Vehicle Detection and Compass Applications using AMR Magnetic Sensors

Michael J. Caruso, Lucky S. Withanawasam
Honeywell, SSEC, 12001 State Highway 55, Plymouth, MN USA 55441
<www.ssec.honeywell.com>

ABSTRACT

The earliest magnetic field detectors allowed navigation over trackless oceans by sensing the earth's magnetic poles. Magnetic field sensing has vastly expanded as industry has adapted a variety of magnetic sensors to detect the presence, strength, or direction of magnetic fields not only from the earth, but also from permanent magnets, magnetized soft magnets, vehicle disturbances, brain wave activity, and fields generated from electric currents. Magnetic sensors can measure these properties without physical contact and have become the eyes of many industrial and navigation control systems. This paper will describe the current state of magnetic sensing within the earth's field range and how these sensors are applied. Several applications will be presented for magnetic sensing in systems with emphasis on vehicle detection and navigation based on magnetic fields.

INTRODUCTION

Magnetic sensors have been in use for well over 2,000 years. Early applications were for direction finding, or navigation. Today, magnetic sensors are still a primary means of navigation but many more uses have evolved. The technology for sensing magnetic fields has also evolved driven by the need for improved sensitivity, smaller size, and compatibility with electronic systems. An integrated circuit based magnetic sensor, optimized for use within the earth's magnetic field, will be presented—anisotropic magnetoresistive (AMR) sensors. Applications using AMR magnetic sensors are emphasized.

A unique aspect of using magnetic sensors is that measuring magnetic fields is usually not the primary intent. A secondary parameter is usually desired such as wheel speed, presence of a magnetic ink, vehicle detection, or heading determination. These parameters cannot be measured directly, but can be extracted from changes, or disturbances, in magnetic fields. Conventional sensors, such as temperature, pressure, strain,

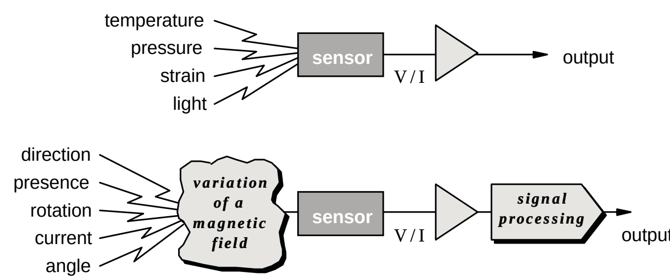
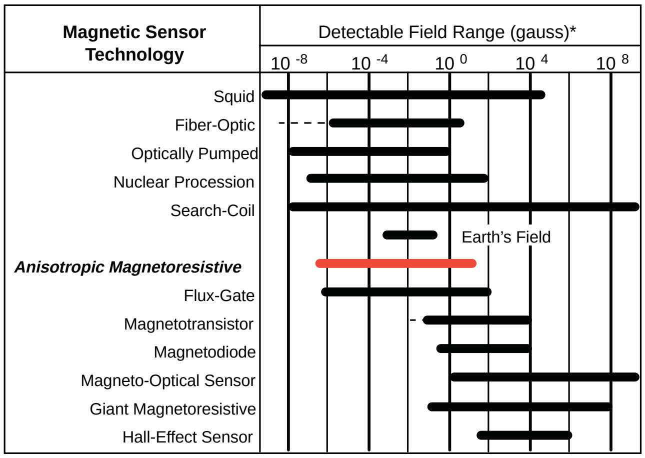


Figure 1–Conventional vs. Magnetic Sensing

or light sensors can directly convert the desired parameter into a proportional voltage or current output—see Figure 1. On the other hand, using magnetic sensors to detect direction, presence, rotation, angle, or electrical currents can only indirectly detect these parameters. First, the enacting input has to create, or modify, a magnetic field. A current in a wire, a gear tooth moving past a permanent magnet, or a ferrous object moving within the earth's magnetic field can create this field variation. Once the magnetic sensor detects that field variation, the output signal requires some signal processing to translate the sensor signal into the desired parameter value. This makes magnetic sensing a little more difficult to apply in most applications. But understanding these field variation effects can result in very reliable and accurate sensing of parameters that can be difficult to sense otherwise.

One way to classify the various magnetic sensors is by the field sensing range. These sensors can be arbitrarily divided into three categories—low field, medium field, and high field sensing. Sensors that detect magnetic fields less than 1 microgauss will be classed low field sensors. Sensors with a range of 1 microgauss to 10 gauss will be considered earth's field sensors and sensors that detect fields above 10 gauss will be considered bias magnet field sensors for this paper. Table 1 lists the various sensor technologies and illustrates the magnetic field sensing ranges [1].



* Note: 1gauss = 10^{-4}Tesla = 10^{5}gamma

Table 1–Magnetic sensor technology field ranges

This paper will focus on the anisotropic magnetoresistive (AMR) sensors, which are optimized to work within the earth's magnetic field range. AMR sensors can reliably detect both the magnitude and direction of the earth's magnetic fields to 1 part in 12,000. Applications for vehicle detection and navigation using AMR sensors will be described in detail.

EARTH'S FIELD SENSORS *(1 microgauss to 10 gauss)*

The magnetic range for the medium field sensors lends itself well to using the earth's magnetic field. Several ways to use the earth's field are to determine compass headings for navigation, detect anomalies in it for vehicle detection, and measure the derivative of the change in field to determine yaw rate.

Anisotropic Magnetoresistive (AMR)

William Thompson, later Lord Kelvin [2], first observed the magnetoresistive effect in ferromagnetic metals in 1856. This discovery had to wait over 100 years before thin film technology could make a practical sensor for application use. Magnetoresistive (MR) sensors come in a variety of shapes and form. The newest market growth for MR sensors is high density read heads for tape and disk drives. Other common applications include automotive wheel speed and crankshaft sensing, compass navigation, vehicle detection, current sensing, and many others.

The anisotropic magnetoresistive (AMR) sensor is one type that lends itself well to the earth's field sensing range. AMR sensors can sense dc static fields as well as the strength and direction of the field. This sensor is made of a nickel-iron (Permalloy) thin film deposited on a silicon wafer and is patterned as a resistive strip. The properties of the AMR thin film cause it to change resistance by 2-3% in the presence of a magnetic field. Typically, four of these resistors are connected in a Wheatstone bridge configuration (Figure 2) so that both magnitude and direction of a field along a single axis can be measured. A common bridge resistance is 1 kohm. For typical AMR sensors, the bandwidth is in the 1-5 MHz range. The reaction of the magnetoresistive effect is very fast and not limited by coils or oscillating frequencies. The key benefit of AMR sensors is they can be bulk manufactured on silicon wafers and mounted in commercial integrated circuit packages. This allows magnetic sensors to be auto-assembled with other circuit and systems components.

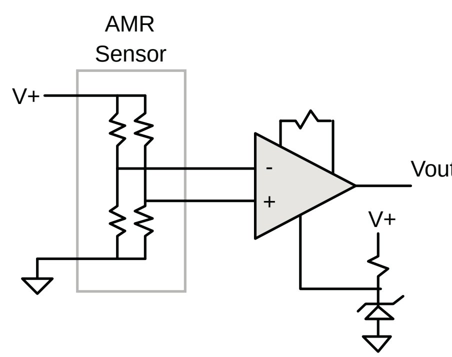


Figure 2–AMR sensor circuit

AMR Sensor Characteristics

AMR sensors provide an excellent means of measuring both linear and angular position and displacement in the earth's magnetic field. Permalloy thin films deposited on a silicon substrate in various resistor bridge configurations provide highly predictable outputs when subjected to magnetic fields [2,3,4]. Low cost, high sensitivity, small size, noise immunity, and reliability are advantages over mechanical or other electrical alternatives. Highly adaptable and easy to assemble, these sensors solve a variety of problems in custom applications.

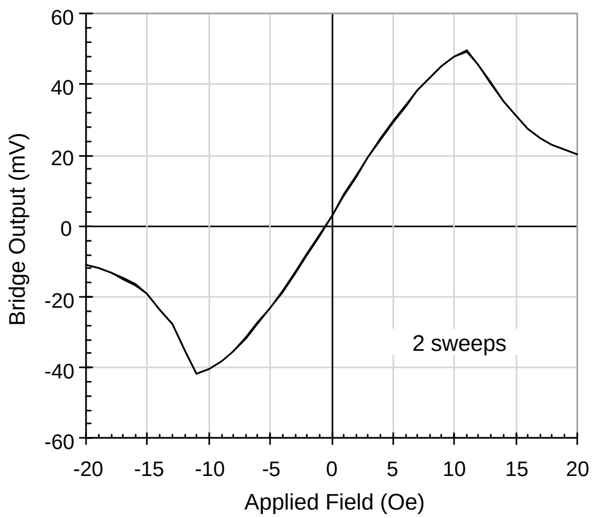


Figure 3–AMR output transfer curve

A characteristic of the Permalloy film is that it changes resistance (ΔR) when exposed to a variation in an applied magnetic field—hence the term magnetoresistance. This causes a corresponding change in voltage output as shown in Figure 3. The sensitivity of the bridge is often expressed as mV/V/Oe. The middle term (V) of this unit refers to the bridge voltage, Vb. When the bridge voltage (Vb) is set to 5 volts, and the sensitivity (S) is 3mV/V/Oe, then the output gain will be 15mV/Oe. Through careful selection of a bridge amplifier, output levels of 1 microvolt can be achieved. This results in a magnetic resolution of 67 microOersted, or 1 part in 15,000 per Oersted. If the bridge output is amplified by a gain of 67, then the total output sensitivity would be 1V/gauss (=67 x 15 mV/gauss). If a full-scale range of ± 2 gauss is desired, this implies a 4-volt output swing centered on the 2.5V bridge center value—or a span of 0.5 to 4.5V. This signal level is suitable for most A/D converters. Using an AMR sensor and amplifier, precise magnetic field information can provide field magnitude as well as directional information.

There are well described design techniques to build extremely sensitive magnetic sensor subsystems. By simply switching the magnetic properties of the Permalloy film, the sensor offset voltage as well as the sensor and amplifier offset drift with temperature can be eliminated. On-chip offset straps can be used to auto-calibrate the AMR sensor while in an application during normal operation. Output gain variation with temperature can be greatly reduced by using a closed-loop feedback technique so that the sensor always operates in a zero field environment. These techniques, and others, can be found in references [5,6,7].

AMR SENSOR APPLICATIONS

AMR sensors available today do an excellent job of sensing magnetic fields within the earth's field—below 1 gauss. These sensors are used in applications for detecting ferrous objects such as planes, trains, and automobiles that disturb the earth's field. Other applications include magnetic compassing, rotational sensing, current sensing, underground drilling navigation, linear position sensing, yaw rate sensors, and head tracking for virtual reality.

Vehicle Detection

The earth's field provides a uniform magnetic field over a wide area—say several kilometers[2]. Figure 4 shows how a ferrous object, a car, creates a local disturbance in this field whether it is moving or standing still. AMR magnetic sensors can detect the change in the earth's field due to the vehicle disturbance for many types of applications.

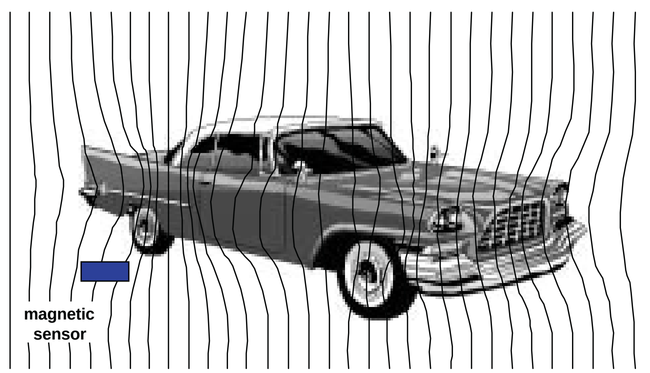
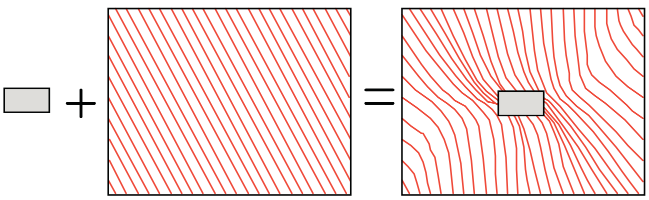


Figure 4–Vehicle disturbance in earth's field

Applications for vehicle detection can take several forms. A single axis sensor can detect when a vehicle is present, or not. The sensing distance from the vehicle can extend up to 15 meters away depending on its ferrous content. This is useful in parking garages to give drivers entering it a choice of where the most available spaces to park. Another use is to detect approaching trains to control the crossing gates. In this application, two sensors could be used to detect presence, direction of travel, and speed to give the controller enough information to control the crossing gates.

The magnetic disturbance of a large ferrous object, such as a car, can be modeled as a composite of many dipole magnets. These dipoles have north-south orientations that cause distortions in the earth's magnetic field. The distortions are most obvious at the engine and wheel locations but can also vary depending on what ferrous items are in the interior, on the rooftop, or in the trunk locations. The net result is a characteristic distortion, or anomaly, to the earth's magnetic field that is unique to the shape of the car (see Figure 5). These distortions are also referred to as hard iron effects, or distortion, of the vehicle.



Ferrous Object + Uniform Magnetic Field = Field Disturbance

Figure 5–Ferrous object disturbance in uniform field

VEHICLE CLASSIFICATION

Magnetic disturbances can be used to classify different types of vehicles—cars, vans, trucks, buses, trailer trucks, etc. When a vehicle passes close to the magnetic sensor, or drives over it, the sensor will detect all the different dipole moments of the various parts of the vehicle. The field variation will reveal a very detailed magnetic signature of the vehicle.

A three-axis AMR magnetometer placed in the lane of traffic will provide a rich signal output for vehicles passing over it. Figures 7 and 8 show a three-axis magnetometer output for two vehicles passing directly over it. The vehicle in Figure 7 is a Silhouette van, and the vehicle in Figure 8 is a Saturn sedan. The four curves represent the X, Y, Z, and magnitude of the variation in the earth's field for the vehicle driving south. The X-axis points west, the Y-axis points south and the Z-axis is in the up direction. The starting point for each curve is the earth's magnetic field values for the sensor location:

Field at location (X,Y,Z) = (-24, -187, -554) mgauss

The type of vehicle can be classified using these variations with the use of pattern recognition and matching algorithms. From the magnetometer output curves in Figures 7 and 8, several observations reveal how the vehicles cause variations in the earth's magnetic field. The largest deviation in each curve is when the engine block passes over the sensors. This produces the largest peak around time mark 51 in Figures 7 and 8. The Y and Z axes between the two vehicles have a lot of similarities, but for this case, the X-axis is unique to each vehicle type.

If the vehicle speed is known, then the length of the vehicle can be determined. By using a second Y-axis sensor placed, for example, six feet apart, the peak signal from the engine variation can be used to measure the time it takes for the vehicle to pass six feet. Vehicle speed is determined from the time traveled over a specific distance (6 ft.). Having calculated the vehicle's speed, its length can be determined by observing the magnitude of the disturbance curves—bottom curves in Figures 7 and 8. The vehicle length is a critical input to the classification algorithm in making the vehicle type selection.

VEHICLE DIRECTION AND PRESENCE

For vehicle presence and direction detection the field variations do not require so much detail as for vehicle classification. It is also undesirable to make cuts in the road to bury a sensor in the lane of traffic. It is preferred to place the sensor curbside, along the lane of traffic being monitored, without cutting into the road surface. AMR magnetic sensors can easily be configured to reliably detect vehicles curbside based on the earth's field variation it creates.

The test setup for vehicle direction and presence is shown in Figure 6. The three-axis magnetic sensor is at ground level and the X, Y, Z axes orientations are shown above with respect to the vehicle direction.

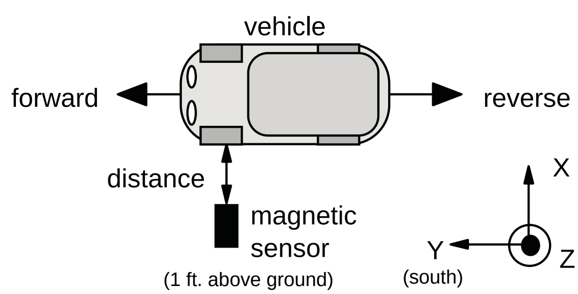


Figure 6–Vehicle and magnetic sensor orientations for drive-by tests

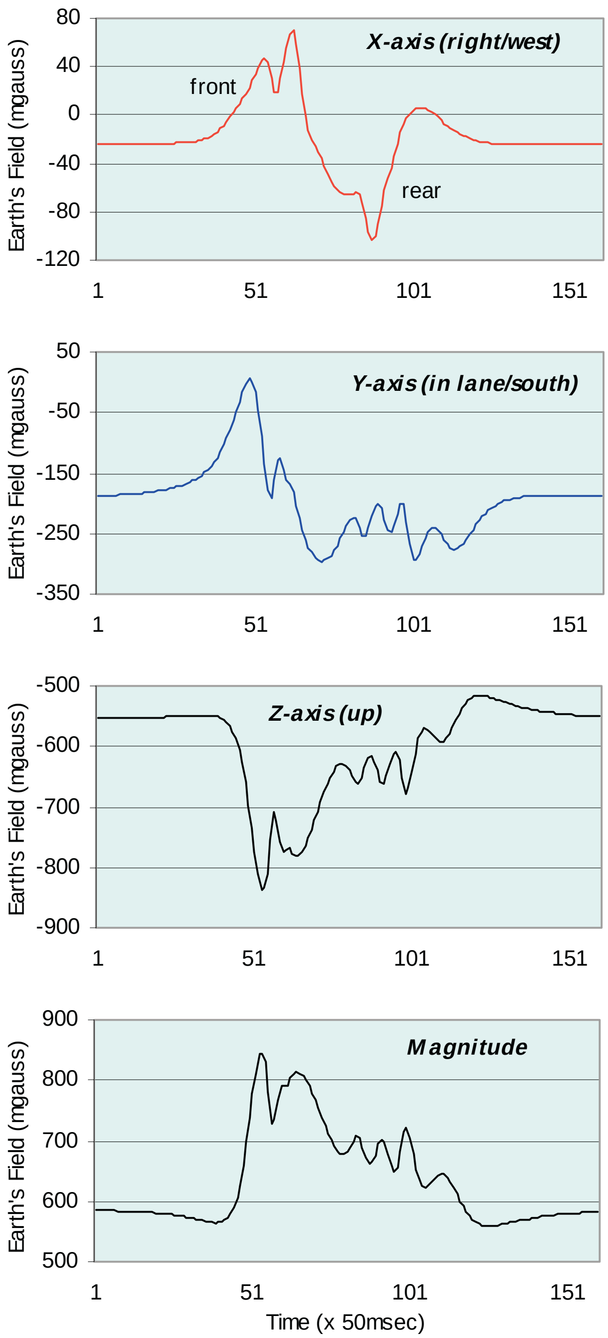


Figure 7—Earth's field variations for a van (Silhouette) driving over magnetometer. Vehicle traveling south.

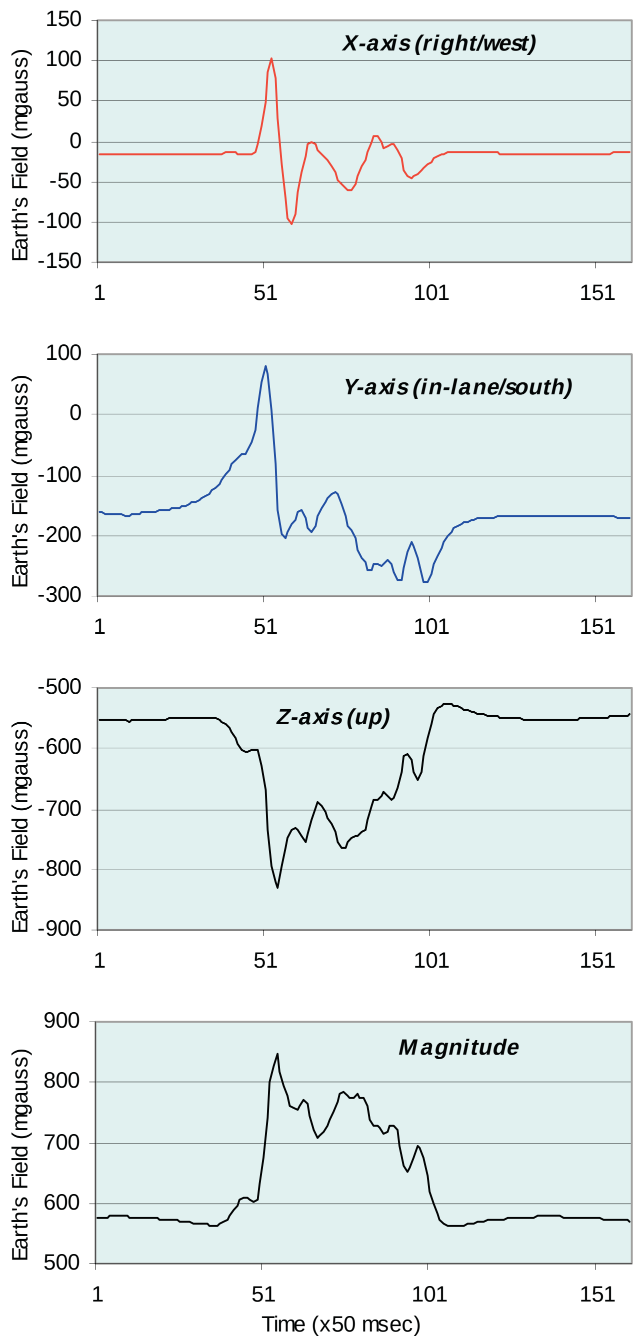


Figure 8—Earth's field variations for a car (Saturn) driving over magnetometer. Vehicle traveling south.

For this test, a car (Saturn sedan) was driven past the magnetic sensor at a distance of 1 foot and 3 feet. The X, Y, Z curves are shown in Figures 9 and 10. The difference between the figures is that for Figure 9 the sensor was 1 foot from the car as it passed by in a north-south direction. In Figure 10, the sensor was 3 feet from the car as it passed by in an east-west direction. Each curve has two vehicle deviations: the first is the car traveling in the forward direction, the second is the car traveling in reverse (backing up). As the car drove by the sensor, the X, Y, Z curves in Figure 9 show several more details about the vehicle than those in Figure 10. This detail is from the individual dipole moments of the vehicle affecting the sensors at a closer distance. Also, note the peak amplitudes are reduced for the curves in Figure 10 due to the sensors being further from the car as it passed by. The speed of the vehicle differs in the forward and reverse portion of the curve; backing the car up (reverse) was at a slower speed. The X and Z axes of Figures 9 and 10 have a noticeable peak as the engine passes the sensor. The body of the car affects each axis a little differently. Also of importance is the symmetry of the curve for the car passing over in the forward direction and then in the reverse direction. The similarities in the curve shapes for the car traveling north-south verses east-west are also an important characteristic. This indicates that each small section of the car produces a repeatable signature variation in the earth's field that can be referenced for this vehicle, or type of vehicle. Thus, the vehicle's signature can be reliably detected when driving in either direction.

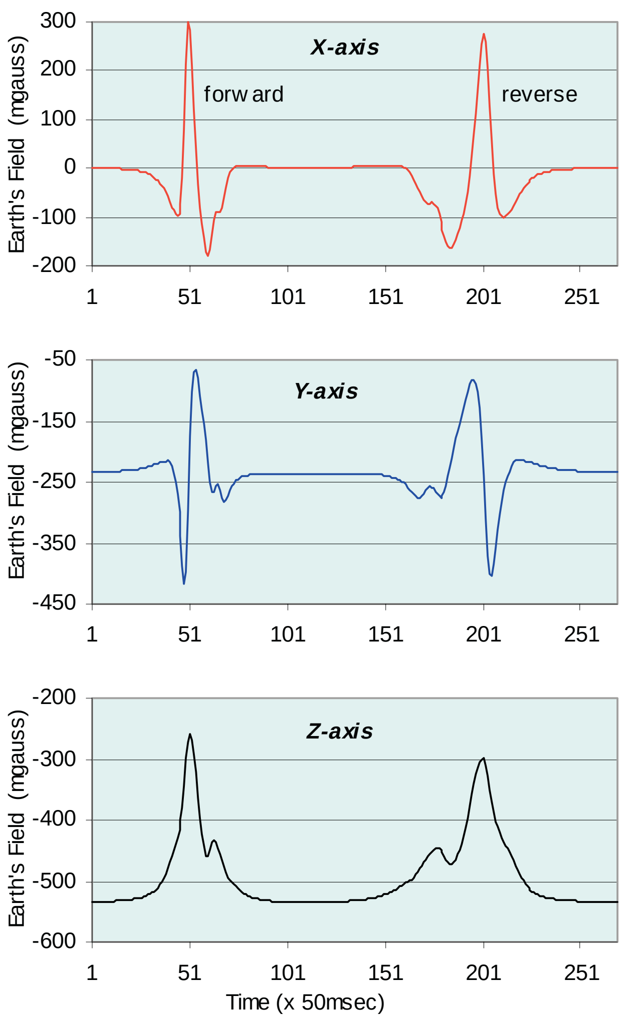


Figure 9–The X,Y, and Z magnetic variations from a car traveling in the forward (south) and reverse (north) direction. The sensor was one foot above ground and one foot from the car as it passed by.

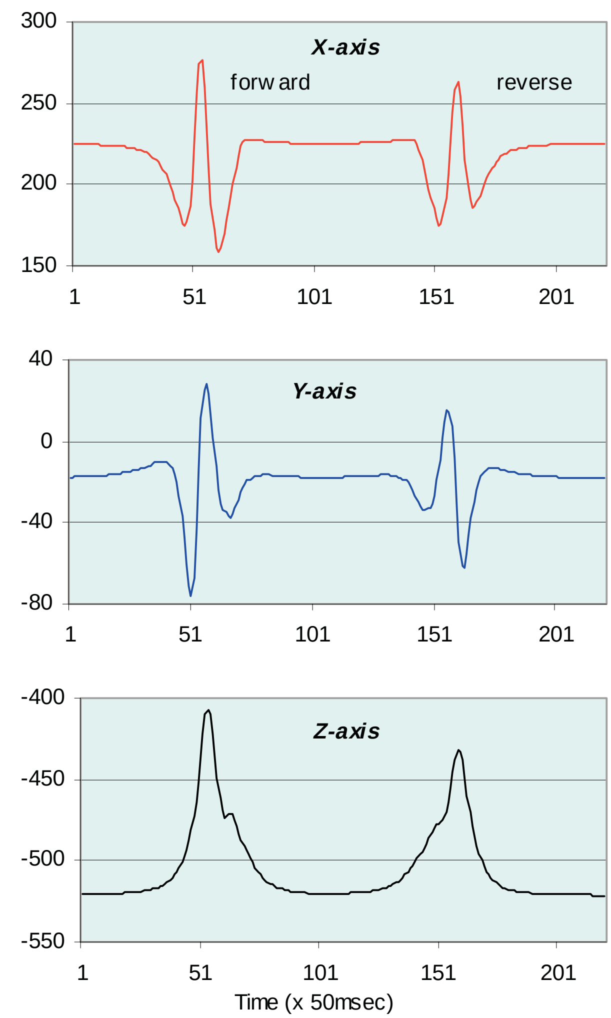


Figure 10–The X,Y, and Z magnetic variations from a car traveling in the forward (west) and reverse (east) direction. The sensor was one foot above ground and three feet from the car as it passed by.

Vehicle Direction

Another useful type of vehicle detection is the direction a vehicle is moving past the sensor. This may be useful for safety reason such as highway on-ramps that are not obvious, traffic through tunnels to activate warning lights, and train movement detection to operate crossing gates. By understanding the variation of the earth's field from a vehicle passing by, the direction can be determined just by using a single axis sensor.

The axis along the direction of travel can be used to determine the direction of the vehicle (see Figure 11). When there is no car present, the sensor will output the background earth's magnetic field as its initial value. As the car approaches, the earth's magnetic field lines of flux will be drawn toward the ferrous vehicle. If the sensitive axis of the magnetic sensor points to the right and the car is traveling left to right, then the magnetometer will initially see an decreasing field as more flux lines bend toward the oncoming car. That is, the first magnetic deviation from the sensor's initial value will be to swing in the negative direction.

When the car is directly inline with the sensor, the magnetic variation through the car looks the same as the starting point—the sensor output curve returns to the initial value. As the car leaves to the right, the flux lines will bend toward the car in the positive sensor axis. This will cause the sensor output to increase above the initial value. When the car is out of range of the sensor, it will again return to the initial value. The left-hand curve in Figure 11 shows the sensor response to a vehicle moving left-to-right. When the car is traveling in the opposite direction, the flux lines are attracted toward the car in the positive sensor direction causing an initial increase in the sensor output. The right-hand curve in Figure 11 shows the sensor response to a vehicle moving right-to-left.

This model can be represented by the Y-axis curve in Figure 9. As the vehicle approaches from the left (driving south), with the sensor axis also pointing south, the initial sensor output should be a field change moving in the negative direction (refer to Figure 11). The Y-axis in Figure 9 shows that it indeed drops—becomes a larger negative field around the 51 time mark. As the vehicle leaves to the right of the sensor, the field will increase as the flux lines follow the vehicle away from the sensor. The sensor output increases as the vehicle leaves and returns to the initial level when it is out of range. Note that there are two bumps in the tail end of the curve, around the 60 time mark. The rear axle and spare tire in the trunk of the car most likely causes these.

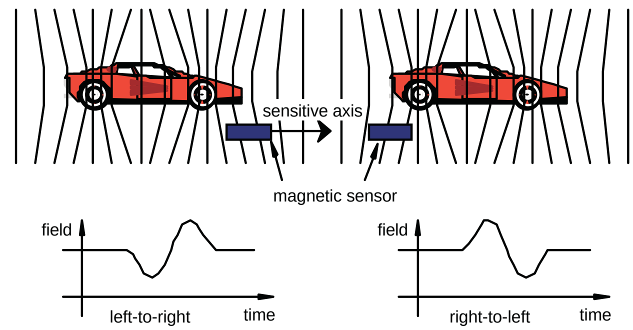


Figure 11–Direction sensing for vehicles driving over magnetic sensor.

For the last half of the Y-axis curve in Figure 9, the car is backing up and traveling by the sensor in the opposite direction. This part of the curve is a mirror reflection of the first half. It is stretched out a little more during to the slower speed backing up. The key characteristic is that the signal level will first peak low when going past the sensor in this direction as opposed to first peaking high when passing in the opposite direction. A simple check of the initial field strength deviation will indicate which direction the car is traveling.

Vehicle Presence

The Z-axis field, component in the up direction, can be used to indicate the vehicle presence. This curve peaks when the vehicle is directly inline with the sensor axis. For the case of a one foot distance to the sensor (Figure 9), a smoothed version of this curve can be used to indicate presence. Threshold levels can be established to eliminate false sensing from neighboring lanes of traffic and vehicles at a distance.

Another way to detect vehicle presence is looking at the magnitude of the magnetic variation:

$$\text{Magnitude} = (X^2 + Y^2 + Z^2)$$

The magnitude variation indicates the overall disturbance to the earth's field. Figure 12 shows magnitude curves for a car (Saturn) passing by the sensor at distance of 1, 5, 10, and 21 feet.

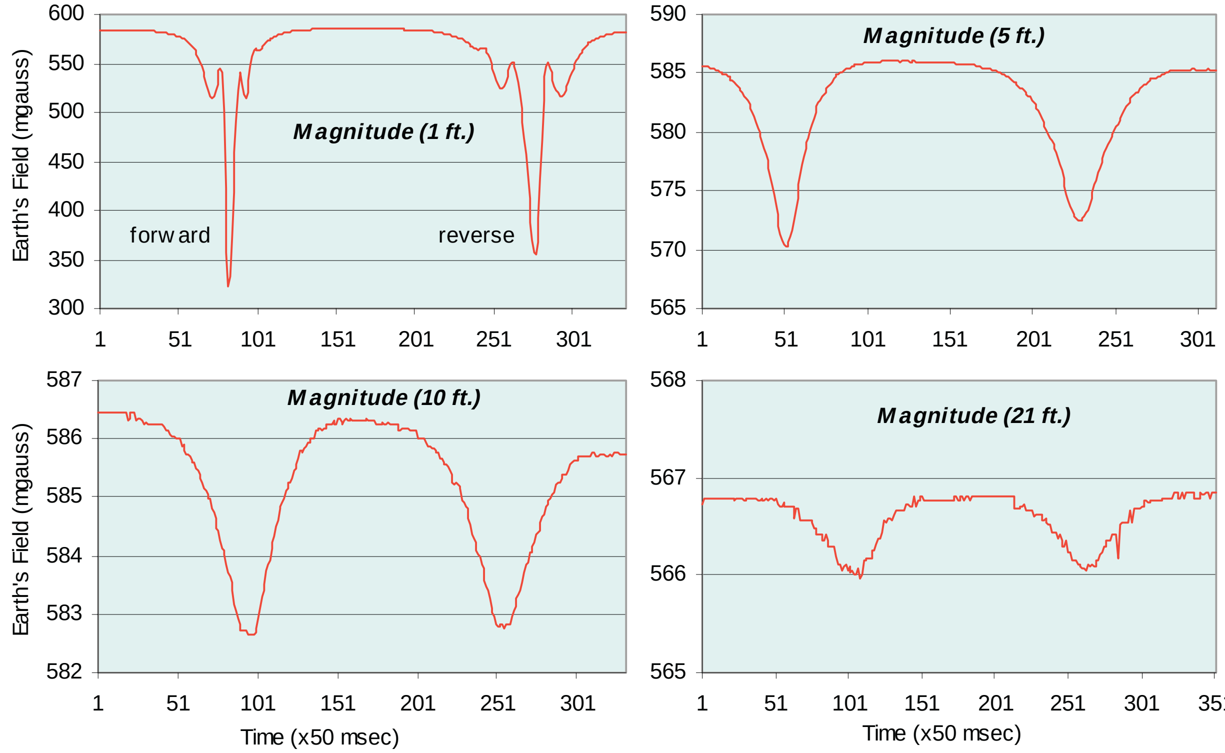


Figure 12–Magnitude of magnetic field variations for a car traveling forward and reverse at distances of 1, 5, and 10 feet (moving north-south) and 21 feet (moving east-west).

The shapes of the curves in Figure 12 are similar for each distance but the signal strength is quite different. The change in signal strength falls off quite rapidly for distances of 1 to 5 feet. Figure 13 shows this rapid decrease in the change in magnitude. This effect can be beneficial when a sensor has to detect vehicles in a single lane of traffic with other lanes present.

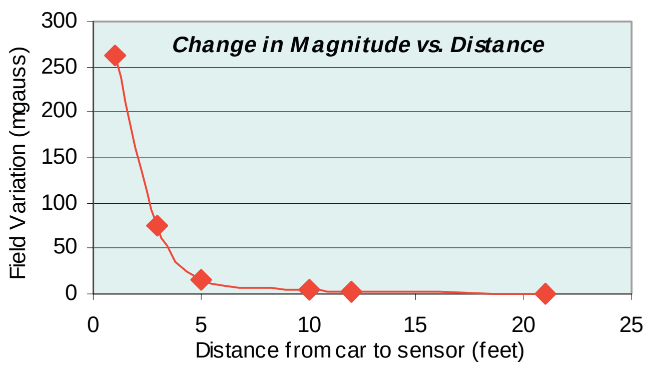


Figure 13–Magnitude change if field variation for car passing sensor at various distances

AMR magnetic sensors work well for normal curbside sensing ranges of one to four feet. Both presence and direction can be determined by observing the magnetic field variations as a vehicle passes by. The benefit of this type of sensing is that no cutting is required in the pavement and the sensor can be located in aluminum housing.

Based on the needs of the vehicle detecting application, the level and type of the field variation required will determine where the sensor is located and at what distance. Placing the sensor in the road for the car to drive over may be best suited for speed determination and vehicle classification. Having the sensor at a further distance along the roadside may be best for vehicle detection and direction sensing.

COMPASSING AND NAVIGATION

Honeywell's MR sensors are particularly designed for 'low' magnetic field applications. That is, 2 to 3 times the earth's magnetic field strength. In the previous section we discussed the usage of MR sensor to detect anomalies of the earth's magnetic field created by ferrous objects, and how to take advantage of these anomalies in traffic detection and vehicle classification applications. Such applications use the earth's field in an indirect way to detect presence or absence of magnetic objects. On the contrary, directly detecting the earth's field is a natural extension of the MR sensors, and what is exactly required in compassing applications. The high resolution and low noise characteristics of Honeywell MR sensors exceed the requirements for high resolution, high accuracy compasses.

Magnetics and the Earth's Field

Origin of magnetism runs back over 2500 years to the discovery of a particular kind of rock that has the ability to attract iron. Today this mineral is known as magnetite, the English called it the *lodestone,* and chemist would prefer Fe_3O_4. Magnetite was a common mineral throughout the world and was in abundance in modern day Turkey. It was also known that pieces of iron themselves would become lodestone-like when touched or rubbed by magnetite. This and the discovery that a free hanging magnetized needle would point to the same direction gave birth to the magnetic compass. Thanks to Seventeenth Century scientist William Gilbert, we know the above phenomenon is due to the magnetized needle aligning with the earth's magnetic field [8]. Modern compasses operate under the same principles perhaps with a tighter meaning for *same* direction.

The earth's magnetic field from which the magnetic compass heading is derived has field strength of 0.5 to 0.6 gauss, and can be approximated with fields generating from a magnetic dipole model as shown Figure 14. This is equivalent to placing a long bar magnet magnetized along the length at the center of the earth. Poles of this bar magnet would have to be offset (~11.5°) from the geographic poles of the earth. The south pole of the magnet would represent the north geographic pole.

The earth's field points down in the Northern Hemisphere parallel near the equator and points up in the Southern Hemisphere. This global variation is captured in to what is known as the *Dip angle*, defined as the angle the magnetic filed makes with the local horizontal plane. The Dip angle then would change with *latitude* and has a range of ±90 degrees.

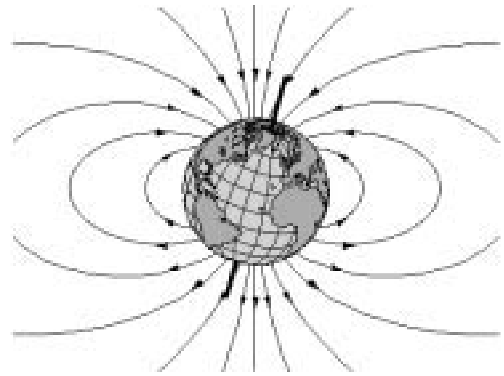


Figure 14–The earth's magnetic field can be approximated by a dipole field

As mentioned before, a compass needle would settle pointing along the local magnetic field vector, that otherwise is known as the local magnetic north. Because the magnetic and geographic poles do not coincide, the magnetic north and geographic north are not aligned in general. This local variation is described by the quantity variation, or declination, angle. Simply it is the angular difference between the magnetic and geographic north expressed as Easterly or Westerly. The declination angle has been mapped over the entire globe and is marked on navigational charts or available electronically as tables or is generated by mathematical model calculations. This information makes a magnetic compass a globally useful device.

Electronic Compass

With the advent of magnetic sensors that operate within the earth's magnetic field such as fluxgate or AMR, an electronic version of the magnetic compass became a possibility. Such a device has definite advantage over the mechanical version due to its electrical output, high accuracy achievable and the ability to integrate it in to control loops.

The electrical output of these sensors is proportional to the magnetic field strength along its sensitive axis. When such a sensor is spun around a horizontal plane starting from magnetic north, the output is a cosine function of the heading angle. A minimum of two sensors that are arranged mutually perpendicular would eliminate the ambiguity in electrical output with respect to heading direction as seen in Figure 15. These signals can be used to control the rudder of a ship to maintain a predetermined course, even though the heading direction in an absolute sense is unknown.

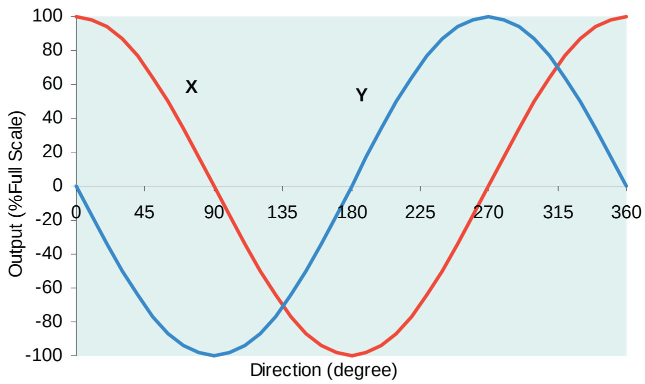


Figure 15–Output of two orthogonal magnetic sensors rotated horizontally in the earth's magnetic field showing Sine and Cosine functions.

Figure 16 shows an electrical block diagram of an electronic compass providing a numerical output of the heading direction. Azimuth or the heading is calculated by the equations given below [9]. The X sensor defines the forward direction and the Y sensor is to the right.

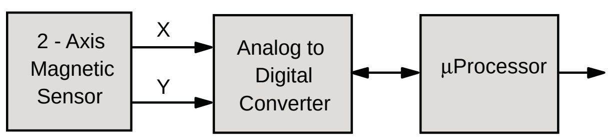


Figure 16–Functional block diagram of a two-axis compass

Heading = 90 - ArcTan(X/Y)•180/Pi (Y>0)
= 270-ArcTan(X/Y)•180/Pi (Y<0)
= 180 (Y=0 and X<0)
= 0 (Y=0 and X>0)

This two-axis compass device will perform well as long as it is kept horizontal and is useful in hand held applications. However, operation of the compass while it is not level can result in considerable amount of heading error. These errors can be quite large as shown in Figure 17 for various pitch levels. This heading error has directional dependence and increases with the pitch angle. There is no heading error for north or south travel. The Y sensor is essentially at zero output and therefore the heading is independent of the value of Y sensor. Also, the larger the dip angle the greater the heading error.

More often than not the compass is installed in dynamic environments of an aircraft, a boat, or a land vehicle. It is not possible to guarantee the compass will be always level. This reduces its usefulness in such installations. One approach for overcoming this problem is to gimbal the magnetic sensors by mechanical means. Hence, the magnetic sensors are constantly kept in the local horizontal plane, assuring the heading accuracy from the above calculations.

Another approach is known as the strapdown or electronically gimbaled compass. This design would use three magnetic sensors and an additional sensor to find the local gravity direction—usually in terms of roll and pitch. Knowing the tilt, the horizontal components of the earth's magnetic field can be mathematically calculated from the 3-axis magnetic reading. This approach adds more complexity to the problem compared to the mechanically gimbaled solution. However, reliability and the ability to compensate for nearby magnetic effects makes this approach desirable.

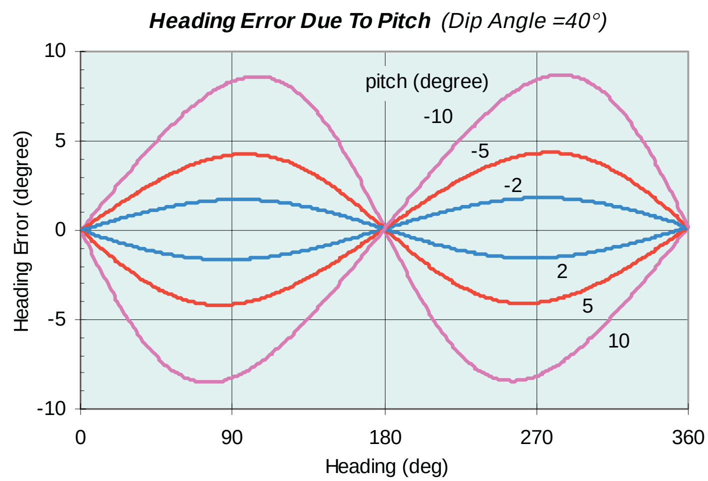


Figure 17–Heading error of a two-axis compass with pitch angle, simulated for a dip angle of 40 degrees.

Electronically Gimbaled Compass

These designs incorporate a sensor to determine the orientation of the compass with respect to the local level plane. To measure pitch and roll information, a two-axis tilt sensor, or a two- or three-axis accelerometer is commonly used. Pitch and roll are common terms in the aviation industry and pitch refers to the angle the nose of the aircraft makes with the horizontal, and roll refers to the angle the right wing makes with the horizontal. Liquid filled tilt sensors are commonly used, and they work on the simple fact the top surface of a liquid will always be level. Three electrodes are placed inline at the bottom surface of the sensor. The resistance of the outer electrodes to the center will change with tilt. These three electrodes constitute a potential divider, the output of which is the tilt signal.

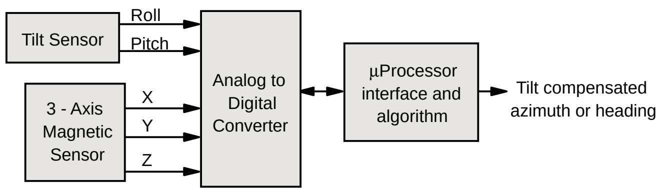


Figure 18–Functional block diagram of a strap-down electronic compass.

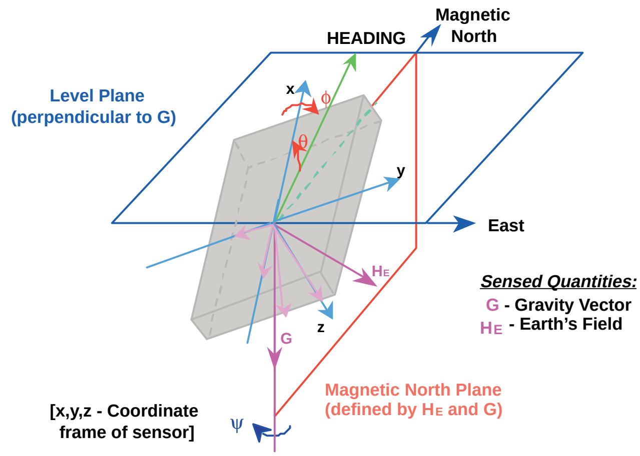


Figure 19–Illustration of Gravity and Magnetic vectors in the compass coordinate system.

Accelerometers, particularly the more advanced Micro-Electro-Mechanical Systems (MEMS) type, are becoming more popular and cost effective. The MEMS device consist of two micro-machined structures to form the plates of a capacitor. Each consists of many fingers and one is stationary. Under the influence of the gravitational force the free structure would displace to produce a change in capacitance. The device outputs a voltage proportional to the component of the gravity force along the sensitive axis. It is important to note that both these sensors rely on the gravitational force or the gravitational acceleration.

Block diagram of a strap down electronic compass is shown in Figure 18. The microprocessor controls the drive circuitry for the magnetometers and tilt sensors, collects data and process them to output heading information. This type of implementation is often referred to as the tilt compensated compass to mean that the compass output is independent of its tilt. Generally, it is not necessary to tilt compensate for the full ±90 degrees, and the requirements of a particular application would dictate the tilt range.

The mathematical approach behind is to measure the magnetic field components in the coordinate frame of the compass device, and also to measure the pitch and roll. With the pitch and roll information the magnetic components are transformed to the local level plane coordinate system. Then the heading can be calculated using the transformed X and Y quantities as defined in Figure 19.

The horizontal magnetic components (X_H, Y_H) are used to determine the heading direction. These values can be found for any roll and pitch orientation by using the following formula:

$$X_H = X \cdot \cos(\phi) + Y \cdot \sin(\theta) \cdot \sin(\phi) - Z \cdot \cos(\theta) \cdot \sin(\phi)$$
$$Y_H = Y \cdot \cos(\theta) + Z \cdot \sin(\phi)$$

Where θ and ϕ are the rotational angles to transform compass to local level plane.

Alternatively, the heading can be calculated through a vector method as outlined below. [10]

1) Calculate the vector quantity **G** x $\mathbf{H}_E$ = **E**ast direction
2) Calculate a vector pointing to right of the package by **G** x **X** = $\mathbf{Y}_H$
3) Then the heading angle ψ is calculated by evaluating the vector dot product $\mathbf{Y}_H.\mathbf{E}$

Magnetic Sensor Requirements

The magnetometers should resolve 0.1% of the available horizontal component in order to get 0.1 degree resolution in the heading output, and accurate to 0.5% to achieve 0.5 degree heading accuracy. It turns out the heading calculation is ratiometric in the field components measured and therefore absolute value of the magnetic field components are not necessary. It is important to have all three magnetic sensor gains equal. The tilt sensor should be able to produce absolute values of pitch and roll of the compass. Any tilt error is amplified by the factor approximately 2•tan (dip angle) in heading error. It is not difficult to see how unforgiving this can be!

There are a number of suppliers of compass products with 0.5 to 3 degree heading accuracy, each having different tilt compensation ranges. These compasses find applications in many fields and are increasing with the growth of GPS navigation. A mobile TV broadcast unit may use a compass to keep the satellite antenna focused on the satellite; or a receiving antenna on a ship to continuously track the satellite. A compass can guide a remote controlled vehicle to a desired destination; weather data buoys in the ocean can determine the direction of wind and ocean currents. Compass output integrated with electronic charting systems can assist a pilot to navigate a vessel safely to the pier in bad weather. There are more traditional applications in general aviation and marine navigation.

Compass Installations

Field performance of a compass will greatly depend on the installation site within the host, like a vehicle. After all, the compass depends on the earth's magnetic field to provide heading, and any distortions of this magnetic field by other sources should be compensated for in order to produce accurate heading.

Magnetometers have an upper limit to field range and maximum field values. Fields encountered at the compass location should be within the magnetometer field range. Sources of magnetic fields include permanent magnets, motors, electric currents—either dc or ac, and magnetic metals such as steel or iron. The influence of these sources on compass accuracy can be greatly reduced by placing the compass far form them. Some of the field effects can be compensated by calibration. However, it is not possible to compensate for time varying magnetic; fields for example, the fields generated by motion of magnetic metals, or unpredictable electrical activity of a current carrier near by. Again, the best remedy is distance! Finally, never enclose the compass in a magnetic metallic housing.

Distortions To Earth's Field

The magnetic distortions are categorized into hard iron and soft iron effects. Hard iron effects arise from permanent magnets and magnetized iron or steel in the host. These add field components along the axes of the magnetometer having constant magnitude; this magnitude does not depend on the host's orientation.

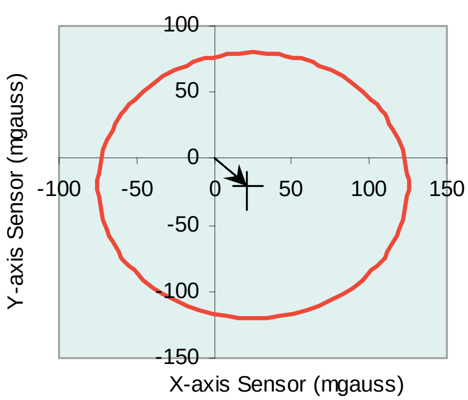


Figure 20–X and Y axes output when rotated horizontally in the earth's field shows hard iron offsets.

Figure 20 illustrates this effect for the case of X and Y magnetic sensors. The net effect is the earth's magnetic field is offset from the center. This type of disturbance will result in heading errors as illustrated in Figure 21 and is known as one-cycle errors.

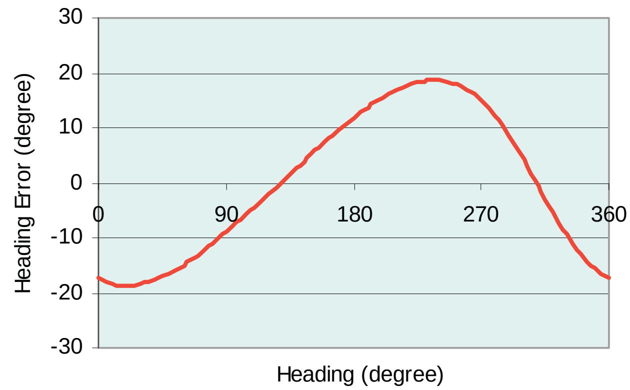


Figure 21–Heading error due to hard iron effect known as single-cycle errors.

The soft iron arises from the interaction of the earth's magnetic field and the magnetically soft material of the host. The soft metals distort the earth's magnetic field lines. The amount of distortion depends on the orientation as well as the magnetic characteristics of the host. Soft iron influence on the filed values measured by X and Y sensors are depicted in Figure 22. Figure 23 illustrates the heading errors associated with this effect and is known as two cycle errors.

Calibration Routines

Compass manufacturers provide calibration methods to compensate for hard and soft iron effects. Each of the calibration methods is associated with a specified physical movement of the host system to sample the magnetic space surrounding the compass. These physical calibration procedures can be as simple as pointing the host in three known directions, or as complicated as moving in a complete circle, moving in a circle with pitch and roll, or pointing the host in 24 orientation including variation in tilt. It is impossible for a marine vessel to perform the 24-point calibration, but a land vehicle may. If the host can only sample the horizontal field components during the calibration procedure, then, in general there would be uncompensated heading errors with tilt. Often heading error curves are generated through several known headings to improve heading accuracy.

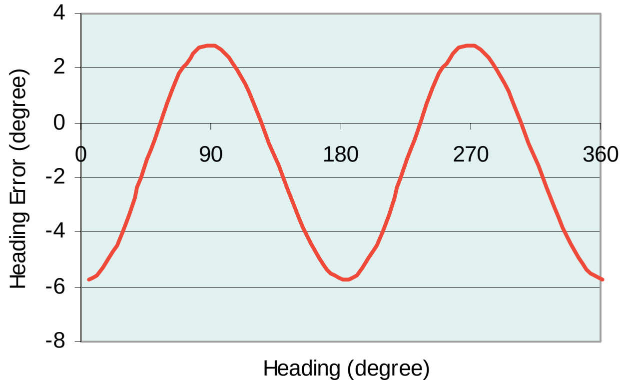


Figure 22–Output of X and Y axes when rotated horizontally in the earth's field near soft iron metal.

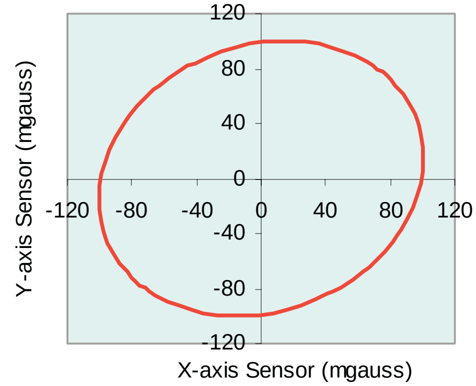


Figure 23–Two-cycle heading errors cause by soft iron distortions.

Hard iron offset fields will vary from location to location within the same host and so will the effects of soft iron. Compass has to be mounted permanently to the host to get a valid calibration. This particular calibration is valid for the location and orientation of the compass. A new calibration is required even if the compass was reoriented in the same location. A gimbaled compass can not satisfy these requirements and hence the advantage of using a strapped down device. It is possible to use a compass without any calibration if the need is only for repeatability but not accuracy.

Acceleration Effects

Any acceleration of the compass will effect the tilt or accelerometer output and is associated with heading errors. An aircraft making a turn will cause the tilt sensors to experience the centripetal force in addition to gravity and the sensor output will be in error. However, for most applications the acceleration is small or is in effect for a short duration, making a magnetic compass a useful navigation tool. Inertial reference systems would be the solution for applications that can not tolerate these heading errors. These systems would weigh, cost, and consume power at least 10 times compared to those of a magnetic compass.

CONCLUSION

We have discussed two AMR sensor applications, both using non-evasive techniques. AMR sensors are designed to operate in the earth's field range with high sensitivity and low noise. These provide a clean magnetic signal to detect the field components or small perturbations. The strengths of the sensors are employed to detect presence, direction, and classification of vehicles. Several examples provide evidence for the practicality of using AMR sensors. Magnetic sensors can be utilized in compass applications that exceed the requirements for high accuracy. Two-axis and the electronically gimbaled three-axis compass solutions were discussed. Magnetic compasses are susceptible to hard iron and soft iron errors; these can be accounted for and eliminated. We have shown that AMR sensors are well suited to handle vehicle and traffic detection as well as compassing applications.

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