Angular position sensing with 2-Axis Hall IC 2SA-10

Introduction

The 2-axis Hall-Effect Integrated Circuit 2SA-10 presented in this application note advances non-contact sensing to a new level by making available the ability to sense 360 degrees of angular position from a single Hall-Effect sensor packaged in SOIC-8. This IC device gives the designers of non-contact sensors the ability to solve many sensing solutions that have been very difficult, if not impossible, using standard, single axis Hall devices. This unique IC provides the core sensing element in 0-360 degree rotary sensors, encoders, resolvers, and joysticks. The basic operation of this technology and several of the many applications will be presented.

Two-axis Hall-Effect IC basic operation

The 2-axis Hall sensor is based on IMC (Integrated Magnetic Concentrator) technology which integrates a standard CMOS process and planar magnetic concentrators. Four sets of Hall elements are placed on the silicon die at the edge of a very small (< 0.2 mm) ferromagnetic disk concentrator. This disk consists of a high permeability and low coercive-field ferromagnetic layer, bonded to the surface of the chip surface. The flux concentrator converts the field components parallel to the device surface into a component perpendicular to the device surface allowing the use of conventional CMOS Hall technology in its fabrication. The perpendicular component of the magnetic field is strongest near the edge of the disk where the Hall elements are located. Flux concentrators provide field magnification without amplifying the device noise.

Hall elements are located at the four quadrants of the disk to provide X and Y outputs, Figure 1. Only one Hall element is required for each axis, however additional gain can be realized and offset reduced by measuring the differential voltages from two devices at each quadrant position. The differential outputs from the X1, X2 and Y1, Y2 Hall elements are processed by the integrated electronic circuitry which includes biasing, amplification, offset cancellation and temperature stabilization functions.

Full scale linear outputs of 2.5 volts plus and minus 2.0 volts can be obtained at field strengths as low as 20mT (200 gauss). The Vx and Vy outputs are balanced with minimal offsets and because of the single die construction, the two outputs are not only matched, they have excellent tracking performance.

Several unique performance characteristics inherent in this technology make it ideal for precision sensing applications. They are 1) very low non-linearity of less than 0.1% and 2) very low hysteresis of less than 0.03 %.

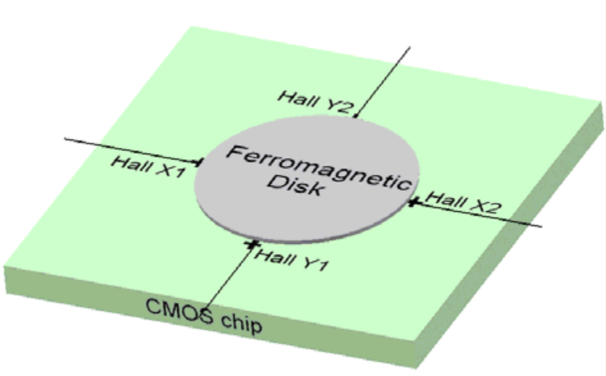


Figure 1a - The integrated ferromagnetic concentrator located at the center of the silicon die with the Hall elements located at the edges of the disk

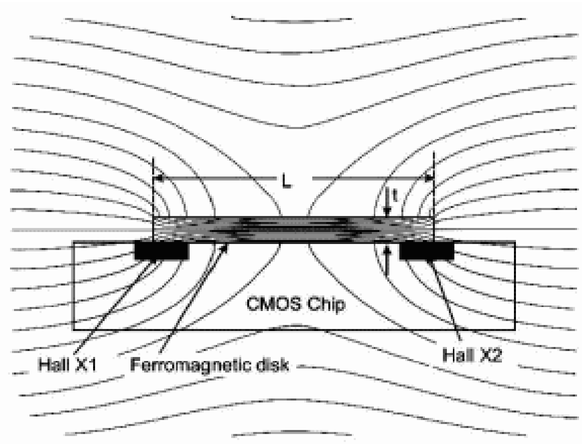


Figure 1b - Parallel flux fields are converted to perpendicular flux fields which are sensed by the Hall

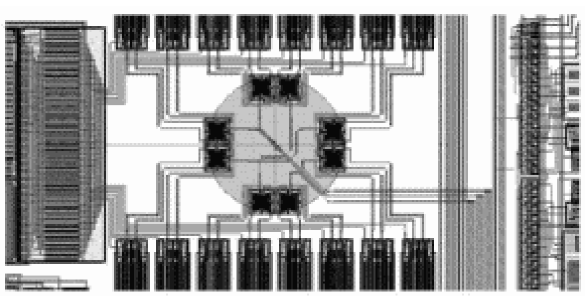


Figure 1c - Layout detail showing the four sets of Hall elements with pi/2 shift.

360 Degree absolute angular position

There are many non-contact angular position sensors using either standard linear Hall IC's or two-axis magnetoresistive sensors. Solutions with linear Hall IC's usually require two sensors at 90° angle shift and a bulky and expensive ferromagnetic yoke to provide an accurate angle signal. Solutions with magnetoresistive sensors provide an output signal with a period of only 180° and need external amplification and offset compensation. The two-axis linear Hall IC 2SA-10 overcomes the drawbacks of both these solutions. It senses over 360 degrees of rotation and provides by amplified Sin/Cos output signals the absolute position information over this range. As shown in Figure 2, a magnet, which is magnetized across its diameter is attached to a shaft and rotated above the IC around the axis of the magnet and IC centerline.

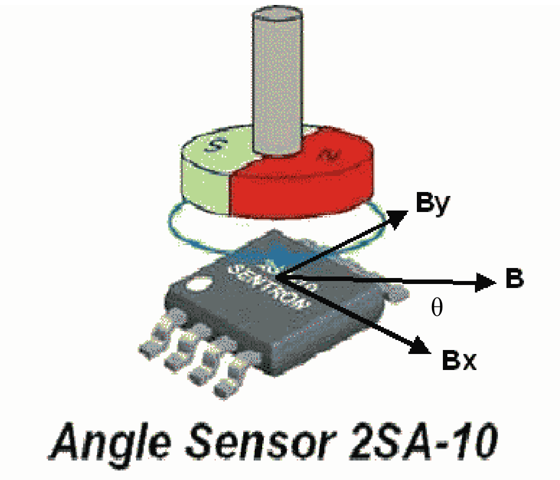


Figure 2 -The 2-axis IC produces outputs proportional to the Bx and By field components of the magnet rotating above the sensor.

As the shaft is rotated, the IC senses the magnetic vector of the field from the magnet and generates signals Vx and Vy that are proportional to the Sin and Cos signals respectively. As shown in the following equations, a voltage representing the absolute angle (a) can be derived from calculating the arctan of the voltages Vx and Vy using a small 8 bit microcontroller or equivalent processor. See Figure 3.

$$Vx = Sx * B*\cos(\theta).$$

$$Vy = Sy * B*\sin(\theta)$$

The IC gain sensitivities, Sx and Sy, are closely matched and track over temperature, therefore we can make an assumption that Sx and Sy are equal

If $Sx = Sy = S$:

Then $Vy/Vx = S*B*\sin(\theta) / S*B*\cos(\theta)$

$= \sin(\theta) / \cos(\theta) = \tan(\theta)$

Therefore: $\theta = \arctan(Vy/Vx) =$ **Vout**

The arc-tangent function repeats every 180º and becomes infinite at 90º and 180º when Vx = 0, however this can easily be accounted for by using the following equations:

For $(Vx>0, Vy>0)$, $\theta = \arctan(Vy/Vx)$

For $(Vx=0, Vy>0)$, $\theta = 90^{\circ}$

For $(Vx<0)$, $\theta = 180^{\circ} + \arctan(Vy/Vx)$

For $(Vx=0, Vy<0)$, $\theta = 270^{\circ}$

For $(Vx>0, Vy<0)$, $\theta = 360^{\circ} + \arctan(Vy/Vx)$

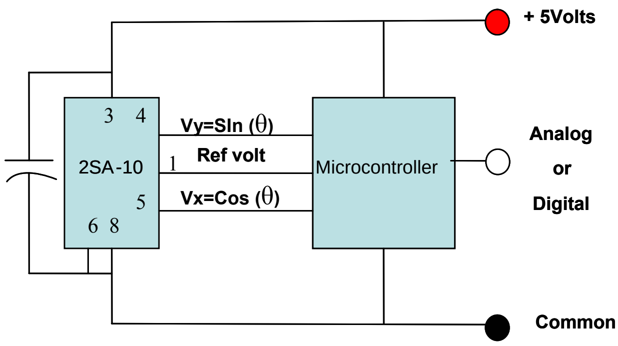


Figure 3a - The outputs from the 2-axis IC are processed by a microcontroller to create an output proportional to the angle of rotation

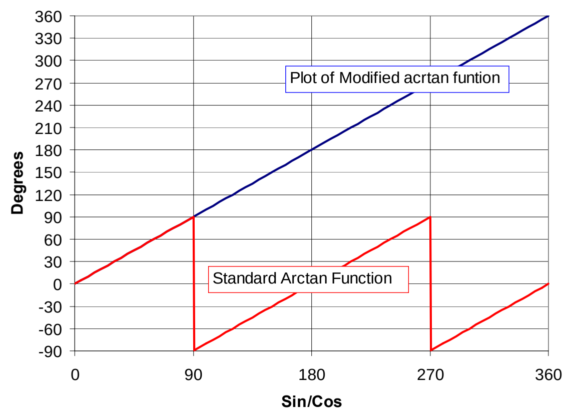


Figure 3b - Typical arctan function vs. output with above equations

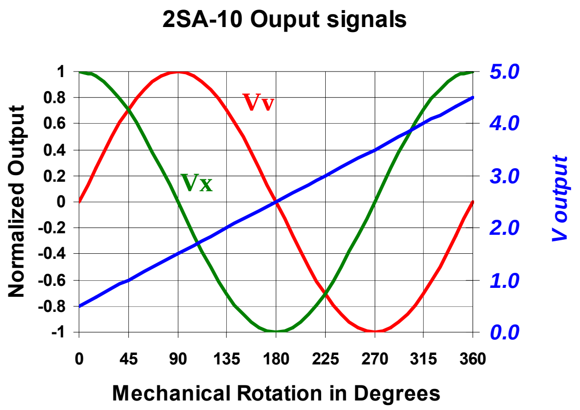


Figure 3c - Linear output voltage as a function of Vx (Cos θ) and Vy (Sin θ).

The above equations require the microcontroller to perform arctan math functions which take time to calculate, another technique which is faster, is to incorporate a memory map to do the arctan function as a lookup table. The Vy/Yx is computed then compared to the memory map with the full resolution of the 360 degree rotation desired. The number of memory locations will depend on that resolution. For example, if a reading of approximately 0.1 degree is desired, 1024 locations plus knowing the plus and minus values of Vx and Vy, can provide 4096 increments for 360 degrees of rotation (0.088°).

The potential variability resulting from changes in S or B are canceled out by dividing Vy by Vx, therefore the analog output voltage representing the angle is independent of magnet strength, temperature effects and gain sensitivity of the IC. The output becomes a function of the magnetic field vector orientation only and will always represent the absolute mechanical position of the magnet over the full 360 degree range. Power can be removed and re-applied without loosing the absolute position of the magnet. Figure 4 illustrates a typical angular sensor using the 2SA-10.

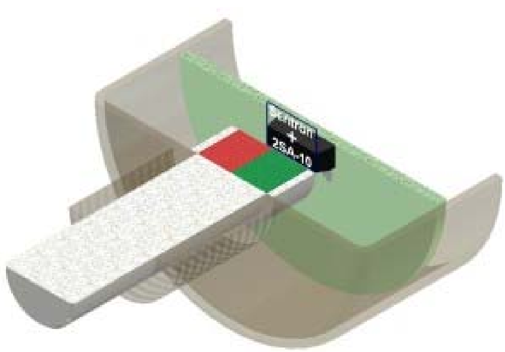


Figure 4 - Cutaway of a typical angular position sensor using the 2-axis Hall IC

The magnet creates a DC field which will project through any non-ferromagnetic material such as aluminum, 300 series stainless steel and plastics. Because of this, the 2-axis IC and associated electronics, if desired, could be mounted in a hermetically sealed metal housing and be mechanically isolated from the rotating mechanism. Another advantage to this configuration is that it imposes zero "drag" on the rotating mechanism. A sensor using this technology for example, could measure the position of a valve inside a sealed housing by mounting a magnet on the internal shaft and the sensor on the outside, Figure (5).

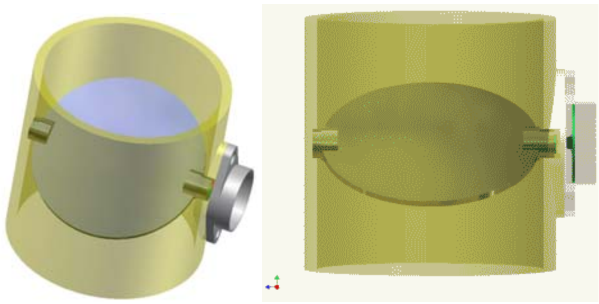


Figure 5. The 2-axis IC and associated electronic circuitry located inside a non-magnetic metal housing can also sense rotation of a mechanism through a metal structure such as a valve shown here.

Having to incorporate a microcontroller to calculate the angle might be considered a negative, but with the microcontroller and the 360 degree information from the IC, the potential sensor solutions are numerous and functionality is greatly expanded. Any custom output curve can be programmed, outputs can be analog, PWM, PPM, or serial data. Mechanical alignment of the magnet to the sensor can be can be eliminated by simply resetting the starting point within the 360 degree range.

Single-axis joysticks

The 2-axis linear Hall offers a simple solution for non-contact single-axis joysticks. Figure 6 illustrates a configuration where the magnet (magnetized across the diameter) is mounted in the shaft of the stick handle and a 2-axis linear Hall IC is mounted on a PCB that is attached to the frame of the device. By placing a sensor on each side of the handle, a dual redundant joystick can be constructed. The IC is located on the centerline of the magnet axis. The angle of rotation can be acquired by calculating the arctan of Vx and Vy similar to the 360 degree rotary application described above. With the microcontroller and the 360 degrees of position information from the sensor, numerous output curves can be generated and the need for mechanical alignment of the sensing device to the rotating handle be can eliminated.

$$V\ out = \arctan(Vy/Vx)$$

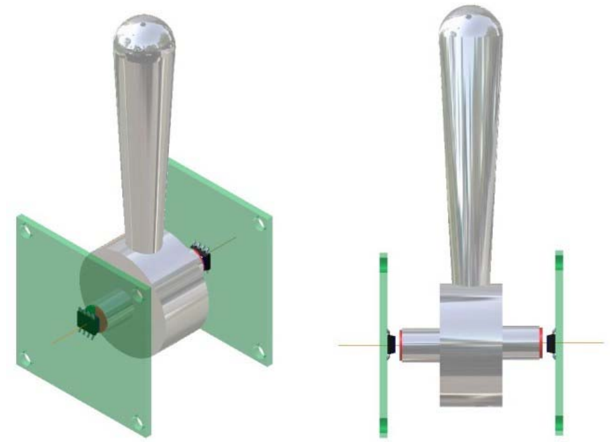


Figure 6 - The 2-axis IC can be mounted on the axis of rotation of a single axis joystick to directly measure the angle of rotation. Two independent sensing circuits can be used to provide redundant outputs.

Two-axis joysticks

Most two-axis joysticks measure their position by mounting two potentiometers to the shafts of a gimbaled system and extracting the X and Y coordinates from these sensors. With a single 2-axis IC mounted at the center of rotation of spherical rotation and a magnet mounted in the handle simple, two-axis, non-contact joysticks can be constructed as shown if Figure 7

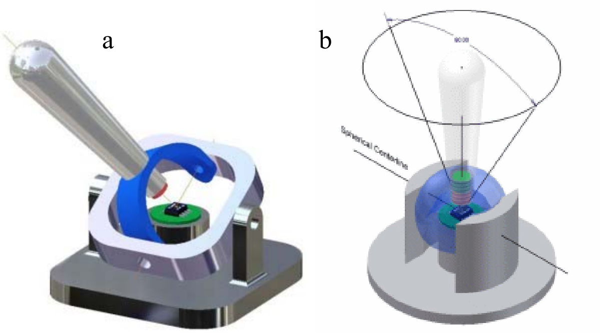


Figure 7 - Gimbaled mount, joystick with 2-axis IC located at the spherical center of rotation. X and Y outputs are linear within +/- 30 º (a). Ball joint, two-axis joystick with IC at spherical center of rotation (b)

The X and Y outputs from the IC are proportional to the vector of the field generated by the magnet that is magnetized along its axis..

The profile of this magnetic field vector is a sine wave with the field vector in the X-Y plane, being zero when the joystick is in its neutral position. See Figure 8. A sine wave has a linear range of less than 1% non-linearity over a 60 degrees range around the zero degree angle. Since most joystick applications have a typical operating range of +/- 30 degrees, the linear output voltage generated by this single 2-axis IC, is well suited for simple, non-contact two-axis joystick applications. With this application, there are no calculations required and the X and Y outputs are directly proportional to the magnet strength and IC sensitivity and can be used directly as shown in Figure 9. Depending on the accuracy requirements, the output levels may have to be calibrated to the mechanical position to compensate for variability in magnetic field strength, B, and circuit sensitivity.

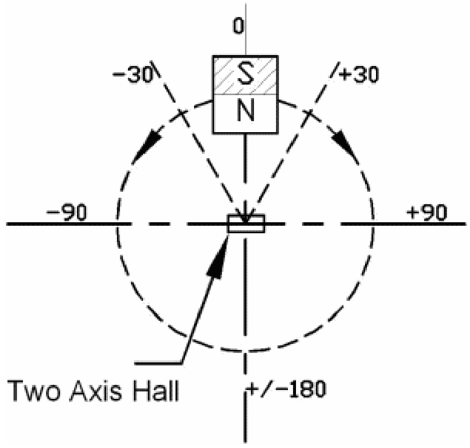


Figure 8a - The magnet is rotated around the 2-axis IC which is located at the center of spherical rotation

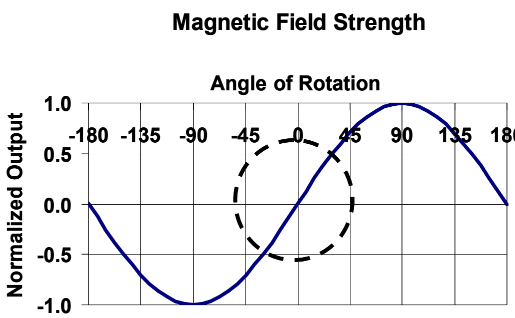


Figure 8b - Expanded view of the Sine wave showing the approximately 60º linear range centered about the zero degree angle.

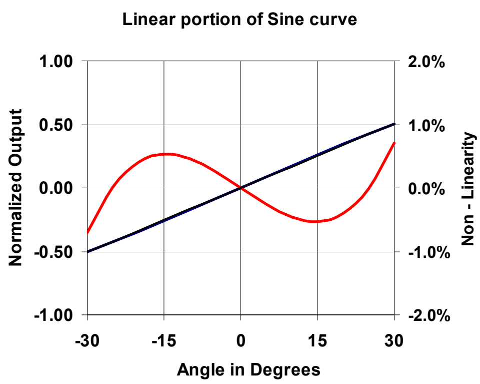


Figure 8c - The non-linearity is shown in red and is less than 1% of full scale

Linear outputs from the 2-axis IC provide X and Y outputs from the joystick +/- 30 degree stroke. The 2.5 V +/- 2.0 volt outputs are referenced to the IC's ½ Vdd (2.5V) reference voltage. The outputs are ratio-metric to the supply voltage.

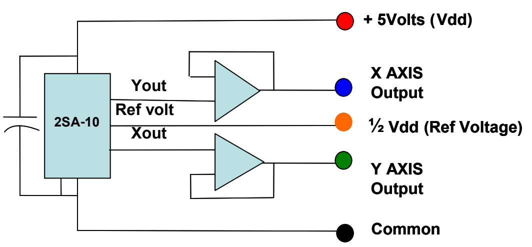


Figure 9 - Linear outputs from the 2-axis IC provide X and Y outputs from the joystick +/- 30 degree stroke. The 2.5 V +/- 2.0 volt outputs are referenced to the IC's ½ Vdd (2.5V) reference voltage. The outputs are ratio-metric to the supply voltage.

High resolution sensor

The example shown in Figure 10 illustrates a way to obtain higher resolution and improved accuracy in a rotary position sensor by using two "X-Y" ICs and two magnets. The magnet associated with the IC on the lower pcb is a single pole-pair magnet and provides a "coarse" measurement by producing one electrical cycle of sine and cosine signals per revolution. The magnet associated with the IC on the upper pcb is a multiple ring magnet and provides a "fine" measurement by producing "n" electrical cycles of sine and cosine signals per revolution, where n = number of pole pairs. Each electrical cycle has a resolution of 0.1º, therefore the total resolution for one complete revolution is 0.1º / n. If n = 8 pole pairs, the resolution becomes 0.1º / 8 = 0.0125º or 45 arc-seconds. The coarse information from the lower pcb is used to locate which sector (pole pair) of the multi-pole ring magnet is in front of the upper pcb IC.

Within one pole pair, or measurement range of 360º/n, the accuracy is also improved by n: Accuracy = 0.5º /n and overall accuracy of one 360 degree revolution can be significantly improved with electronic calibration. The "fine" and "coarse" signals are processed by a microcontroller to generate an output with significantly improved resolution and accuracy. The multi-pole magnet needs to be able to generate approximately +/- 20 to 40mT at the center of the IC in order to obtain +/- 1 to 2 volt output levels.

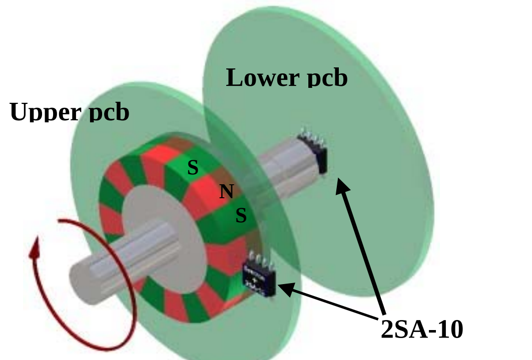


Figure 10 - A multi pole magnet and a single pole pair magnet are used to generate fine and coarse measurements of the angular position.

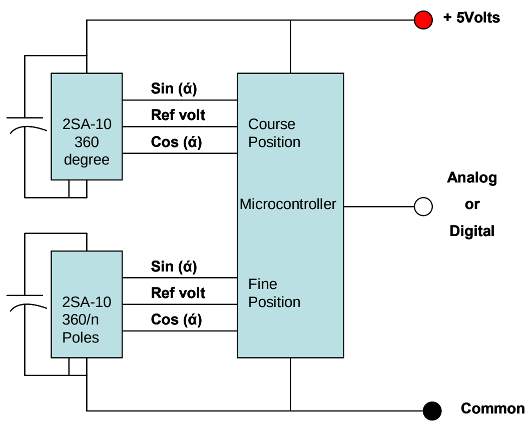


Figure 10b - Basic circuit to process the signals from the two 2-axis IC's .

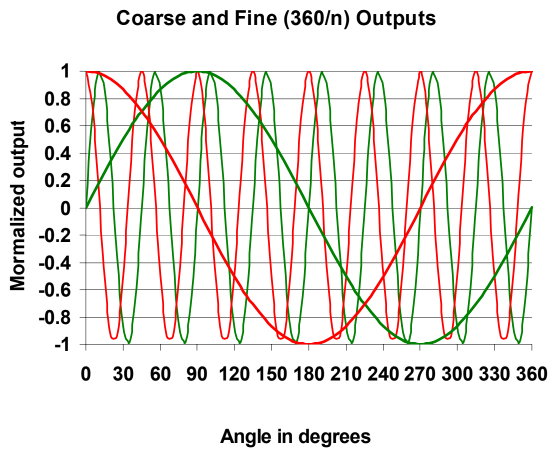


Figure 11 - Graph showing the two sets of outputs from the fine and coarse outputs. For every full resolution, one cycle of Sine and Cosine signals are generated from the coarse sensor while 8 cycles of Sine and Cosine are generated from the fine sensor.

Compass

Another unique application shown in Figure 12 is an electronic compass using the 2-axis linear IC with its 360 degree sensing range. The IC can be mounted over a mechanism which allows a free floating magnet. As the magnet rotates and aligns with the earth's magnetic field, it creates a field vector which is aligned with the orientation of the magnet. The field strength from the magnet is much stronger than the earth's field, which is only about 60uT (600 milligauss) and too low compared to the sensor full scale range. The magnet's stronger field can be detected by the sensor and its horizontal flux lines generate Sine and Cosine voltage signals at the IC's Vx and Vy outputs as the compass magnet rotates around the center of rotation. As with the angular sensor described above, these Vx and Vy output signals can be converted to an analog or digital voltage proportional to the angle θ.

$$V\ out = \arctan(Vy/Vx)$$

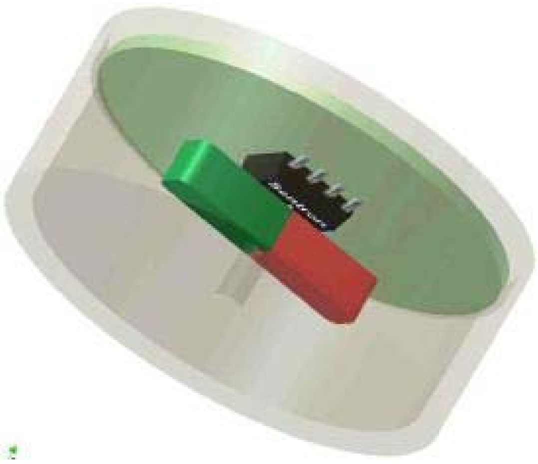


Figure 12a - A side view shows the north seeking magnet just below the 2-axis sensor which senses magnetic fields parallel to the magnet.

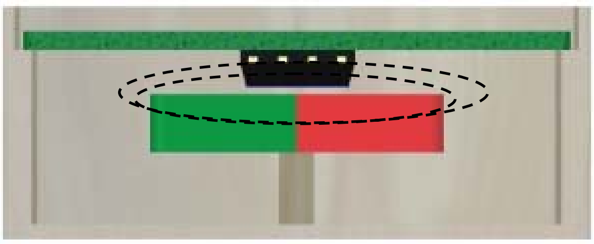


Figure 12b - The earth's field seeking magnet is mounted on low drag bearing assembly allowing free movement

Brushless DC motor control

By placing a 2-axis linear Hall on the end of a brushless DC motor and a magnet inserted into the shaft as shown in Figure 13, two phase, quadrature control signals are generated from the single 2-axis IC. The 2-axis linear IC has a maximum angular speed of 100,000 RPM. The advantage the 2-axis Hall in this application is the elimination of the physical mounting tolerances of the discrete Hall devices that are normally used in DC brushless motor controls. Angular position accuracies can be improved by a factor of greater than 5 as shown in figure 16. This technology can easily be extended in the future to provide three phase outputs.

Figure 13a - The 2-axis IC is shown here mounted on the end of a DC motor to provide two phase quadrature signals

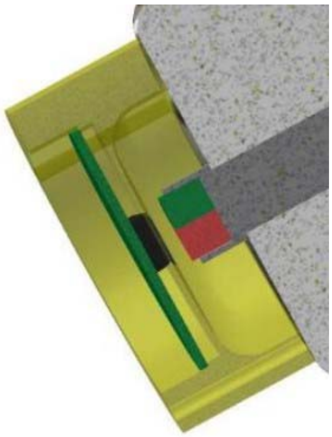


Figure 13b - A magnet is mounted on the end of the rotating shaft. The IC can operate up to 100,000 RPM.

The accuracy of Hall placement in a brushless DC motor is important to maintain precision timing for the motor control. There are a number of error sources that contribute to the total error with two discrete Hall ICs and are listed below:

- Sensitivity mismatch: 5%
- Angular placement: +/- 0.25 mm

- Radial Placement: +/- 0.25 mm
- Temperature tracking: 400 ppm/C

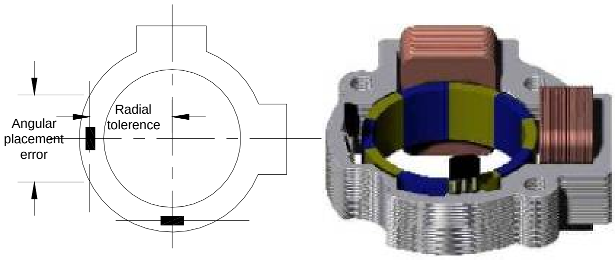
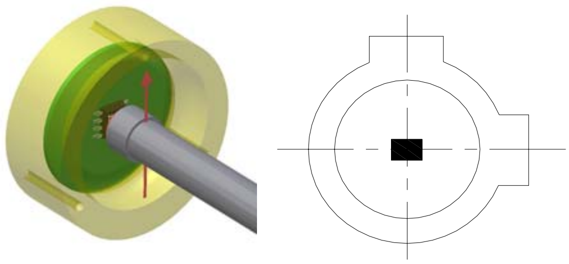


Figure 14 – Typical two-phase brushless motor control Hall placement.

The 2SA-10 eliminates some sources of error and significantly reduces the others and provides an overall accuracy improvement of 5 to 10 times. See Figure 15. The error sources for the 2SA-10 are as follows:

- Sensitivity mismatch: 1.5%,
- Phase error: 0.3º,
- Temp drift mismatch: <50ppm/C



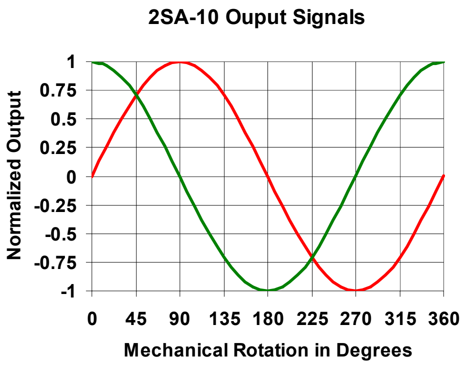


Figure 15 – Only one 2-axis IC located on the centerline of rotation is required to provide quadrature Sine and Cosine signals with high accuracy.

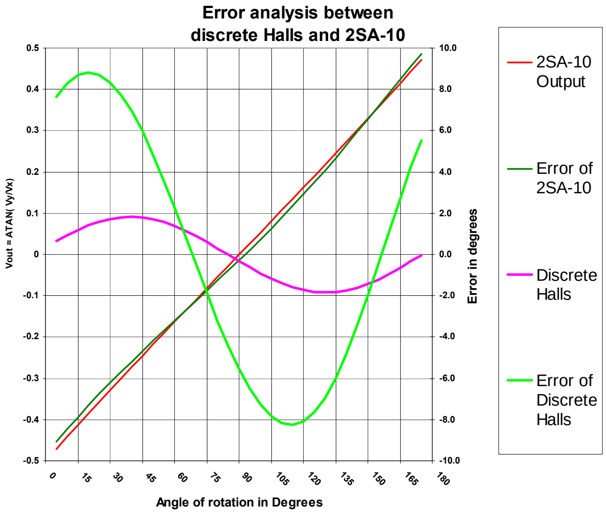


Figure 16 – Comparison of 2SA-10 accuracy and two discrete Halls.

Conclusion

Having the ability to simultaneously sense two components of magnet field at the same point in a single integrated SOIC is unique and, as shown in this note, is capable of solving numerous non-contact rotary position solutions that in the past, have not been in available to the sensor designer. This application note has focused on rotary position type applications only, however there are many other uses of this technology such as single axis linear sensing, 2-axis linear position sensing and surface flux anomaly detection.

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