PRODUCT DESCRIPTION

Technical Paper
STP 97-8B

INNOVATION IN APPLICATIONS-SPECIFIC HALL-EFFECT TRANSDUCERS MERGES DIRECTION-DETECTION SENSING WITH VELOCITY SIGNALS

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ABSTRACT

A new, monolithic Hall-effect sensor IC merges a venerable speed-sensing function with an innovative solution to direction detection to solve a very long-standing need for a fully-integrated device that incorporates both capabilities. This special-purpose HED (Hall-effect device) exemplifies the latest progress in unique magnetic-sensing technology. Conceived and designed for directly sensing both direction (usually rotational) and speed (also normally rotational), this new Hall-effect transducer provides individual digital logic signals that register direction and velocity.

This silicon Hall-effect circuit incorporates two separate, independent Hall-effect elements, their associated amplifiers, plus their latching circuits. The highly sensitive Hall sensor elements (plates) are precisely separated by 1.5 mm, and the two digital outputs are internally coupled to circuitry that decodes velocity and direction. A low-drift BiCMOS process technology is used to guarantee magnetic symmetry of the individual latches, and this helps sustain the necessary signal quadrature relationship. An on-chip regulator powers these direction-detection ICs from 4.5 V to 18 V.

FUNCTIONAL DESCRIPTION

Very critical to this new direction-detection IC is two distinct, individual Hall-effect elements, and an exact spacing of 1.5 mm. Each latch of the two separated sensor circuits is independently actuated by a rotating (or linear) flux field; each latching section consists of an amplifier, Schmitt trigger circuit (hysteresis), and a latching output.

A varying magnetic field induces internal signals (HIGH or LOW) in the separate latching sensors; and these digital signals constitute the logic inputs for the decoding circuitry, which provides a logic-compatible direction-detection signal.

The exact proximity of the latch circuitry enables tight matching of the magnetic switch points, and on-chip trimming circuitry improves the matching via adjustments in gain and offset. In addition to powering both the linear and logic circuitry, the internal voltage regulator offers a level of noise immunity from the incoming supply. This device is a 'merged technology' sensor, and incorporates bipolar for analog circuitry with CMOS logic for the digital decoding, etc.

The A3422 is a low-hysteresis device that has been optimized for designs employing high-density ring magnets. The output is an open-collector npn, and a pull-up resistor is needed.

MAXIMUM LIMITS of DIRECTION SENSOR

Because the direction-detection sensor lineage stems from vehicular (automotive) applications, one of the absolute maximums (reverse battery) reflects its original stimulus. Also, the upper temperature limit (+150°C) applies to automotive systems.

Table 1: Absolute Maximum Ratings

Supply Voltage, V_{CC}	18 V
Magnetic Flux Density, B	Unlimited
Output OFF Voltage, V_{OUT}	V_{CC}
Output Sink Current, I_{OUT}	30 mA
Package Power Dissipation, P_D	500 mW
Operating Temperature Range, T_A	
Suffix 'EKA'	-40°C to +85°C
Suffix 'LKA'	-40°C to +150°C
Storage Temperature, T_S	-65°C to +170°C

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Magnetic characteristics and distinctions

The high-resolution IC is sensitive and suitable for use with high-density magnets. The essential magnetic characteristics are:

Max. Operate Point, B_{OP}	+85 gauss
Min. Release Point, B_{RP}	-85 gauss
Min. Hysteresis, B_{hys}	10 gauss
Operate Differential, $B_{OP1} - B_{OP2}$	±60 gauss
Release Differential, $B_{RP1} - B_{RP2}$	±60 gauss

NOTE — Characteristics are limits over the device operating temperature range.

The direction-detection IC is packaged in a 5-lead SIP with the connections shown in figure 1. Note: the lead designations are viewed from the 'branded' (part number labeling) front surface of the 5-lead mini-SIP.

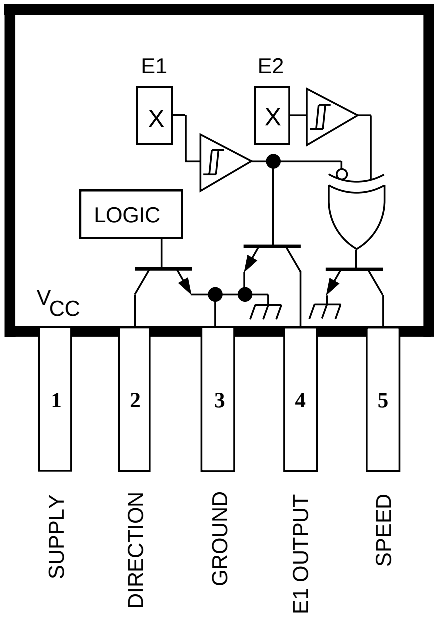
OPERATION of DIRECTION-DETECTION IC

Circuit response to applying power

Upon applying power, the digital circuitry resets, then loads the 'D' flip-flops with the power-up states of each Hall-sensor comparator. Hence, a known prior condition is created for the direction-detection circuitry, and the DIRECTION output is also reset to an OFF state should this power-up happen while the device is in the hysteresis band. Also, the two comparators are both reset to their OFF state should a power-up occur while the IC is in its hysteresis band. If the flux field exceeds the operate point, the comparators will power-up in an ON (LOW) state ($B > B_{OPA}$, $B > B_{OPB}$). Quadrature and direction-detection digital circuitry links the two Hall-effect latches (A and B) in a configuration that provides (when appropriately activated) two distinct, independent signals representing the velocity and direction of the magnetic field passing the face of the device. Prerequisite to updating the direction signal is the need to sustain a quadrature relationship between the ring magnet pole width, the sensor-to-sensor separation, and (secondarily) the magnetic switch points. For an optimum design, the sensor should be activated by a ring (or linear) magnet having a pole width equal to twice the sensor separation. Basically, this magnetic-pole relationship induces a sinusoidal flux field having a period (termed T) that corresponds to four times the sensor-to-sensor separation. The quadrature correlation can also be sustained for designs using a magnet with a T that meets the following relationship:

$nT/4 = 1.5$ mm (where n is an odd integer).

As explicit examples, ring or linear magnets with a pole pair width equivalent to those in table 2 provide the proper quadrature relationship. Because high-density, high-flux magnets are not low-cost components, the choice of ring or linear magnets should be very deliberate. As mentioned earlier, the recommended pole width is ≥2x the spacing between the two sensor elements (1.5 mm); this equates to ≈8 poles/inch (but not low cost).



Dwg. PH-015

Figure 1: Direction-detection IC connections

Table 2: Quadrature relationship

Odd integer, n	T (mm)
1	6
3	2
5	1.2

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Internal logic circuitry provides outputs indicating speed and direction of the magnetic field passing the front of the 5-lead mini-SIP. The functional block diagram of the direction-detection sensor is depicted in figure 2. The individual Hall-effect sensors are labeled E1 and E2. The output of E1 is inverted and connected to the exclusive-OR gate (XOR) and this output provides the SPEED (velocity) signal.

The signal from sensor E1 and the internal speed pulses (inverted E1 XOR'd with E2) are decoded to supply a DIRECTION output; and this output is HIGH (OFF) for a direction of E2 to E1 (right-to-left with a south pole). Alternatively, a left-to-right motion (E1 to E2) and a south pole will induce a LOW (ON) output state. The circuitry incorporates internal delays to effect an updating of the DIRECTION signal preceding the SPEED.

Figure 3 illustrates the sensor-to-sensor spacing, the E1 and E2 loci, and active area depth of the Hall elements.

The DIRECTION signal is updated with each and every transition of the E1 Output and E2 Output. Note: the E2 Output is an (internal) signal only; this configuration permits utilizing edge-triggered up-down counter circuitry without any possibility of the loss of signal pulses.

The response of the device to the magnetic field induced by a rotating gear is shown in figure 4. Note the phase shift between the two integrated Hall sensors. The initial operation depicted is an E1-to-E2 motion of the south pole. Note: the E2-to-E1 direction changes the phase relationships of the latches, E1 and E2, and DIRECTION output; but without any effect upon the SPEED signal.

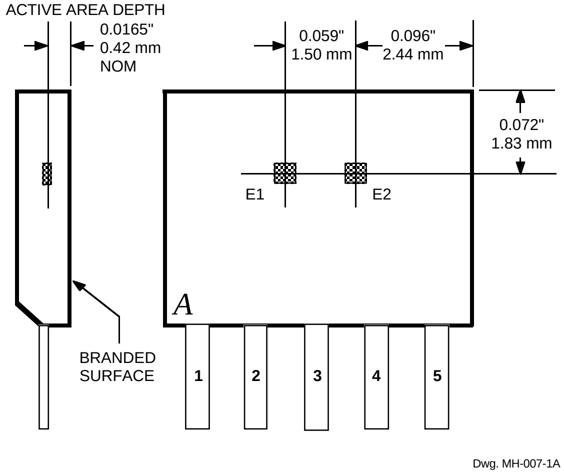

Figure 3: Sensor locations (5-pin SIP)

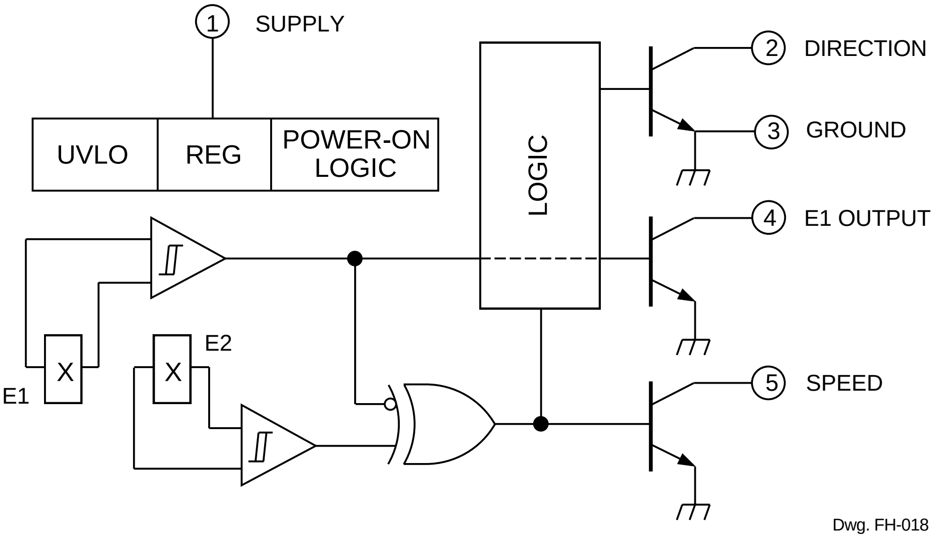

Figure 2: Hall-effect direction-detection sensor diagram

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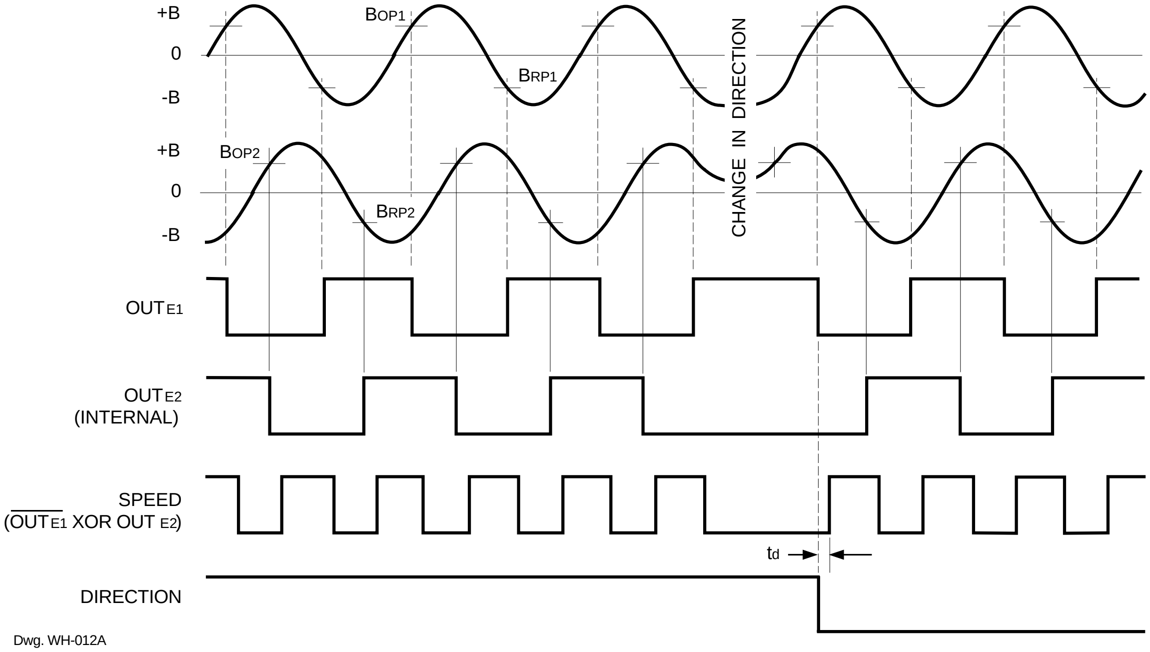

Figure 4: Timing diagram and operating waveforms

During changes in direction, the circuitry imposes an internal delay (td in figure 4) while the logic updates the DIRECTION signal. The typical time is ≈1 µs, and the specified maximum is 5.0 µs.

In addition to the voltage regulator and power-on logic mentioned previously, these sensor ICs also include an under-voltage lockout circuit (UVLO in figure 2). During power-up, the HED supply voltage must reach 3.5 V (typical value) before a sensor is active. Alternatively, when power is shutdown, the under-voltage hysteresis is 0.5 V; and these preclude any sensor instability during a transition from the powered state to shutdown.

Another specification relates to applying power to the sensor. The maximum power-on time cannot exceed 50 µs; ramping the supply voltage (V_{CC}) from 0 V to 4.5 V must occur in <50 µs.

Although the direction-sensor supply maximum is 18 V, operation at 5 V is recommended for two reasons. First, the internal heating is diminished; and, secondly, pull-up resistors to 5 V alleviate complexity, simplify the design, and reduce costs. The value of these pull-up resistors depends upon the interface loading (current, capacitance, etc.), and high-value pull-ups are (usually) suitable.

Magnetic operating points

Per 'Magnetic Characteristics' the operate points of the device was listed. Typical operation for the A3422 is shown in figure 5. The decrease in operate and release points are controlled by a (slight) downward shift in the hysteresis; this offsets the slight flux loss in ferrite magnets.

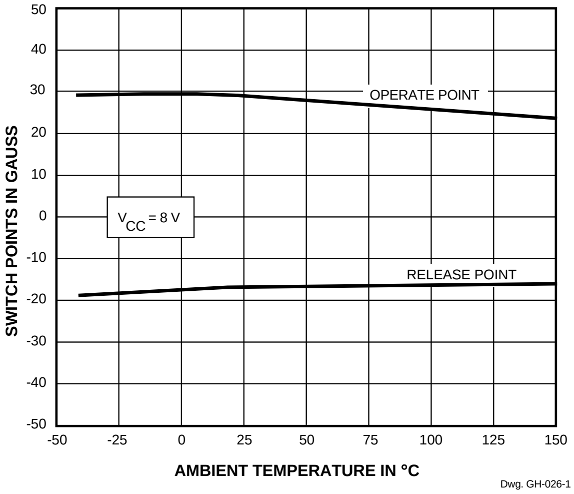

Figure 5: Typical switch points

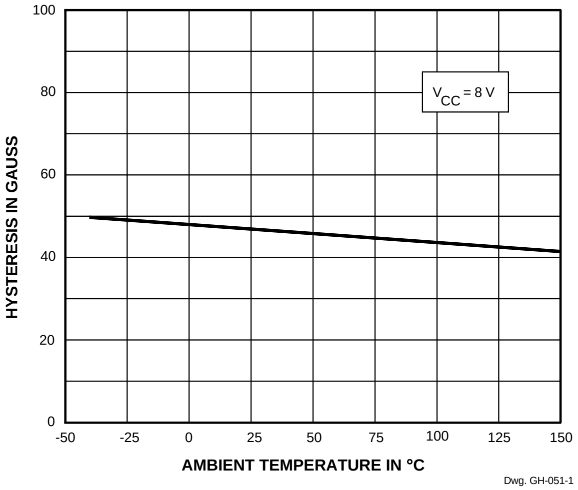

Figure 6: Typical hysteresis

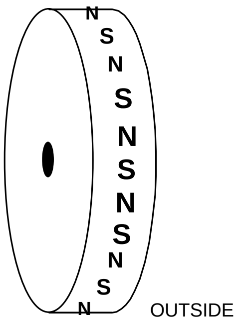

Figure 7: Ring magnet (outside perimeter)

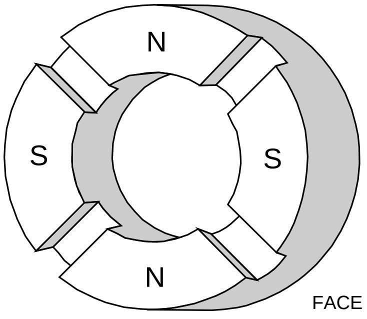

Figure 8: Rotary ‘face’ magnet (slotted)

The hysteresis vs. temperature characteristics of the A3422 are shown in figure 6; the ‘flat’ curve represents the low-hysteresis, high-resolution of the device. The HED characteristics reflect the flux loss that ferrite magnets exhibit with rising temperature.

Hysteresis, B_{hys}
T_A = -40°C .... ≥10 gauss
T_A = +25°C .... ≥10 gauss
T_A = Maximum* .... ≥10 gauss

The typical hysteresis for the A3422 is 45-50 gauss; thus, the device specifications are rather conservative. However, this sensitive HED has no minimum operate point nor any maximum release point. Because the sensor IC is a bipolar latch, an alternating, multiple north/south-pole magnet is an absolute prerequisite to operation.

MAGNET CONFIGURATIONS

A variety of magnetic compounds, configurations, shapes, etc. afford potential solutions for sensing velocity and direction. As mentioned, multi-pole magnets are imperative, and the magnet might be fabricated from such typical materials as Alnico, Arnox ceramic, samarium-cobalt, neodymium, etc. Even ‘plastic’ magnets may be exploited (if field strength is sufficient to operate the sensor).

Perhaps the most common configuration, figure 7, shows a ‘ring’ form with its multi-pole magnetic fields on the outside diameter. Obviously, this is a rotating application such as a motor shaft.

Another multiple-pole, rotating variation appears in figure 8. This ‘face’ orientation is shown as a notched version; however, a ‘solid’ face is also very feasible (and should result in a simpler and lower cost magnet).

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A linear ‘face’ magnet is portrayed in figure 9; and this configuration allows sensing very lengthy motion with direction and velocity signals. Because this ‘linear’ configuration might exploit a ‘plastic’ magnet material; forming arcs, cam-shapes, etc. may also be very feasible (excepting tight, sharp bends, very small radius curves, etc.).

Another illustration (originally created to portray sensing a straight-line motion with either linear or digital Hall ICs) is shown in figure 10. With a multiple-pole ‘face’ magnet (like figure 9), sensing both direction and velocity is very viable. The limitations of sensing accuracy and resolution are (primarily) dependent upon the pole pitch of the magnets (sensor limitations are essentially 2x the Hall element spacing of 1.5 mm [≈0.059"]).

Other alternatives are left to the ingenuity of the designer. Also, the various suppliers of magnets can be of meaningful assistance with determining the magnetic materials, configurations, size, etc. that influence a Hall-effect-based velocity- and direction-detection sensing system. To reiterate, the critical factors in utilizing these Hall-effect ICs for direction detection are: (1) magnet pole pitch, (2) proper flux density, and (3) moderate resolution requirements (these Hall sensors cannot supplant very expensive, high-resolution encoders or resolvers). However, these direction detection sensors (with ring or linear magnets) are a very inexpensive solution for requiring modest positional resolution with directional signal.

As cited previously, the sensor-to-sensor spacing is 1.5 mm (≈59 mils), and the accuracy of the separation of sensor elements is <±1 micron - a very definite advantage over discrete alternatives with mechanical positioning tolerances that could (easily) exceed 100 µm (100 microns/≈4 mils).

Photolithographic alignment of these Hall sensors provides <±1 micron tolerance, but another key constituent is the programmed ‘trimming’ of these ICs. The two orthogonal, quadratic elements are each end (and centered) on the die (photo, figure 11); and (though these are 5-lead ICs) there are 24 pads located on the periphery of these chips.

Comparable to other recent Hall-effect sensors, these direction-detection ICs are programmed for magnetic operation, gain, hysteresis, etc. as they are being (initially) tested. ‘Trimming’ of circuit parameters offers tightened operating limits, etc.

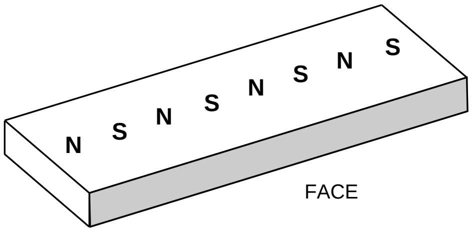

Figure 9: Linear ‘face’ magnet

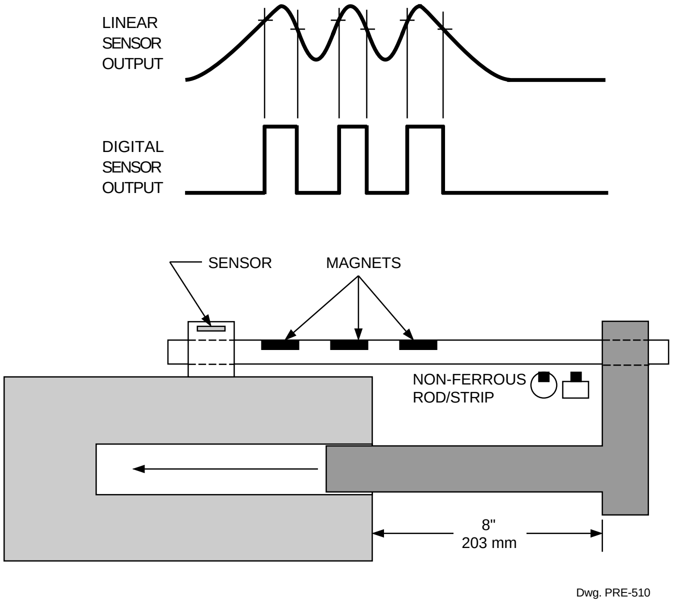

Figure 10: Linear direction-sensing example

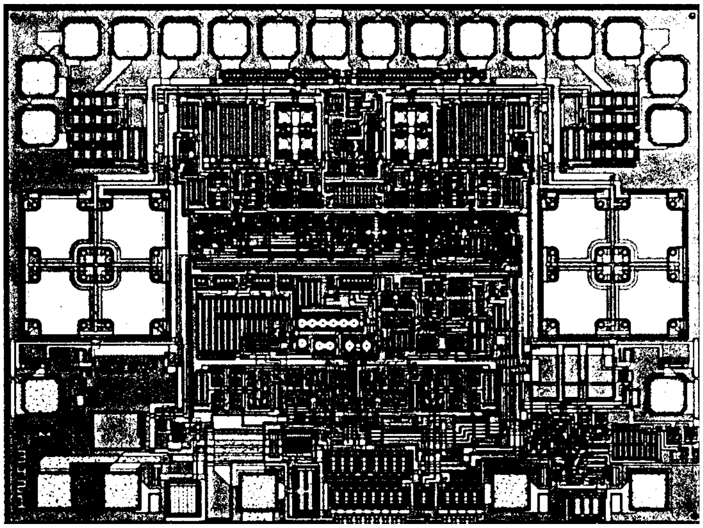

Figure 11: Chip photo of direction-detection IC

DIRECTION and VELOCITY SENSING

Many, very diverse system movements are within the capabilities of the direction detection sensors. Although not limited to, the potential applications could readily include the following examples:

Linear Motion
- Conveyer belts, etc.
- Pistons (up-down and travel)
- X, Y, and Z movements

Oscillatory
- Cams (ex: a ‘Geneva’)
- Pistons (also linear motion)

Rotating Motion
- Gears
- Impellers
- Levers (rotation of pivot arm)
- Pulleys
- Screw-driven motion
- Shafts
- Valves (rotary)
- Wheels

This is a representative listing of the possibilities for direction and velocity sensing. Typically, the Hall sensors are stationary and the magnet(s) are in motion; but that is not a prerequisite condition. The relationship of the sensor and magnet is most likely to be tangential (rotating applications) but can also be parallel (linear actuators, etc.).

SUMMARY and CONCLUSION

An innovative, applications-specific Hall-effect device provides a very small, inexpensive solution for sensing both direction and velocity. Although the positional resolution cannot compare to opto-electronic encoders, etc., this new Hall sensor is far superior to optoelectronic sensors in many designs. The HED superiority is associated with:
- Susceptibility of opto’s to dirt, dust, oil, etc.
- Limited temperature range of optoelectronics
- Degradation (aging) with time of opto sensors
- Ambient light affects opto sensors (not Hall)
- Higher cost of optoelectronic sensor designs

Also, reed switches are often contendors to Hall ICs; and these low-cost devices do not require a power supply (an advantage over Hall ICs), but HEDs are preferable based upon the following:
- Contact and bounce issues with reed switches
- Finite life of reed switches (wearout mode)
- Accuracy of reed switches is inferior
- Not (directly) compatible with logic inputs
- Direction detection is very formidable problem

This new direction-detection IC is expected to impact motion sensing in commercial, consumer, and industrial designs; low-cost, high-reliability, ‘contactless’ direction sensing is now a reality.

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Figure 4 was corrected December, 1999.

References to the A3421 high hysteresis, low resolution sensor were deleted February, 2002.