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Hall effect instruments, evolution, implications, and future prospects

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ABSTRACT

Since the revolution in solid state electronics, many innovative principles were investigated for a better and simpler design. Thus, Hall effect-based sensors and instruments gained importance. To employ this principle in several operating conditions and with different setups, several researchers contributed significantly over the decades, which ultimately led to the establishment of industries producing a wide range of Hall devices. The objective of this paper is to review the available configurations and current status of the Hall effect-based technologies. A detailed discussion is carried out on the various types of existing Hall-based devices, such as linear sensors, field-programmable sensors, switches, latches, speed and directional sensors, and vane sensors. The effect of materials and the influence of several undesired effects (such as offset voltage, temperature, noise, and drift) are also investigated. The compensation/reduction techniques are mentioned therein, and interested researchers are encouraged for the development of new techniques. This paper concludes with the discussion on the market scenario (such as electronics sector and automotive industry) and progression in current research on Hall devices while projecting some new research directions in this field.

NOMENCLATURE

ADC	analog-to-digital converter
AEPS	advanced electric propulsion system
BLDC	brushless direct current
CMOS	complementary metal oxide semiconductor
HET	Hall effect thruster
IC	integrated circuit
JFET	junction field effect transistor
PWM	pulse width modulation
RPM	rotations per minute
SENT	single edge nibble transmission
TPO	true power-on
TTL	transistor transistor logic

I. INTRODUCTION

The phenomenon of production of voltage across a current carrying conductor strip, when placed in a transverse magnetic field, is called the Hall effect.[1] The magnitude of the output voltage is given by

$$E_H = R_H \frac{BI}{h}, \tag{1}$$

where R_H is the Hall coefficient dependent on the material properties and h is the material thickness. Hall transducer's sensitivity is a linear function of the input current I and the strength of the applied magnetic field B. Figure 1 shows a basic Hall effect sensor consisting of a power source, the Hall device, and an amplifier.

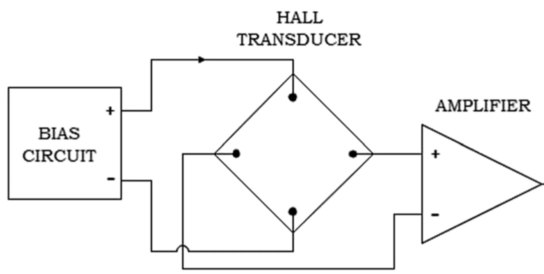

FIG. 1. Basic Hall effect sensor assembly.

An equivalent electrical circuit of a Hall effect transducer is shown in Fig. 2. The gain or sensitivity of the transducer is represented by voltage sources in the equivalent circuit. The resistors in each branch represent the input and output resistances of the transducer. The value of each resistor depends on the dimensions of the Hall element. In the case of complete symmetry, all resistors have equal values. In this figure, the quantity V_{B+} or V_{B-} refers to the bias voltage, S is sensitivity, B is the magnetic flux density, R_{IN} is the input resistance, and R_{OUT} is the output resistance.

The Hall effect transducer has found applications in numerous low power devices, such as magnetic field measuring instruments, gyrator, isolator, circulator, electrical compass, magnetic field meter, and phase discriminator. The advantages of Hall-effect-based integrated devices are the integration of interfacing electronics and the Hall element on a single silicon chip and built-in voltage isolation from the current path. Nowadays, the transducer is used along with the associated electronic circuitry that is specifically designed to ensure it is working properly. Numerous applications require electronic processing of the signals obtained from the transducer.[2] The devices, equipped with proper electronics, can be used for measurement up to a range of ±200 A. These devices can be configured for higher current applications using the current divider configuration.

The electronic circuit used with the transducer is called an interface. An interface should have a compatible input range with the variation in the transducer output signal. To put these sensors with the on-board circuitry, the sensors are combined or "integrated" with signal processing hardware in one small device.[3] Maupin and Geske[4] identified Hall effect sensor integration technology in monolithic silicon built-in circuits with various signal conditioning circuits. When working with a transducer, it is preferred to build a circuit model consisting of primitive electronic components, so simulation and modeling of these devices become essential.[5] Modeling and simulation of these sensors can help determine the sensor behavior in a circuit.[6] In manufacturing, automotive, and communications systems, the demand for low-cost, small-sized current sensor solutions providing accurate data has risen rapidly over the past decade.

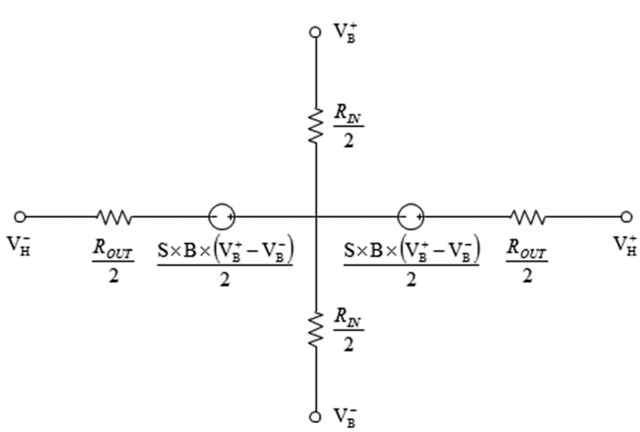

FIG. 2. Electrical model for the Hall-effect sensor.

A large number of devices have been proposed using the Hall effect.[7] Heremans[8] presented a review of solid state magnetic devices, including Hall generators and their applications. A comprehensive survey of devices based on the Hall principle was conducted by Grubbs[9] in the 1950s. The survey conducted by Heidari and Nabaei[10] revolves around modern day magnetic sensors based on the Hall effect. These studies bring us to the need of an updated discussion on the present state of Hall effect devices. This paper presents an in-depth review of the Hall effect-based devices, important contributions and modifications to this technology, its popularity, the external effects (undesired effects) limiting its use, and the current research and market scenario.

This paper further consists of two sections: Section II discusses the various types of Hall-based devices in detail. It includes linear sensors, switches, latches, and speed and direction sensors. Section III consists of the problems that are experienced while working with Hall sensors and the proposed fixes for the same. The vital role of the material chosen for the production of Hall sensors is also discussed in Sec. III. It also deals with the power requirements of a Hall sensor and the temperature ranges of common linear sensors.

II. HALL EFFECT-BASED DEVICES

Integrated circuits (ICs) consisting of the Hall-sensor are generally based on the following three basic architectures: linear, digital, and speed sensing, which can be further deployed for various purposes. The major Hall effect-based devices are the following:

1. linear sensors,
2. field-programmable sensors,
3. switches (unipolar, bipolar, and omnipolar),
4. latches,
5. speed and directional sensors (gear tooth sensing, single-point sensing, and differential gear tooth sensors),
6. vane sensors, and
7. flexible Hall sensors.

The above-mentioned devices are discussed in detail in Subsections II A–II H with their principle and working, as well as the research and commercial angle wherever possible. Later, certain application-specific devices are also mentioned. Several other devices may also be designed by simply employing customized electronic circuits with a simple Hall transducer.

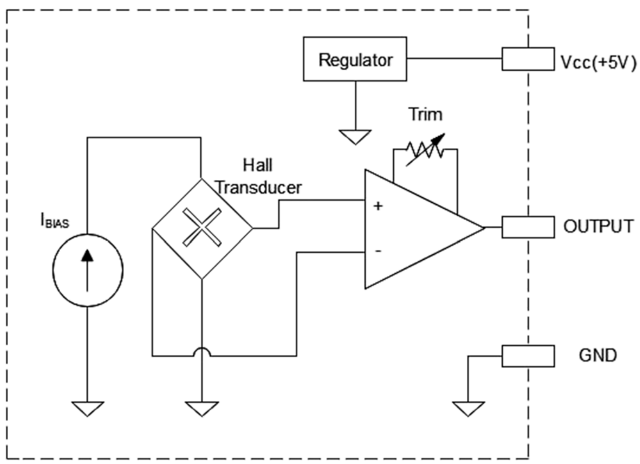

FIG. 3. Linear Hall-effect sensor assembly.

A. Linear sensors

Linear Hall sensors produce an output directly proportional to the strength of the applied magnetic field, and these do not have discrete switching states. An accurate and cost efficient linear Hall sensor with a digital output can be developed by employing a delay removal circuitry.[11] Schott and Popovic[12] demonstrated how the integrated silicon Hall devices could be linearized without any additional error correction.

Figure 3 shows the linear architecture of the Hall integrated circuit consisting of a source, the Hall transducer, and the circuitry for proper and consistent biasing of the sensor and an amplifier stage.

B. Field-programmable sensors

Initially, the Hall ICs were pre-programmed at the time of manufacturing. This was simply a one-time solution, but for different applications we shall require to program it accordingly. This purpose was achieved by field programmable linear sensors that allow the user to make adjustments in the Hall device before using it in the end product. A basic field programmable linear Hall effect sensor is shown in Fig. 4.

These provide better compatibility and accuracy[13] with a potential application in the automobile industry.[14] Typically, a field-programmable sensor has a provision of adjusting several features, viz., course and fine gain, output offset voltage, output clamp, and adjustable temperature compensation.

Motz *et al.*[15] presented a sensor for camshaft applications that included a programmable True Power-on (TPO) switching level, which becomes effective after the initial power-up phase in which one could program the following:

1. TPO function (B_{TPO}) magnetic switching point with 10 bit resolution;
2. output behavior of the switch that maybe inverted; and
3. for achieving the highest phase accuracy (optimum switching point, B_{CAL}), one can program the 9 bits reserved for the digital algorithm.

C. Switches

In several situations, knowing that the strength of the magnetic field is not important, but simply the information that whether the applied magnetic field is above some threshold limit or not is sufficient. In such applications, Hall effect switches are employed. Since

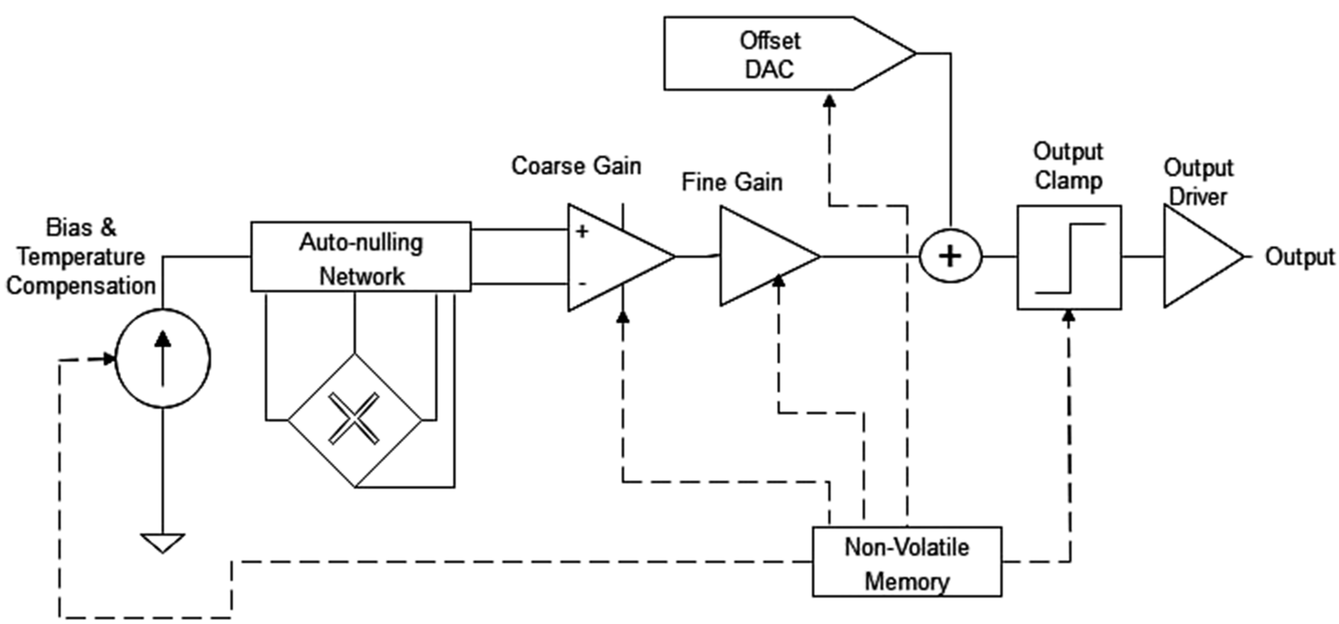

FIG. 4. Field programmable linear Hall sensor assembly.

the Hall switch has an on/off state analogous to the two binary states, these are often referred to as digital Hall-effect sensors.

A digital Hall-effect sensor is nothing but a simple linear sensor accompanied with a threshold sensor/detector and an output driver. These digital sensors are designed in such a way that the field on their face is detected as a positive field if it is close to the south pole and as a negative field if it is close to the north pole. The digital sensors respond to the magnetic field as an algebraic quantity. The interpretation is such that a "positive" field is always considered greater than a "negative" field. Hall effect switches have a potential application wherever voltage control is required like in an electrostatic spray gun. The spraying voltage is controlled using the Hall-effect circuitry.[16] North-pole switches remain "on" when the magnetic field is absent and turn "off" only if a sufficiently strong negative field is applied.

The turn-on threshold magnetic field and the turn-off threshold magnetic field determine the behavior of the digital sensor. Switch-point stability refers to the Hall switch drift whenever there is a variation in the temperature of the surroundings. Owing to these effects, limits are specified on the working conditions. Change in behavior of the digital sensors under extreme working conditions can impact the performance of the entire system, which is obviously undesirable. A general operation of the Hall switch is shown in Fig. 5, where B_{OP} is the turn-on threshold magnetic field and B_{RP} is the turn-off threshold magnetic field.

A digital Hall effect sensor can be of three types: unipolar, bipolar, and omnipolar. Unipolar sensors require either of the two magnetic poles to operate. These turn "on" when the sensor threshold value is exceeded by the applied magnetic field. In the absence of magnetic field, it may or may not latch, which means that it can function as a switch or as a latch or even as a north pole switch.

Bipolar sensors turn "on" when they are in proximity to one magnetic pole and turn "off" when they are brought in proximity to the opposite magnetic pole. These sensors retain their present state in the absence of magnetic field.

Omnipolar sensors turn "on" when they are in proximity to a strong magnetic field of either polarity. Removal of magnetic field turns them "off." The omnipolar sensor can be constructed using a pair of unipolar sensors mounted in the opposite directions with their outputs wired together.

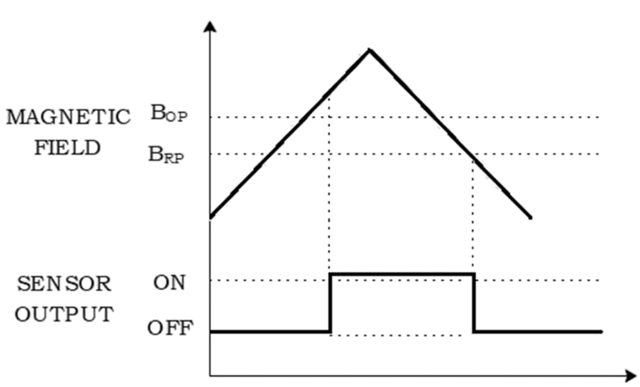

FIG. 5. Digital sensor reaction to the magnetic field.

D. Latches

If the south magnetic field is present on one of the faces of the switch or the north magnetic field on its opposite side face, the Hall effect switch turns "on." When the magnet is removed, it turns "off." A Hall effect latch, however, operates like a switch, but it stays "on" even if the magnet is removed. However, just as the north pole is moved near the latch or the current is switched "off," it turns "off." Figure 6 depicts the comparison between the reactions of a switch, north-pole switch and a latch.

E. Speed and direction sensors

For application in electrical drives and the automobile industry, there is a need to determine the speed and location of ferrous gears. Over several decades, the ability to transform the repeated moving teeth into an electrical impulse was desired. Purely mechanical systems have previously been used for this purpose, but these are restricted to low speed and low duty cycle applications due to the associated wear and tear problem. The wheel rotation sensing is quite useful in anti-lock brake systems. The concepts of these systems have been modified and optimized to provide more than anti-skid capabilities, now offering extended vehicle handling advancements.

Hall sensors in speed sensing sense magnetic targets that are fixed to the rotating mechanism (shaft) as it moves past the Hall sensor. The magnetic targets incorporated in the Hall effect-based speed sensors can either be discrete or a ring magnet. To employ discrete magnetic targets, there are two configurations in which the magnet poles can be arranged, either the successive magnets can present the same pole to the sensor or they can have alternating poles facing the sensor.

Speed sensing can be achieved by the following techniques: gear tooth sensing, single-point sensing, and differential gear tooth sensing. These are described below.

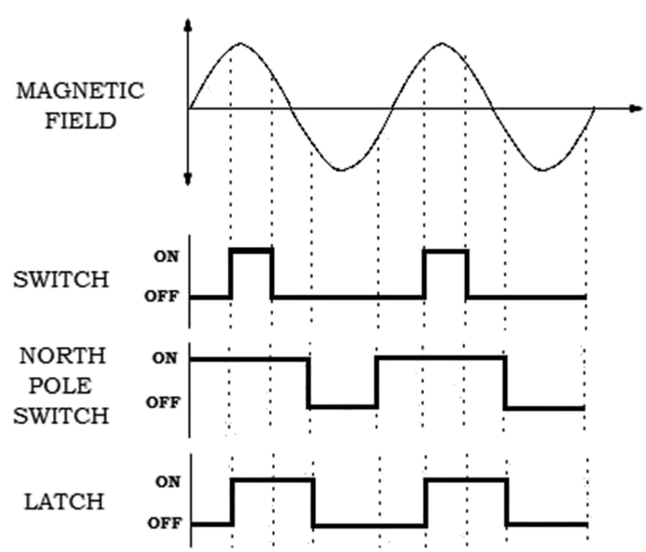

FIG. 6. Response of a switch, north-pole switch, and a latch to the magnetic field.

1. Gear tooth sensing

Hall effect gear tooth sensing detects the air-gap flux fluctuation between a magnet and a ferrous gear tooth that passes it.[17] These signals from the Hall element are digitalized and then subjected to digital signal processing to get the final output.

To detect the passing gear teeth, a magnetic field source must be provided to the sensor assembly. This can be simply accomplished by installing a permanent magnet, positioned in such a way that the gear teeth's surface lies on its axis of magnetization. As the magnetic flux tends to follow a pathway with lower reluctance, whenever a tooth travels across the magnet's surface, the flux passes through the lower reluctance pathway provided by the gear tooth. This increases the flux density between the Hall sensor face and the gear tooth. This is used in modern automotive primary distributor ignition systems and to control multi-port sequential fuel injection systems.

This concept can also be employed to determine the air gap between a magnetic pole and a ferrous material[18] or the proximity of a ferrous material[19] and to sense the angular position of a rotatable member.[20,21] The simple mechanism is shown in Fig. 7. As the detection of the absence or presence of a target is difficult, many gear tooth sensors are designed primarily for the detection of target characteristics when they move past the sensor.

2. Single-point sensing

In a single point gear tooth sensing system, the magnitude of a magnetic field is measured using just one Hall transducer. To optimize the sensing of change in the magnetic field, the transducer is positioned between the target and the pole face of a magnet. Magnetic responses at various sensor-to-target air gaps, as seen by the sensor, are shown in Fig. 8.

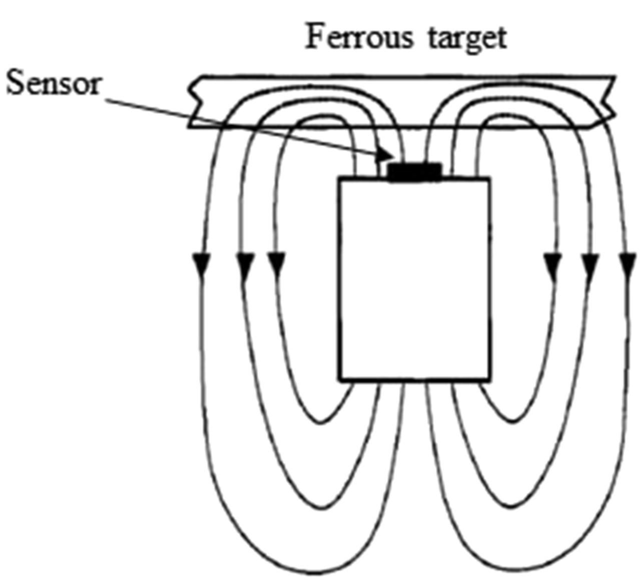

FIG. 7. Magnetic flux alteration by a ferrous target.

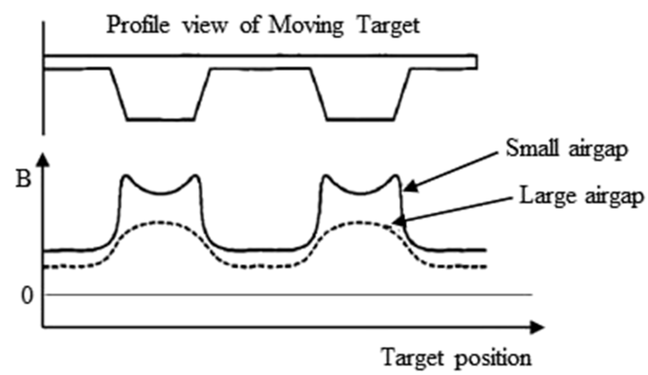

FIG. 8. Response of a pole face sensor.

3. Differential gear tooth sensors

Differential gear tooth sensors make use of two Hall effect transducers mounted on a single IC, placed next to each other. For the Hall-effect sensor in differential arrangement to work properly, it is necessary that the transducers detect different magnetic field strengths.[22] Thus, Hall transducers are lined up about 2 mm apart on most of the commercial differential gear tooth sensor ICs. By subtracting the signals received from the two individual sensors, an estimate of the gradient is obtained.

Additionally, the rotational direction can also be determined using two separate Hall sensors. For direction sensing, ring magnet targets with alternating pole faces are used. Hence, the sensors are basically Hall-effect digital latches. The two obtained output signals are 90° out of phase in a specific configuration. Which signal will lead, and which one will lag behind, depends on the target rotation direction. A similar assembly can also be employed to develop an angular position encoder.[23] Bienczyk[24] proposed an angle measured with the help of a compact version of the Hall effect position sensor for determining the angle of rotation of the moving components of an artificial human-hand shaped manipulator. Hall-effect-based direction sensors are also used for auto-pilot applications.[25,26]

Metz *et al.*[27] developed a system for contactless determination of angles using four Hall devices on a single board. Haberli *et al.*[28] introduced a contactless Complementary Metal Oxide Semiconductor (CMOS) magnetic sensor for angle measurement with an on-chip read-out circuit. A circular Hall transducer has been developed for angular position sensing suitable for contactless 360° absolute angle encoding.[29] Stoica and Motz[30] presented a chopped vertical Hall sensor for the identification of the magnetic encoder wheels' speed and motion direction, which achieves low offset and low noise even with poor intrinsic sensitivity and high voltage dependency of the offset typical to vertical Hall devices.

Brushless Direct Current (BLDC) motors have become quite cheap and common in many different applications. Due to their relative simplicity, cheap price, and efficient operation in a large range of loading conditions and speeds, the Hall-sensor-controlled BLDC motors are favored in several applications. In many low-precision motors, the sensor positioning could be quite inaccurate.[31,32] Many advanced controls often depend on the Hall-sensor position/speed calculation.[31] Enhanced functioning of the BLDC motor can be accomplished by filtering Hall-sensor signals.[33] Vertical Hall sensors, or parallel field systems, have been widely researched over the last decade[34] and predominantly used in the application of 3D magnetic field and angular movement sensors.[35–38]

Speed sensors based on the Hall effect can withstand very fast speeds, but design and processing limitations cause difficulty at high speeds and often produce erroneous results. The restriction of the architecture and processing exists on the Hall sensor IC itself. While the Hall transducer frequency itself is very small, it is the aspect of signal processing that poses difficulties. The sensor IC's precise frequency response depends on the configuration and process technologies with which it is deployed. Nevertheless, several Hall-effect sensor ICs can reliably detect targets at frequencies approaching 25 kHz, which translates to a target of 25-teeth spinning at 60 000 RPM.

F. Vane sensors

A vane sensor based on the Hall effect principle is a contactless sensor/switch consisting of an incorporated Hall effect circuit and a specialized magnetic circuitry, which is enclosed in a plastic envelope. These can even be used under extreme environments, as these instruments are enclosed in a special plastic envelope. This is used in heavy equipment, injection circuitry, robotics, and many other fields.

It can be used as a trigger in electronics[39] in the automobile industry and can be used in control engineering in those places where maintenance-free work is required, for example, shaft encoders, RPM sensors, limit switches, scanning of coding disks, position sensors, and speed measurements.

Such sensors also seen broad use for the ignition timing controls[40] in the automotive industry. Here, the vane sensor is used with a circular target providing a set of steel flags, which can move through the throat of the vane switch. The usual shapes, as shown in Fig. 9, are notched cups and toothed wheels.

G. Flexible Hall sensors

Hall sensors based on the CMOS have been used in most applications due to active development and the various reasons such as cost and size. New and emerging areas of application such as wearable technologies and robotics require the sensors to be thin and mechanically flexible. Graphene, having excellent electronic and mechanical properties, facilitates the fabrication of flexible Hall sensors. Flexible graphene-based Hall sensors fabricated by Wang *et al.*[41] show a voltage and current normalized sensitivity comparable to rigid silicon-based Hall sensors. These sensors can be further enhanced using a flexible encapsulation or high-quality graphene encapsulated in hexagonal boron nitride (hBN). Satake *et al.*[42] proposed Fe–Sn nanocrystalline films for flexible magnetic sensors having high thermal stability. Collomb *et al.*[43] developed graphene Hall sensors for high resolution ambient magnetic imaging by exploiting the high carrier mobility and tunability of the material.

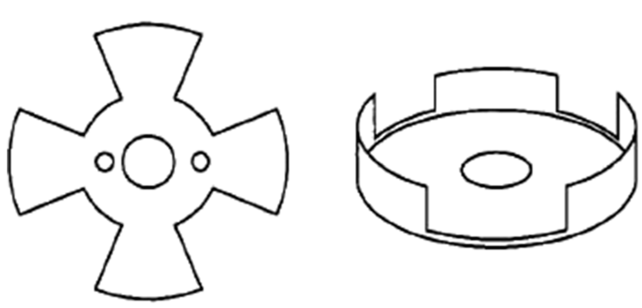

FIG. 9. Vane target design: disk shaped target (left) and cup shaped target (right).

H. Application-specific devices

One of the application specific devices based on the Hall effect is its use for spacecraft propulsion. This device is known as the Hall Effect Thruster (HET) or Hall thruster or Hall-current thruster. HETs have benefited from considerable theoretical and experimental research since the 1960s. It is a type of ion thruster, where an electric field accelerates the propellant. HETs use a magnetic field to regulate the axial movement of the electrons and then use them to ionize the fuel, accelerate the ions rapidly to generate energy, and incapacitate the ions in the plume. Hall thrusters work on a range of propellants, with xenon and krypton being the most common. Hall thrusters may boost their exhaust to speeds from 10 km/s to 80 km/s. The HET has potential uses to provide control of the direction and location of orbital satellites, and usage as a primary propulsion system for medium-sized space vehicles.

Based on the in-flight experience, Koppel and Estublier[44] found that HETs possess the capabilities to be employed as a main propulsion system. Moreover, these do not show any degradation over time, instead the thruster operation improved over time with reduced discharge current oscillations and reduced operating temperatures.[45]

Hall effect-based sensors are being used in bio-medical applications as well. The advantages offered in the field of medicine by magnetic means, as compared with techniques employing scintillation counting, include zero sample background intrusion, long-term reliability, and the potential to produce multianalyte arrays. Sandhu *et al.*[46] described InSb micro-Hall sensors with high sensitivity for use in magnetic micro-bead detection-based biosensor systems. Nano- and micro-Hall-effect sensors are addressed in Ref. 47 for room-temperature scanning Hall probe microscopy. A specific magnetic imaging device consisting of a room temperature scanning Hall probe microscope was developed.[48]

To measure the three spatial components of magnetic flux density with high precision, models based on the Junction Field Effect Transistor (JFET)[49] and NPN transistor[50] were proposed. Models for 3D vertical Hall sensors in CMOS technology[51,52] and single chip 3D Hall sensors[53] came up, but the measurement proved to be challenging due to the following:

1. offset voltage problem, the stability, and the frequency dependent noise of the sensors;
2. Large non-orthogonality errors for which three magnetic sensor devices are required to be as close as possible; and
3. the mapping algorithm between the sensor determined value and the target value that needs to be highly precise.

According to the study conducted by Roumenin *et al.*,[54] a single chip CMOS technology-based 3D Hall magnetic sensor was a possible solution, which was later developed by Pan *et al.*[55] Apart from these, a CMOS Hall sensor-based immunoassay platform has also been presented by Aytur *et al.*[56] The Hall-effect principle is also employed to propose a voltage amplifier, which can achieve huge amplification.[57]

III. UNDESIRED EFFECTS: CAUSES AND COMPENSATION

Like every other electronic/electrical devices, the Hall device is not ideal. Moreover, it is subjected to environmental conditions that are not always favorable. In this section, the causes and compensation of all such undesired effects are thoroughly discussed, which influence the Hall output.

A. Low output voltage

Most Hall-based devices cannot power massive electrical loads directly since their output drive capacities are very low of about 10 mA up to 20 mA. An open-collector (current sinking) NPN transistor is connected to the output for massive current loads. This transistor acts as an NPN sink switch in its saturated region, thus shortening the output terminal to ground when the flux density introduced is greater than that of the pre-set "on" point. The output switching transistor may either be an open collector transistor setup, an open emitter transistor, or both having a push–pull output kind setup that can sink sufficient current to directly power several loads, including LEDs, lamps, relays, and motors. Open-collector and open-drain outputs (shown in Fig. 10) are common since their interface is simple. Using solely a pull-resistor enables one to deploy these with both Transistor Transistor Logic (TTL) and CMOS electronics, as well as with common micro-controllers.

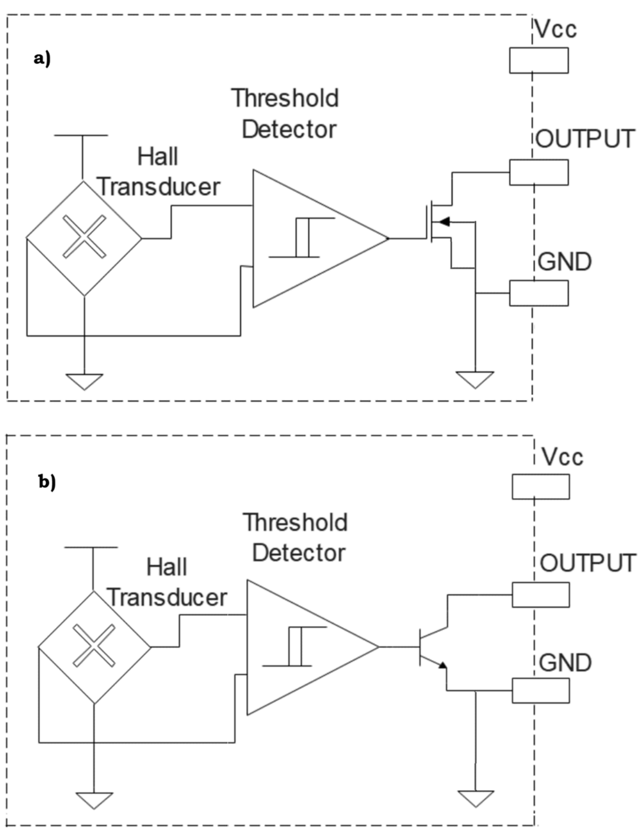

FIG. 10. Output drives: (a) open-drain and (b) open-collector.

B. Choice of material

The dependence of Hall devices on the current and magnetic field is quite clear, so we draw our attention toward the influence of the choice of material. A study has been conducted to test materials such as yttrium, lanthanum, cerium, neodymium, and praseodymium at various temperatures.[58] Other investigations involving materials such as lutetium, ytterbium, thulium, and samarium in Ref. 59 and thorium, uranium, zirconium, titanium, and niobium in Ref. 60 were also conducted. These studies emphasized how pronounced the Hall effect was in different materials. It was also found that the Hall effect in materials, such as uranium, zirconium, and titanium, is greatly dependent on temperature and purity of the material. Determining the electron mobility of the material in use is the main factor to identify the sensitivity of a Hall effect sensor. Higher the electron mobility, more sensitive the sensor. Therefore, InSb,[46] GaAs,[61] InP, InAs,[62] and graphene[63,64] seem to be the most suitable materials for sensors based on the Hall effect.

As evident from a study conducted by Abderrahmane *et al.*,[65] the micro-Hall sensors based on multilayered $MoSe_2$ show high sensitivities, making the material promising for the fabrication of Hall sensors.

C. Effect of temperature

The behavior of a Hall sensor is consistent only under a given set of environmental conditions. The environmental factor that mostly influences the behavior is temperature rise. This strong temperature dependence due to the use of ferromagnetic materials in such sensors can be attributed to the polarized conduction electrons and their spin–orbit interaction, as discussed by Karplus and Luttinger.[66]

Certain devices are available for wide ranges. These sensors can be specially constructed to withstand extreme temperature ranging from $-270°$ to 300 °C by enclosing them in a specially designed package to survive under such extreme temperatures.[67] Lu *et al.*[68] reported AlGaN/GaN hetero-junction structures for a square-shaped Hall effect sensor working in the broad temperature range with very low temperature cross sensitivity.

D. Drift and ratiometry

Sensitivity drift can occur in Hall devices due to the temperature effect or stress in the Hall element. Some of the linear devices can show drift in sensitivity of about ±5% over a given temperature range. The thermal dependence of the sensitivity of the Hall sensors can be reduced as proposed by Mahfoud *et al.*[69] The drift due to stress can be compensated using special circuitry.[70] Some bipolar Hall sensors may have excellent stability but terrible characteristics of offset drift.

Compensation of temperature variations may be feasibly accomplished by including an amplifying system with the original system along with a temperature-responsive negative-feedback coupling, as given in Ref. 71. Ausserlechner *et al.*[72] presented a system that continuously measured the relevant stress components, estimated the sensitivity drift, and digitally corrected it. Their system, in laboratory tests, could keep the drift of magnetic sensitivity well below 1%.

Costly and cumbersome precision amplifiers and correction circuits are sometimes used in efforts to attain decent performance, including linearity and temperature range stability. It can therefore be accomplished economically using a specific IC architecture in which the various elements are assembled in the same epitaxial layer, providing effective temperature compensation.[73]

If a device's sensitivity and zero-flux offset are linear supply voltage functions, then it is referred to as having a ratiometric output. These are helpful in situations where an Analog-to-Digital Converter (ADC) is fed by the output of a Hall-effect sensor.

The drawbacks of ratiometric sensors include power supply noise rejection, and at some point, a stable voltage source is needed. Drift is an unwanted characteristic of Hall-based devices. To get rid of the same and to identify its cause, multiple studies are going on. Over recent decade, there has been a significant increase in studies involving physics to boost the responsiveness of Hall-based impact sensors. One such study conducted by Hung *et al.*[74] resulted in a high field-sensitivity of NiFe/Cu/IrMn trilayer structure-based planar Hall sensors.

E. Noise, offset voltage, and power supply requirements

Noise is any unwanted signal in the output of the system. Linear electronic systems have a noise in their output and so do the systems involving Hall sensors. Hall sensors suffer from the problem of noise at lower frequencies. Contrast in noise properties of distinct integrated magnetic field semiconductor sensors was brought out by Chovet *et al.*[75] There can be various factors that attribute to noise production. One such factor is change in magnetization, and the noise so generated is called Barkhausen noise.[76] Elzwawy *et al.*[77] presented the details of free and forced Barkhausen noises in magnetic thin films with stable multi-domain states. Talantsev *et al.*[78] studied the effect of NiFeCr seed and capping layers in NiFe/Au/IrMn trilayer structures. The results indicated lower values of Barkhausen noise and an improved magnetic field detection limit.

Hall sensors are expected to produce a potential difference only when the conditions for input current and magnetic field are fulfilled. Sometimes, a potential difference is developed in the conducting material even if the magnetic field is absent, but the electric current flows through it. This potential difference, developed even when the magnetic field is not applied, is called the offset voltage. This phenomenon is unwanted as it hinders the sensor from detecting low magnetic fields. Geometrical imperfections are one of the causes for the offset voltage.[79] A study was conducted by Girgin and Karalar[80] to simulate and measure the output offset voltage. The study concluded that factors such as shape of the sensor and proximity effects have an impact on the offset voltage. Paun *et al.* studied the influence of geometry on drift and offset while determining the geometry for best performance. Kanda and Migitaka[81] investigated the stress dependence of the offset voltage in Si Hall ICs. The voltage offset can be reduced in Hall-sensors, as proposed by Kachniarz *et al.*[82] Blanchard *et al.*[83] also presented a method to compensate for the offset voltage as well as to deal with the temperature dependent drift. Liu *et al.*[84] proposed an offset reduction method using two stage signal processing. Montaigne *et al.*[85] developed magnetoresistive sensors based on the planar Hall effect with offset suppression and a resolution below 10 nT. In vertical Hall devices,[86] some common offset reduction methods: orthogonal coupling and spinning current method[87] can be adopted simultaneously to deal with the high offset value.

Hall sensors that are used nowadays have a moderate power supply requirement. A single positive power supply (often +5 V or +12 V) is employed to feed these sensors for operation. Their current requirement is generally in the range of microamperes. These devices also have the ability to behave linearly in this range.[88] A capacitor is connected with the supply to reduce the noise from the system and since these sensors are susceptible to electrical damage, proper care is required so that their ratings are not exceeded. The power consumption of some planar Hall effect sensors can be reduced without compromising the sensitivity by the reduction in operating field range, as proposed by Elzwawy *et al.*[89]

IV. SCENARIO OF RESEARCH IN HALL DEVICES

Several researchers based in both institutes and industries have contributed to several designs of Hall-based devices for different purposes. A few devices are mentioned in Table I.

From Fig. 11 [source: Web of Science (WoS), topic search terms: Hall effect sensor and Hall effect device], it is evident that the number of studies have been increasing every year. The trend pertains to the works directly related to or somewhat dependent on the Hall effect. The publications in the field of Hall devices have also observed a steady growth in the early years of the past decade. By the end of the previous decade, a rapid growth can be observed, which peaks in years 2018 and 2019. A similar growth trend is expected by the end of this year as well.

Table II presents an assessment of several studies while shedding light on progression in Hall-based technology.

One of the fastest growing requirements for Hall effect sensors is the electronics sector. The automotive and the telecommunication sector are also driving the demand. A significant ongoing work is a 40 kW Advanced Electric Propulsion System (AEPS), which is being developed by the NASA. It is the largest planned Hall-effect thruster or HET. It is meant for deep space cargo transportation and for propelling large-scale science missions. The first application of the AEPS is to propel the Power and Propulsion Element module of Lunar Gateway to be launched in 2022.

According to the industry analysis, the COVID-19 pandemic has adversely affected the sensor, control, and automation industry all over the globe and has brought entire economies to the ground.

TABLE I. List of patents on devices based on the Hall effect.

US patent no.	Inventor	Remarks
10073151	Lindemuth[90]	Fast Hall effect measurement system
8666701	Motz[11]	Accurate and cost-efficient linear Hall sensor with digital output
10254354	Cesaretti[70]	Electronic circuit for compensating a sensitivity drift of a Hall effect element due to stress
3613021	Erlangen[71]	Hall-effect amplifying device with temperature compensated characteristic
4760285	Nelson[73]	Hall effect device for providing temperature independent sensitivity using epitaxal layer resistive means
5080289	Lunzer[16]	Spraying voltage control with Hall effect switches and magnet
6457545	Michaud *et al.*[39]	Hall effect seat switch
3875920	Williams[40]	Contact-less ignition system using Hall effect magnetic sensor
5304926	Wu[17]	Geartooth position sensor with two Hall effect elements
6356072	Chass[18]	Hall effect sensor of displacement of magnetic core
3195043	Brig *et al.*[19]	Hall effect proximity transducer
4789826	Willett[21]	System for sensing the angular position of a rotateable member using a Hall effect transducer
4086533	Ricouard *et al.*[20]	Hall effect apparatus for determining the angular position of a rotating part
4086519	Persson[23]	Hall effect shaft angle position encoder
3946691	Freeman[25]	Autopilot employing improved Hall-effect direction sensor
3906641	Freeman[26]	Autopilot employing improved Hall-effect direction sensor

However, this standstill of the manufacturing and production processes is expected to act as a wake-up call for each and every sector, which is expected to lead to a greater adoption of automation and control in the post-pandemic times. This may eventually turn into an opportunity for magnetic sensor market, especially in evolving manufacturing units and supply chains. Figure 12 shows the magnetic sensor market analysis incorporating the uncertainty due to COVID-19 situation.

The demand for magnetic sensors may have decreased in 2020, but considering the above points, a surge in demand is likely in the post-pandemic period, which may eventually compensate for the decline. The forecast by Maximize Market Research Pvt. Ltd. shows

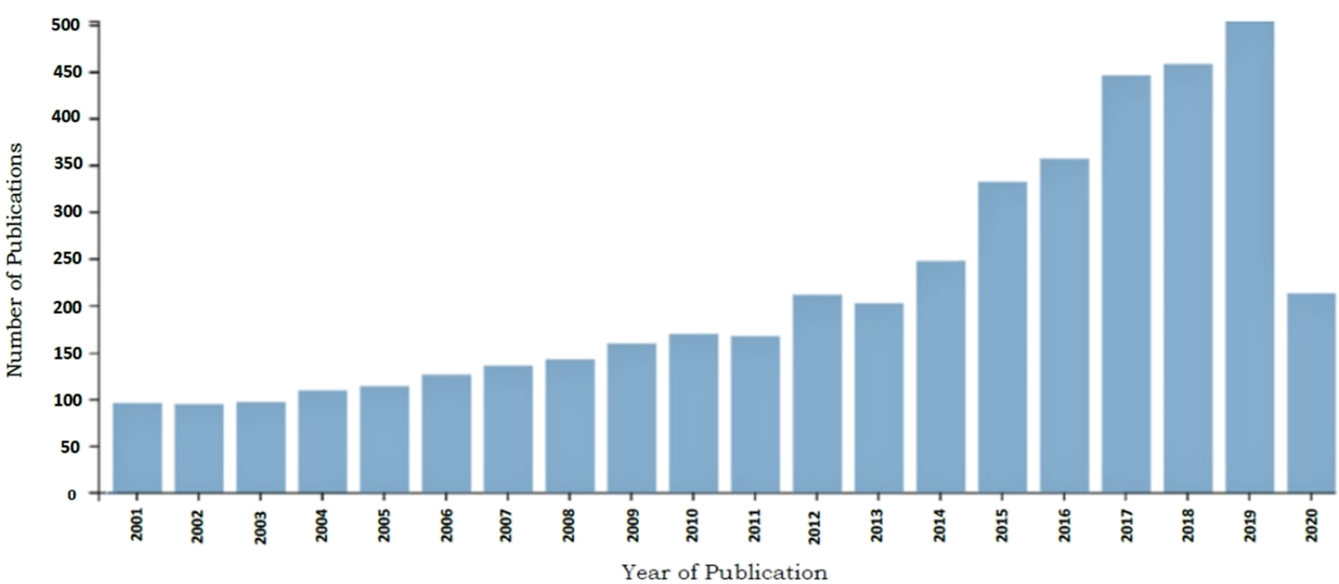

FIG. 11. Publications over the years.

TABLE II. Contrast between some of the works reported.

Topic	Salient points
Promising materials	In 1986, GaAs-based Hall sensors with sensitivity in milliTesla were designed.[61] A highly sensitive InAs sensor with linearity up to 0.18 T was proposed in 1998.[62] Using an ultrathin film InSb micro-Hall sensor, minimum field detection capability reached 77 nT/(Hz)$^{1/2}$, which was successfully realized in 2004[46]
Integrated linear sensors	Heremans[8] developed solid state magnetic field sensors. Schott and Popovic[12] devised a method to linearize the integrated Hall device. Ausserlechner *et al.*[72] presented a way to compensate the piezo-Hall effect in integrated sensors. Hung *et al.*[74] presented a high field-sensitivity planar Hall sensor based on the NiFe/Cu/IrMn trilayer structure
Programmable Hall sensors	For automotive application, a programmable linear magnetic Hall sensor was presented in 2000.[14] It was later enhanced to achieve excellent accuracy.[13] Motz *et al.*[15] worked on a chopped Hall sensor with a programmable "true power-on" function
Speed and direction sensing	In 1978, Ricouard[20] developed a Hall effect apparatus for determining the angular position of a rotating part. These devices were further improved by using gear tooth sensing.[22] A miniature Hall effect position sensor was developed by Bienczyk[24] in 2009
Flexible Hall sensors	In 2019, Oleg *et al.*[63] worked on graphene Hall sensors that were highly linear but with certain limitations. Flexible graphene-based Hall sensors with increased sensitivity were recently designed[64]
Temperature related enhancements	Lu *et al.*[68] proposed AlGaN/GaNAlGaN/GaN heterojunction structures for use in Hall sensors, which provides low temperature sensitivity till 300 °C. Jankowski *et al.*[67] presented the Hall sensor with an extreme operating range of −270 °C to 300 °C
Drift reduction research	Correction of drift due to temperature variations was dealt by Erlangen.[71] In 1988, Nelson[73] suggested epitaxal layer resistive means to provide temperature independent sensitivity. A compensation method for stress caused drift in integrated Hall sensors was proposed.[72] Recently, Cesaretti[70] addressed the issue of drift due to mechanical stress by developing an electronic circuit consisting of a Hall element and a resistor bridge
Noise reduction research	Magnetic field detection limit is a characteristic of the semiconductor material.[75] Elzwawy *et al.*[77] determined that the best performance is obtained from NiFe/NM/NiFe. Talantsev *et al.*[78] enhanced the magnetoresistive response and reduced noise by replacing Ta with NiFeCr seed and capping layers for thin film and cross junctions based on NiFe/Au/IrMn structures
Offset reduction research	Compensation for the temperature-dependent offset of a Hall sensor can be done by calibration at two different temperatures.[83] Montaigne *et al.*[85] developed a new magnetoresistive sensor fabricated using a standard sputtering deposition method directly on Si substrates resulting in huge offset supression. Arrangement of electrical pins on the Hall sensor in an appropriate configuration offers the minimum offset voltage.[82] In 2012, Paun *et al.*[91] determined that out of all the cross-shaped sensors, the XL shaped sensor performed the best. In 2019, Girgin *et al.*[80] concluded that cross-shaped sensors exhibited larger offsets than octagon and rounded square shaped sensors

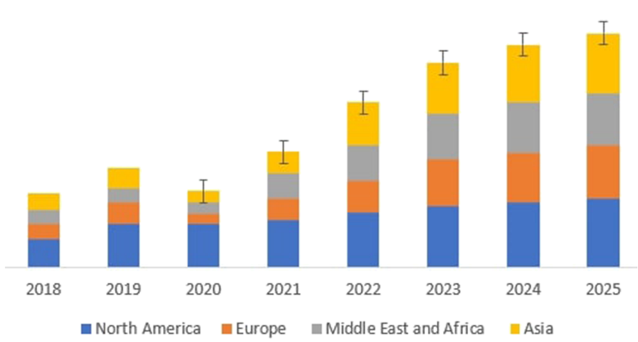

FIG. 12. Magnetic sensor market analysis and forecast.

that the size of global magnetic sensor market is estimated to reach around US$ 7.36 Bn by the year 2026.

V. CONCLUSIONS

This paper provides a detailed review of Hall-based devices. Since the output of a Hall effect-based device is quite low, an amplification circuit is required. In case these are to be used in digital systems, an additional digital signal processing unit is required. This output signal can be delivered as an analog output voltage, as a pulse width modulation (PWM) signal, or even as a modern bus protocol called Single Edge Nibble Transmission (SENT). There are several devices employing the Hall effect principle. The major devices are linear sensors, field-programmable sensors, switches, latches, speed sensors, directional sensors, vane sensors, etc. Linear Hall sensors provide an output that is directly proportional to the applied magnetic field. Digital Hall sensors (switches and latches) do not report the magnitude of the applied field and have discrete switching states. Speed sensing devices can be used to measure the speed and the angular position of a rotating object such as a shaft. These different sensors have different working temperature ranges and power requirements, which are thoroughly discussed in this paper. Like every practical device, the Hall-based devices also have imperfections. Their characteristics are influenced by several undesired effects, such as temperature rise, noise, and drift. The causes and the compensation techniques available in the literature are discussed in this paper. Finally, this paper closes with a brief overview of the scenario in research and marketing. This paper is therefore expected to instigate research in the minds of readers.

AUTHORS' CONTRIBUTIONS

All authors contributed equally to this work.

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DATA AVAILABILITY

The data that support the findings of this study are available within the article.

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