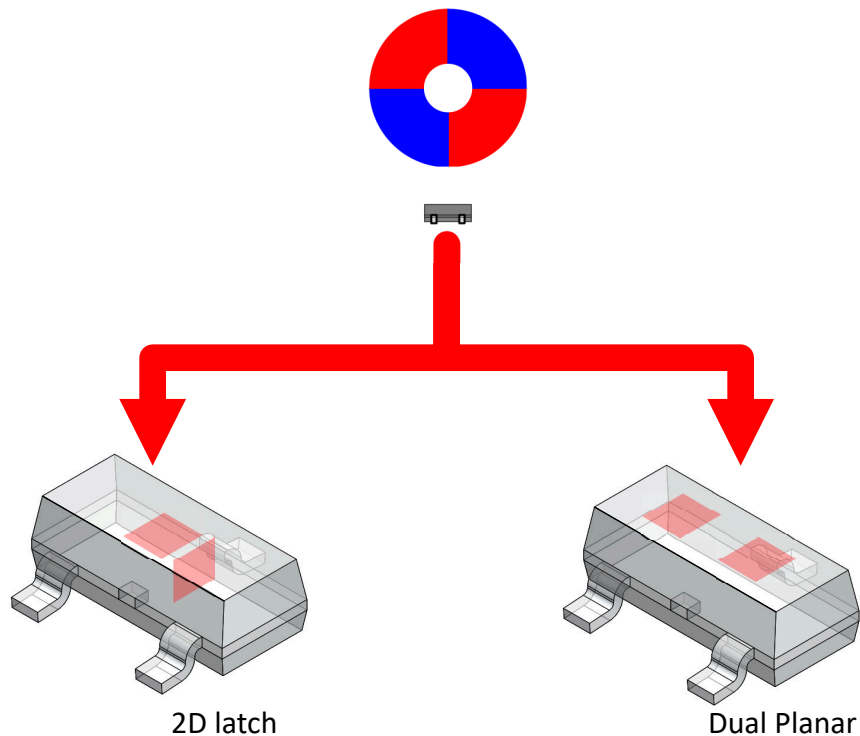

2D latch | Dual Planar

Figure 3-1. 2D and Planar Latch Implementations
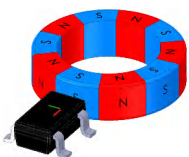
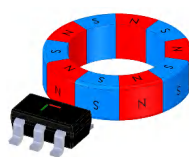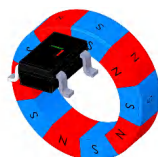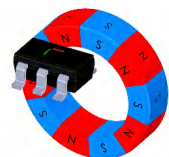**Figure 3-2. XY Outer Edge 1** | **Figure 3-3. XY Outer Edge 2** | **Figure 3-4. XY Side Edge 1** | **Figure 3-5. XY Side Edge 2**

Figure 3-6. ZX Outer Edge 1

Figure 3-7. ZX Outer Edge 2

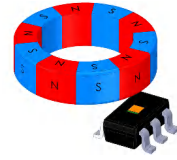**Figure 3-8. ZX Side Edge 1**

Figure 3-9. ZX Side Edge 2

Figure 3-10. ZY Outer Edge 1

Figure 3-11. ZY Outer Edge 2
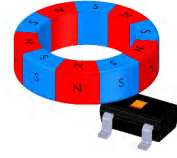

Figure 3-12. ZY Side Edge 1

Figure 3-13. ZY Side Edge 2

Upon selecting the best latch orientation, appropriate magnet-to-sensor spacing must be determined. As noted in the *Introduction*, latches give an active LOW output when the magnetic field is above the operating threshold (B_{OP}), and a HIGH output when the magnetic field is below the release threshold (B_{RP}). The thresholds are separated by hysteresis (B_{HYS}), which prevents noise-induced toggling at a threshold and maintains the state of the last crossed threshold.

Magnet-to-sensor spacing constraints are chiefly dependent upon the field strength of the magnet at the Hall sensors. The key magnet parameters that influence field strength include remanence (with units of milli-Tesla: mT), the number of poles, and the physical dimensions: outer radius, inner radius, and thickness. Other magnet properties to consider are the material, behavior over temperature, and mechanical integrity, which are beyond the scope of this document. A discussion of magnet selection, as well as related references, is found in the TI E2E™ FAQ How Does Magnet Selection Impact Hall-effect angle Measurements?

After determining a viable location for the sensors, verify the sensors have sufficient bandwidth for the system. The motor speed and the number of magnet poles set the rate of change (for example, frequency) of the magnetic field detected by the Hall sensors. Generally, the Hall-sensor bandwidth must be faster than two times the number of poles per second as illustrated in Equation 10.

$$Hall\ Sensor\ BW\ (Hz) \geq (Motor\ Speed\ (RPM)/60) \times (2 \times \#\ Magnet\ Poles) \qquad (10)$$

4 Analysis and Results

First analyze the sensor orientation and spacing relative to the ring magnet. For this design, a magnet and device according to Table 4-1 and Table 4-2 were assessed in a configuration as illustrated in Figure 3-6.

Table 4-1. Ring Magnet Parameters

Parameter	Value
Pole Count	4
Magnet Type	Ferrite (C8B)
Residual Inductance (B_r)	410 mT
Inner Diameter	0.325 in
Outer Diameter	0.615 in
Height	0.39 in

Table 4-2. Hall-Effect Latch Parameters

Parameters	Value
Device Type	2D Latch, speed and direction outputs
Device	TMAG5111
Axis of sensitivity	ZX or ZY
Supply Range	2.5 V to 38 V
Quiescent Current Typical	6 mA
B_{OP} Maximum	2.6 mT
B_{RP} Minimum	–2.6 mT

To perform the analysis, consider a plane located a specified distance (for example, an air gap) away from the radial surface of the magnet. This plane corresponds to the PCB position where the Hall latches are mounted. Depending upon board constraints imposed by the PCB, enclosure, board components, or simply fabrication and assembly tolerances, the device can be offset from directly below the magnet center by some x-offset or y-offset distance as shown in Figure 4-1.
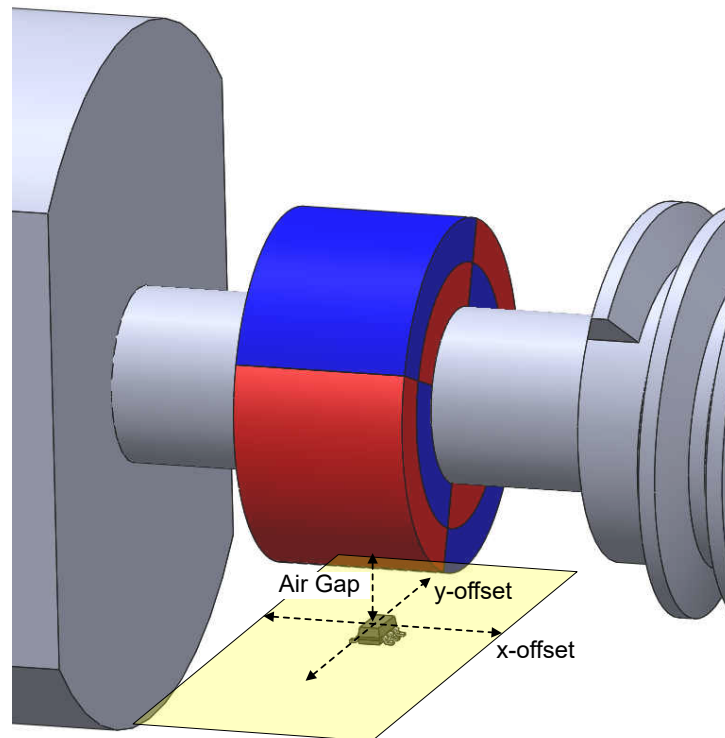

Figure 4-1. Spatial Operating Region

A simulation was conducted of a radial sweep of the ring magnet and the resulting field on the plane below the magnet. Comparing these calculated values to the chosen B_{OP} and B_{RP} thresholds of the Hall sensor allowed an estimate of a set of PCB locations that allow the Hall latch to work properly. The analysis looked at 5° intervals around the point directly below the center of the magnet. The resulting region is shown in Figure 4-2. Outside this region, the sensed field is not sufficiently strong to trigger the latches.
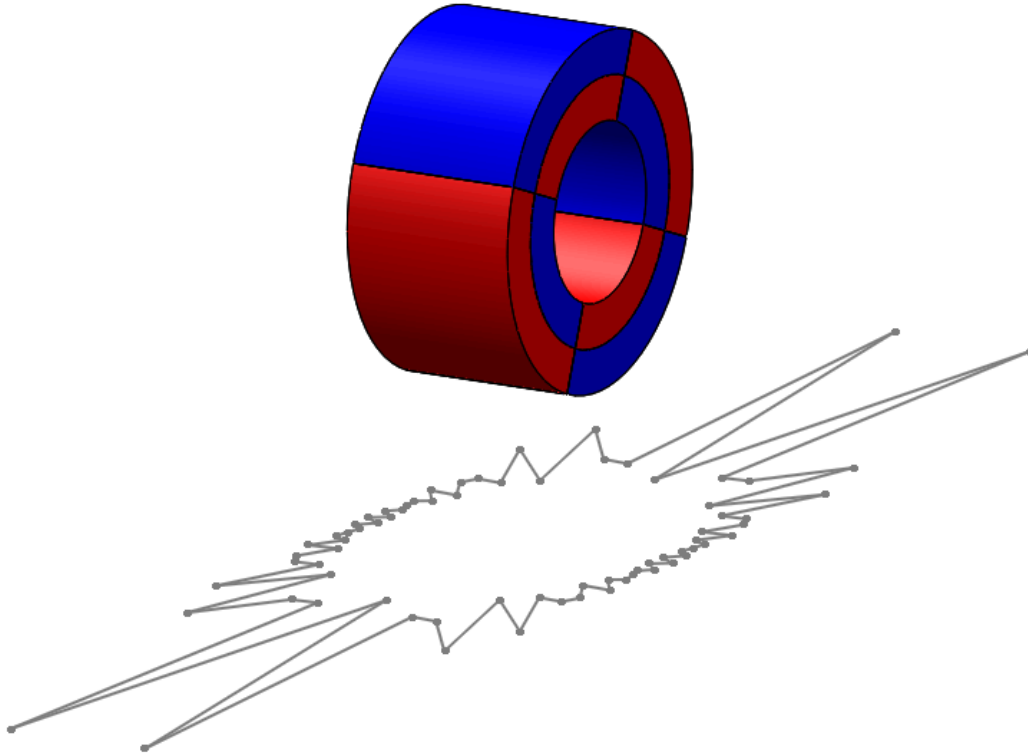
Figure 4-2. Simulated Region With Four-Pole Ring Magnets

The shape and relative size of the simulated region varies with air gap distance (for a given magnet) and the latch trigger thresholds. For this magnet, a typical air gap of 6 mm with ±3 mm tolerance was observed, as indicated in Figure 4-3. The plot in Figure 4-3 shows there is a relatively large region - with respect to the outline of the magnet – which can support the desired sensor and latch behavior, even with loose manufacturing tolerances. However, the area of the region is expected to decrease with increasing air gap between the magnet and device. To gauge how region size varies as a function of air gap distance, Table 4-3 summarizes approximations of the areas for each simulated region, as well as the percentage decrease in the area relative to the area resulting from the 3-mm gap.

Figure 4-3. Simulated Results

Table 4-3. Acceptable Sensor Placement Region Size vs Air Gap

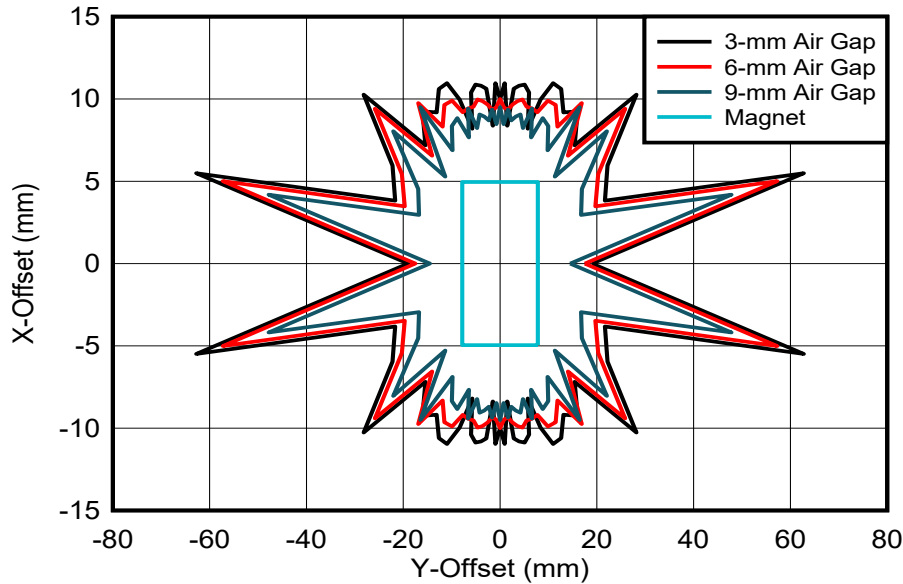| Air Gap (mm)	Area (mm²)	% Decrease With Respect to a 3-mm Air Gap
3	1463	0
6	1250	−14.6
9	922	−37.0

Having established that the Hall latch can properly monitor the magnet for the intended orientation and placement, now determine the required bandwidth. Using the mechanical model and the number of magnet poles, estimate the required motor speed and the required Hall sensor bandwidth.

Equation 8 allows calculation of the total number of motor rotations (R_{REG}) needed to completely open or close a window. Assigning parameter values in the equation based on the ongoing regulator example, a total of 365.7 rotations is calculated.

where

- N_{GL} = # window lever gear teeth = 32
- N_{PG} = # pinion gear teeth =7
- N_{WW} = # worm wheel gear teeth = 80
- N_{WG} = # worm gear teeth =1

$$R_{REG} = \frac{32/7}{80/1} = 365.7 \qquad (11)$$

Assigning the values provided in the regulator requirements into Equation 9, calculate the required motor speed, S_M:

$$S_M = \frac{365.7 \text{ rotations}}{4 \text{ s}} = 91.4 \frac{\text{revolutions}}{\text{second}} = 5485.7 \text{ rpm} \qquad (12)$$

Reality check: the speed of the pinion gear that drives the geared lever is $(N_{GL}/N_{PG})/T_{WIN}$ which gives 4.57/4 = 1.14 revs/s = 68.6 rpm, which aligns with values of some common window motor modules.

Using the computed motor speed in Equation 12, along with magnet pole count and the pulse-to-pole ratio for the device yields the magnet input signal bandwidth . For the TMAG5111 there is 1 pulse-per-pole passing the device. For the TMAG5110 there is 1 pulse on each output per pole pair, thereby halving the required bandwidth

$$\frac{\text{motor revolutions (rotations)}}{\text{window movement duration (s)}} \times \frac{\text{poles}}{\text{rotation}} \times \frac{\text{pulse}}{\text{poles}} = \text{magnetic input signal BW} \qquad (13)$$

Table 4-4. Required Bandwidth per Pole

#Magnet Poles	Required Hall Sensor BW (Hz)
2	183
4	366
6	549
8	731
10	914

How do the estimated Hall sensor bandwidths compare to readily available devices? Three automotive-grade, low-cost, low-power Hall latches - the TMAG5110-Q1, TMAG5111-Q1, and DRV5015-Q1 - have typical bandwidths of 40 kHz, while a third latch, the DRV5011 supports 30 kHz. So at the previously-determined motor speed, and with practical magnet pole counts, the design is well within the bandwidth of readily-available Hall latches.

Another consideration is the resolution of the window position estimate – based on monitoring the motor revolutions – versus the number of magnet poles. Equation 14 shows the relationship between the system requirements and the number of magnet poles. Table 4-5 shows some numerical results from Equation 14. For the TMAG5111, there are 2 states (1 pulse) per pole passing the device. For the TMAG5110, there are 4 states (2 offset pulses) per pole pair. If considering a dual-planar device, there are 2 states per pole pair for the output corresponding to rotational distance, thereby having half the resolution of the TMAG511x devices.

$$\text{window displacement resolution} = \frac{\text{full window range}}{\text{worm gear rotations} \times \frac{\text{poles}}{\text{ring magnet}} \times \frac{\text{device states}}{\text{magnet poles}}} \qquad (14)$$

$$= \frac{457 \text{ mm}}{4.57 \text{ rotations} \times \frac{\text{poles}}{\text{ring magnet}} \times \frac{\text{device states}}{\text{magnet poles}}}$$

Table 4-5. Resolution vs Pole Count

Pole Count	Dual Planar Resolution (mm)	2D Resolution (mm)
2	0.625	0.312
4	0.312	0.156
6	0.208	0.104
8	0.156	0.0781
10	0.125	0.0625
12	0.104	0.0521
14	0.0893	0.0446
16	0.0781	0.0391
18	0.0694	0.0347
20	0.0625	0.0312

Table 4-5 shows that the window step resolution is below 1 mm. While the initial design requirements do not have specified a step size, presume the step size is beneath the average user perception. With an average visual perception around 60 Hz, equivalent to a period of 1/60 Hz = 0.016 s, each visual step is 457 mm/4 s × 0.016 = 1.828 mm at a minimum. However, a user reaction time of around 0.17 s is factored in, then a minimum step of 19.4 mm is observed, or a 4-s open-close duration. Therefore; our four-pole magnet resolution of 0.15 mm is well below what is necessary.

Based on these findings, this preliminary design iteration has quite a bit of margin against failure with a relatively large acceptable placement region, sufficiently low bandwidth, and sufficiently low resolution. At this point prototyping can be pursued. However, such margins suggest there is an opportunity to take another high-level look at the system and determine if modifications to gear ratios, motor speeds, or different magnets yields material cost-savings or greater efficiency. For the Hall-effect feedback stage, a smaller magnet can lower cost because magnets with fewer poles are less expensive.

5 Summary

Designing a motor module is a collaborative effort of system engineers, mechanical engineers, and electrical engineers. Desired user perception guides system requirements that then drive mechanical implementation. Based upon the mechanical implementation, a suitable electronic feedback system can be designed to monitor system operation and ensure proper system operation. Hall-effect latches, such as the TMAG511x, paired with an appropriate magnet provide a flexible and robust solution for such a feedback system.

6 References

- Texas Instruments, *TMAG5110-Q1 What is the role of Hall-effect in car window and sunroof motor modules?*
- Texas Instruments, *What factors should I consider when selecting a magnet for my Hall-effect sensor?*
- Texas Instruments, *TMAG511x 2D Latch Benefits* application note
- Texas Instruments, *How Does Magnet Selection Impact Hall-effect angle Measurements?*

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