Nongimbaled Solid-State Compass

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Abstract

We have developed and evaluated a new solid-state nongimbaled electronic compass. Typical high-accuracy (1-deg resolution) compasses use a mechanical gimbaling method to hold two orthogonal magnetic sensors in a horizontal plane. The limited range of motion of the gimbal restricts the angular operation of the compass but, on the other hand, simplifies the compensation of the compass for its own tilt-related distortions of earth's magnetic field. The challenge of building a rugged and nongimbaled compass involves measuring the three components of earth's field and the gravity vector simultaneously and then developing three-dimensional tilt compensation and magnetic calibration algorithms to correct the measurement for tilt and for the self distortion of earth's field introduced by ferrous materials within the package. We demonstrated better than ±1-deg accuracies under a variety of field exercises.

Introduction

Historically many different magnetic sensor concepts have been used in compass applications. These range from low-cost, low-sensitivity Hall-effect sensors to more sensitive, complex, and expensive fluxgate sensors. These compasses typically contain a gimbal mechanism that keeps the sensor horizontal during the measurement. In the case of the fluxgate compass, a point pivot and fluid-filled compartment are often used to provide the gimbal effect. When a compass cannot be gimbaled, then some means of measuring its tilt or orientation must be provided. Our recent development of a nongimbaled solid-state compass builds directly on our experience in magnetic sensing and our development of magnetoresistive (MR) permalloy material. The MR sensing bridges are produced by IC techniques and can be made on microminiature scales. Although the MR sensors are unique and provide an excellent sensitivity to magnetic fields, they also must maintain a level orientation during the compass measurement, or at least have a measured and accounted for tilt. We have added accelerometer-based tilt sensors and the appropriate compensation algorithms to allow elimination of the gimbal.

Our electronic compass was developed to replace a previously used gimbaled fluxgate compass for a personal navigator concept. This personal navigation system is shown in Figure 1. In this system, the compass must operate quickly, reliably, and accurately while being handheld. Unfortunately, earlier versions of this system used a gimbaled compass and had to contend with the damping and response time issues of the gimbal. We found that the combination of handheld compass operation with gimbal-related delays created a difficult situation. We often found ourselves forced to hold the system steady for several seconds while the gimbal settled out. When the compass gimbal finally stabilized, the heading could be registered and used in the system calculations. We would have preferred to get an instantaneous reading of heading while briefly sighting the compass. In addition, as the personal navigator breadboard evolved toward smaller and smaller package volumes, our MR sensors appeared to be perfectly suited to the application. The new nongimbaled solid-state compass easily met our requirements for the personal navigator.

The personal navigator compass is constructed from a three-axis set of MR transducers to sense magnetic field strength and orientation and a three-axis set of piezoresistive accelerometers to sense the gravity vector. The system incorporates a calibration algorithm to take out local and fixed magnetic field disturbances while actively sensing and compensating for tilt. The magnetic sensing transducers have been packaged with reset coils used to initialize the films for maximum sensitivity, and with feedback coils for closed-loop operation. The piezoresistive accelerometers were chosen for their dc response characteristics. The magnetometer suite, accelerometer package, and analog compass circuitry are shown in Figure 2. The actual size of the magnetometer suite is 0.75 in. × 0.75 in. × 2.5 in. The majority of this volume is occupied by the reset and feedback coils. We have since designed on-chip straps for switching the magnetization vector, and open-loop operation may eliminate the need for the feedback coils. Ultimately, we envision a two-IC package that would contain four magnetoresistive bridges and provide for proper packaging of the three orthogonal sensing axes required for compassing applications.

Figure 1. Personal Navigator System Containing Solid-State Compass

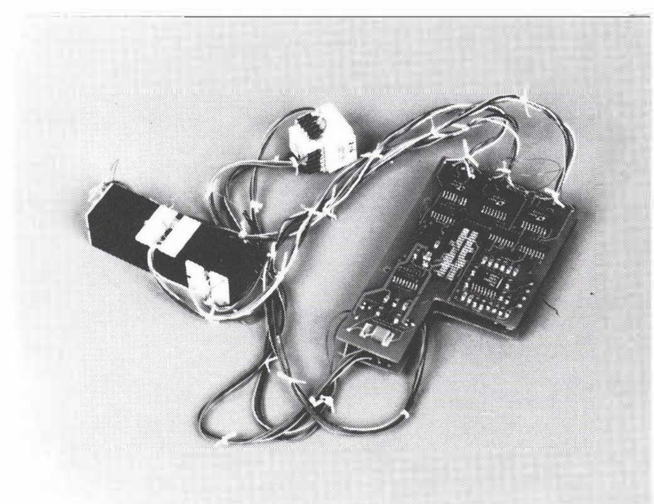

Figure 2. Solid-State Compass Components

Magnetometer Detail

Honeywell's permalloy magnetometer uses the anisotropic magnetoresistive (AMR) effect in thin-film permalloy (a nickel-iron alloy). In this effect, the resistance of a ferromagnetic material depends on the angle between the current flow direction vector and the magnetization vector in the material (θ). This resistance variation has an amplitude of about 2% and has the form $\cos^2\theta$, maximum when the current and magnetization are parallel (or antiparallel) and minimum when they are perpendicular. The highest sensitivity (maximum slope) occurs for θ = 45 deg. The amplitude of this sensitivity depends on both the total (percentage) change in resistance and on the magnetic "stiffness" of the film (the field needed to rotate the magnetization by 90 deg). Because both the current and zero field magnetization will normally tend to align with the long dimension of the film, this high sensitivity can only be obtained if a "biasing" technique is used to rotate one or the other by 45 deg.

The magnetization can be rotated by a bias field generated by a coil, or by a permanent magnet deposited directly onto the film. The biasing method used for this compass (called barberpole biasing because of its appearance) uses high-conductivity "shorting bars" at a 45-deg angle on the film. The current will generally flow along the shortest paths between the shorting bars, or at about 45 deg to the long dimension. The full transducer is a Wheatstone bridge in which all four resistors have the same sensing axis, but have the shorting bars slanting in opposite directions in the two sets of legs such that one set increases in resistance while the other decreases. A barberpole-biased transducer is shown schematically in Figure 3, along with its response to a magnetic field along the sensing axis.

Compass Detail

The MR compass magnetometers provide voltages $\mathbf{v_x}$, $\mathbf{v_y}$, and $\mathbf{v_z}$ with magnitudes representative of their vector components of earth's magnetic field. In addition, the tilt sensor provides $\mathbf{a_x}$, $\mathbf{a_y}$, and $\mathbf{a_z}$ signals whose magnitudes represent their respective components of earth's gravitational field and are used to define **G**. These vector relationships are shown in Figure 4. Basically, north is shown as the Magnetic North plane defined by $\mathbf{H}_{East}$ and **G.** The level plane represents the ideal orientation of the compass package where no tilt compensation is required. However, the tilted rectangle represents the more general tilt and magnetic orientation of the compass package. Assuming that the magnetometers and accelerometers have a fixed orientation within the package, the system microprocessor then samples these signals at an appropriate rate and does a series of vector manipulations to determine the magnetic heading and tilt correction for the package. These manipulations will now be described in greater detail.

The task of nongimbaled compassing must take into account the following issues:

- Heading calculation and tilt compensation,
- Magnetic calibration,
- Temperature compensation.

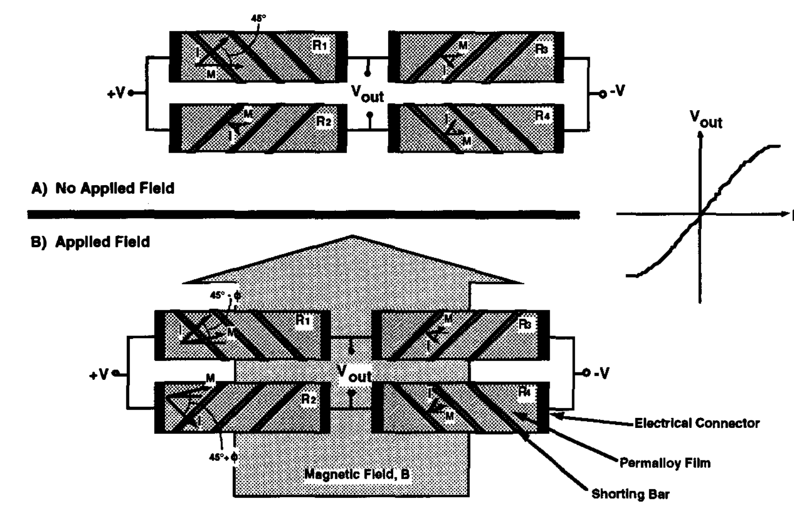

Figure 3. "Barberpole" Biasing with A) No Applied Field and B) Applied Field

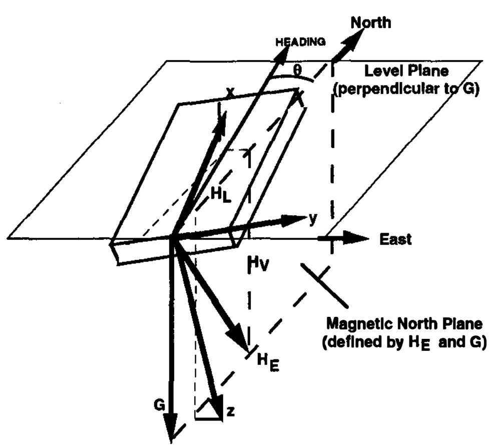

Figure 4. Compass Vector Diagram

Compass Heading Computation and Tilt Compensation

The output of the three magnetic sensors provides a vector of three numbers for the total magnetic field of the earth, $\mathbf{H_e}$, as measured in the x,y,z coordinate system of the package. ($\mathbf{H_e}$ is the total earth field, including a large vertical component, not just the horizontal components.) Three accelerometers, or a two-axis tilt sensor, provide a vector **G**, for the direction of gravity, also expressed in the package coordinate system. From these two vectors the horizontal components of $\mathbf{H_e}$ may be calculated to determine the heading of the compass module. The x axis of the module is taken along the long axis and defines the heading. Normal orientation will define the y axis to the right, and z, down. The compass heading for the module package is defined by the direction of a *vertical plane* through the longitudinal x axis of the package and **G**, regardless of some roll tilt of the package.

Compass heading in the presence of tilt is calculated as follows. All vectors are three-element numerical vectors expressed in the package coordinate system. For brevity, all vectors are assumed to be normalized unit vectors. First, we calculate the four intermediate vectors below. The products are vector cross-products, with the resulting vector being perpendicular to the two arguments. For these calculations, $\mathbf{H_e}$ must first be compensated for case-induced magnetic errors as described above.

- Calculate a horizontal vector pointing east regardless of package orientation, defined as perpendicular to both **G** and $\mathbf{H_e}$: $\mathbf{E} = (\mathbf{G} \times \mathbf{H_e})$.
- Calculate a horizontal unit vector pointing to the right in the package, defined as perpendicular to both **G** and **X** (the package axis): $\mathbf{Y_H} = (\mathbf{G} \times \mathbf{X})$.
- Calculate a horizontal vector pointing to magnetic north regardless of package orientation, defined as perpendicular to both **G** and **E**: $\mathbf{N_H} = (\mathbf{E} \times \mathbf{G})$.
- Calculate a horizontal vector pointing along the heading of the package, defined as perpendicular to both $\mathbf{Y_H}$ and **G**: $\mathbf{X_H} = (\mathbf{Y_H} \times \mathbf{G})$.

From these four vectors, calculate the cosine and sine of the heading angle as vector dot products (giving the cosine of the angle between them):

$$\text{Cos}\theta = +(\mathbf{Y_H} \cdot \mathbf{E}) = +(\mathbf{X_H} \cdot \mathbf{N}),$$
$$\text{Sin}\theta = -(\mathbf{Y_H} \cdot \mathbf{N}) = +(\mathbf{X_H} \cdot \mathbf{E})$$

Finally, the heading angle or compass bearing for the package is calculated as:

$$\theta = \arctan(\text{Sin}\theta/\text{Cos}\theta)$$
(four-quadrant arc tangent function)

Magnetic Calibration

Specifically, magnetic errors can and often do arise from misalignment of the magnetic sensing axes within the magnetometer package, from metals collocated within the package that introduce an induced magnetization dependent upon their orientation to earth's field, from other magnetized objects (i.e., batteries) also within the package, and finally, from fixed external structures such as those encountered with any vehicle-mounted compass. Fortunately, we have found that our formulation compensates for both sensor errors and magnetic perturbations simultaneously and thereby eliminates the need for separate treatment.

The calibration approach proceeds with the following manipulation of vector quantities.

The magnetometer output, the measured fields $\mathbf{H_{measured}}$, are given by:

$$\begin{aligned}\mathbf{H_{measured}} &= \mathbf{H_{earth}} + \mathbf{H_{perm}} + \mathbf{H_{induced}} \text{ (heading error)} \\ &= \mathbf{H_{earth}} + \mathbf{H_{perm}} + \mathbf{M} \cdot \mathbf{H_{earth}} \\ &= \mathbf{H_{perm}} + \mathbf{K} \cdot \mathbf{H_{earth}} \text{ with } \mathbf{K} = (\mathbf{I} + \mathbf{M})\end{aligned}$$

Under ideal conditions, $\mathbf{H_{measured}} = \mathbf{H_{earth}}$, and the heading can be calculated from the measured horizontal components. However, $\mathbf{H_{perm}}$ is a constant term that arises from some residual permanent magnetization of box components, and it rotates with the case. $\mathbf{H_{induced}}$ is a term induced by earth's field magnetizing some package components, and its magnitude and direction changes with the orientation of the package. The values for $\mathbf{H_{perm}}$ and **K** and some form of calibration procedure to obtain them are needed for compensation. These values can be obtained by doing an eight-point compass swing and recording the measured values internally. For the sake of brevity, we do not describe the mathematics for obtaining the coefficients $\mathbf{H_{perm}}$ and **K** from the calibration measurements.

In practice, the compass calibration typically requires that the compass be carefully leveled while measurements are made at the eight cardinal points (0, 45, 90, 135, 180, 225, 270, and 315 deg). This can be done by placing the compass on a test fixture that accurately selects the eight orientations. High accuracy is not required. A sampling loop generated in software rejects the magnetometer data until the device is indeed level. This forces the calibration coefficients to be computed from values not distorted by tilt.

The magnetic compensation formulation is: Given values for the compensation coefficients $\mathbf{H_{perm}}$ and **K**, then the compensated values for earth's field are given by inversion of the above expression:

$$\mathbf{H_{earth}} = \mathbf{K}^{-1} \cdot (\mathbf{H_{measured}} - \mathbf{H_{perm}}) = \mathbf{L} \cdot (\mathbf{H_{measured}} - \mathbf{H_{perm}})$$

where $\mathbf{L} = \mathbf{K}^{-1}$ is the inverse of **K**. Values for $\mathbf{H_{perm}}$ and **L** are stored and used repeatedly until they are replaced by a new set of values from a recalibration.

Temperature Compensation

Sensor offset bias and linearity often show a temperature dependence. Unfortunately, these effects can also result in erroneous heading information if no precautions are taken. Honeywell has devised a proprietary switched-magnetization technique that separates the temperature-induced errors from magnetic sensing errors, thereby allowing the sensor drifts due to temperature to be canceled out. This process has been successfully demonstrated in past compass applications.

Compass Performance

As stated above, compass errors arise from package-induced magnetic effects and from scale factor and alignment errors within the sensors themselves. Figure 5 shows compass measurements taken before and after the magnetic calibration process. Shown in trace A is a precalibration scan where a nearby source of magnetic distortion results in compass errors ranging from –6 to +8 deg. Following a calibration run with the distortion still in place, trace B now shows accuracies within ±1 deg for the total 360-deg scan. Clearly, this type of calibration is necessary for reliable compass operation when attached to or positioned near ferrous materials (i.e., vehicle platforms).

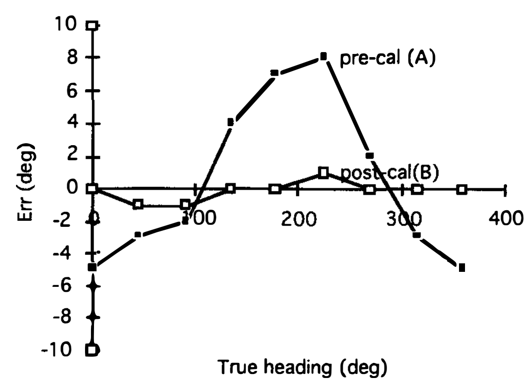

Figure 5. Compass Calibration Plots

Magnetic heading can be defined as the direction of earth's field measured in a horizontal reference plane. However, the elimination or lack of a gimbal means that the magnetic sensors can no longer be assumed to be horizontal. When the three magnetometers that detect their respective components of earth's field are incorrectly assumed to be level, the erroneous field magnitudes they measure will be applied to the calculation of magnetic heading. These incorrect field measurements cannot help but lead to an incorrect compass heading.

We determined that a *calibration* done with an intentional tilt of as little as 1 deg subsequently introduced compass errors of up to 6 deg during later measurements; that is, an incorrect set of calibration and compensation measurements was generated. At this point, our tilt compensation has been demonstrated successfully for normal handheld operation with a single horizontal calibration. In fact, with these calibration and compensation routines, our solid-state compass continued to perform with better than 1-deg accuracy over a variety of tests and field experiments where nominal handheld tilt angles ranged to ±5 deg. Unfortunately, the laboratory measurements shown in Figure 6 confirm that tilts ranging to ±30 deg will require a more complete development of our tilt compensation routines.

Conclusions

A solid-state nongimbaled compass has been developed from Honeywell's MR sensors with the inclusion of a three axis accelerometer to measure the tilt orientation. We have found under conditions of handheld operation that the device provides heading accuracies of ±1 deg. Furthermore, the response time of this device is currently limited only by the switching period of the electronics that switch the materials magnetization vector. We can easily sample magnetic heading in excess of 50 Hz. This rapid response time lets us avoid the typical time delays encountered in other compassing devices while waiting for the gimbals to settle out. The development of our nongimbaled solid-state compass significantly enhanced the performance of the personal navigator and resulted in very consistent and reliable heading accuracies.

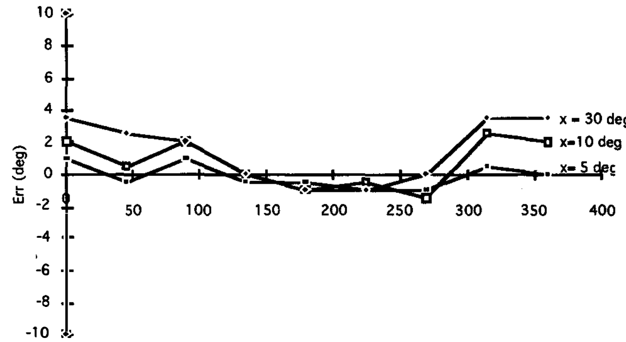

Figure 6. Compass Measurements in the Presence of Tilt