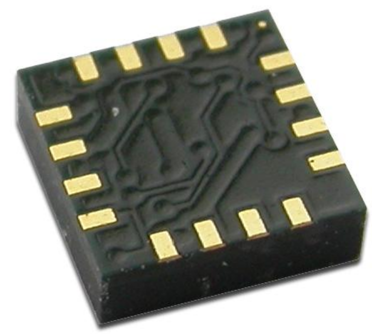
3-Axis Digital Compass IC HMC5883L

Honeywell

Advanced Information

The Honeywell HMC5883L is a surface-mount, multi-chip module designed for low-field magnetic sensing with a digital interface for applications such as low-cost compassing and magnetometry. The HMC5883L includes our state-of-the-art, high-resolution HMC118X series magneto-resistive sensors plus an ASIC containing amplification, automatic degaussing strap drivers, offset cancellation, and a 12-bit ADC that enables 1° to 2° compass heading accuracy. The I^2C serial bus allows for easy interface. The HMC5883L is a 3.0x3.0x0.9mm surface mount 16-pin leadless chip carrier (LCC). Applications for the HMC5883L include Mobile Phones, Netbooks, Consumer Electronics, Auto Navigation Systems, and Personal Navigation Devices.



The HMC5883L utilizes Honeywell's Anisotropic Magnetoresistive (AMR) technology that provides advantages over other magnetic sensor technologies. These anisotropic, directional sensors feature precision in-axis sensitivity and linearity. These sensors' solid-state construction with very low cross-axis sensitivity is designed to measure both the direction and the magnitude of Earth's magnetic fields, from milli-gauss to 8 gauss. Honeywell's Magnetic Sensors are among the most sensitive and reliable low-field sensors in the industry.

FEATURES	BENEFITS
▸ 3-Axis Magnetoresistive Sensors and ASIC in a 3.0x3.0x0.9mm LCC Surface Mount Package	▸ Small Size for Highly Integrated Products. Just Add a Micro-Controller Interface, Plus Two External SMT Capacitors Designed for High Volume, Cost Sensitive OEM Designs Easy to Assemble & Compatible with High Speed SMT Assembly
▸ 12-Bit ADC Coupled with Low Noise AMR Sensors Achieves 5 milli-gauss Resolution in ±8 Gauss Fields	▸ Enables 1° to 2° Degree Compass Heading Accuracy
▸ Built-In Self Test	▸ Enables Low-Cost Functionality Test after Assembly in Production
▸ Low Voltage Operations (2.16 to 3.6V) and Low Power Consumption (100 μA)	▸ Compatible for Battery Powered Applications
▸ Built-In Strap Drive Circuits	▸ Set/Reset and Offset Strap Drivers for Degaussing, Self Test, and Offset Compensation
▸ I^2C Digital Interface	▸ Popular Two-Wire Serial Data Interface for Consumer Electronics
▸ Lead Free Package Construction	▸ RoHS Compliance
▸ Wide Magnetic Field Range (+/-8 Oe)	▸ Sensors Can Be Used in Strong Magnetic Field Environments with a 1° to 2° Degree Compass Heading Accuracy
▸ Software and Algorithm Support Available	▸ Compassing Heading, Hard Iron, Soft Iron, and Auto Calibration Libraries Available
▸ Fast 160 Hz Maximum Output Rate	▸ Enables Pedestrian Navigation and LBS Applications

SPECIFICATIONS (* Tested at 25°C except stated otherwise.)

Characteristics	Conditions*	Min	Typ	Max	Units
Power Supply					
Supply Voltage	VDD Referenced to AGND	2.16		3.6	Volts
	VDDIO Referenced to DGND	1.71	1.8	VDD+0.1	Volts
Average Current Draw	Idle Mode	-	2	-	μA
	Measurement Mode (7.5 Hz ODR; No measurement average, MA1:MA0 = 00) VDD = 2.5V, VDDIO = 1.8V	-	100	-	μA
Performance					
Field Range	Full scale (FS) – total applied field (Typical)	-8		+8	gauss
Mag Dynamic Range	3-bit gain control	±1		±8	gauss
Resolution	VDD=3.0V, GN=2		5		milli-gauss
Linearity	±2.0 gauss input range			0.1	±% FS
Hysteresis	±2.0 gauss input range		±25		ppm
Cross-Axis Sensitivity	Test Conditions: Cross field = 0.5 gauss, Happlied = ±3 gauss		±0.2%		%FS/gauss
Output Rate (ODR)	Continuous Measurment Mode	0.75		75	Hz
	Single Measurement Mode			160	Hz
Measurement Period	From receiving command to data ready		6		msec
Turn-on Time	Ready for I2C commands		200		μs
Gain Tolerance	All gain/dynamic range settings		±5		%
I^2C Address	7-bit address		0x1E		hex
	8-bit read address		0x3D		hex
	8-bit write address		0x3C		hex
I^2C Rate	Controlled by I^2C Master			400	kHz
I^2C Hysteresis	Hysteresis of Schmitt trigger inputs on SCL and SDA - Fall (VDDIO=1.8V)		0.2*VDDIO		Volts
	Rise (VDDIO=1.8V)		0.8*VDDIO		Volts
Self Test	X & Y Axes		±1.16		gauss
	Z Axis		±1.08		
	X & Y Axes (GN=100) Z Axis (GN=100)		510		LSb
General					
ESD Voltage	Human Body Model (all pins)			2000	Volts
	CDM			750	
Operating Temperature	Ambient	-30		85	°C
Storage Temperature	Ambient, unbiased	-40		125	°C
Reflow Classification	MSL 3, 260 °C Peak Temperature				
Package Size	Length and Width	2.85	3.00	3.15	mm
Package Height		0.8	0.9	1.0	mm

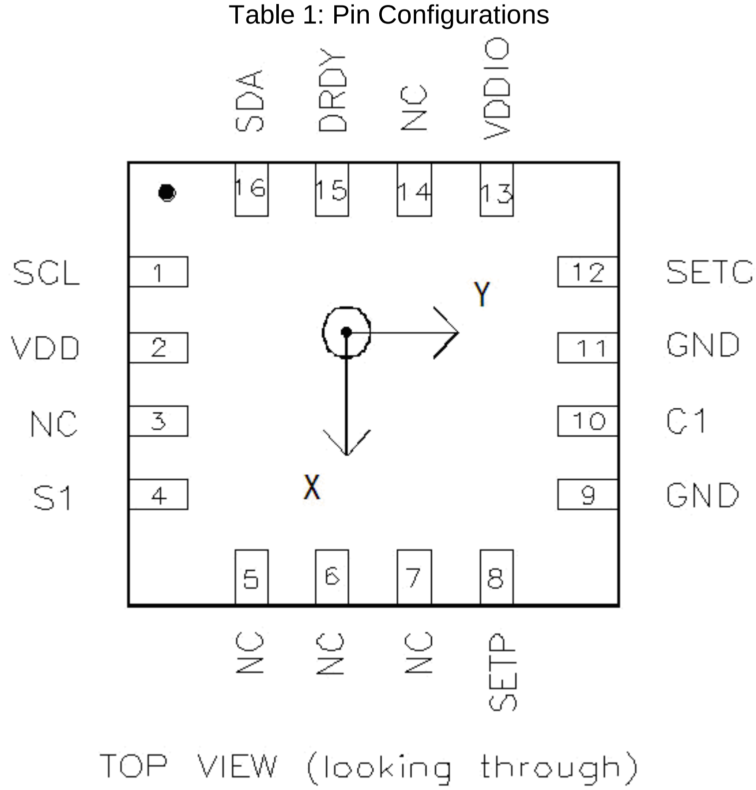
Absolute Maximum Ratings (* Tested at 25°C except stated otherwise.)

Characteristics	Min	Max	Units
Supply Voltage VDD	-0.3	4.8	Volts
Supply Voltage VDDIO	-0.3	4.8	Volts

PIN CONFIGURATIONS

Pin	Name	Description
1	SCL	Serial Clock – I^2C Master/Slave Clock
2	VDD	Power Supply (2.16V to 3.6V)
3	NC	Not to be Connected
4	S1	Tie to VDDIO
5	NC	Not to be Connected
6	NC	Not to be Connected
7	NC	Not to be Connected
8	SETP	Set/Reset Strap Positive – S/R Capacitor (C2) Connection
9	GND	Supply Ground
10	C1	Reservoir Capacitor (C1) Connection
11	GND	Supply Ground
12	SETC	S/R Capacitor (C2) Connection – Driver Side
13	VDDIO	IO Power Supply (1.71V to VDD)
14	NC	Not to be Connected
15	DRDY	Data Ready, Interrupt Pin. Internally pulled high. Optional connection. Low for 250 µsec when data is placed in the data output registers.
16	SDA	Serial Data – I^2C Master/Slave Data

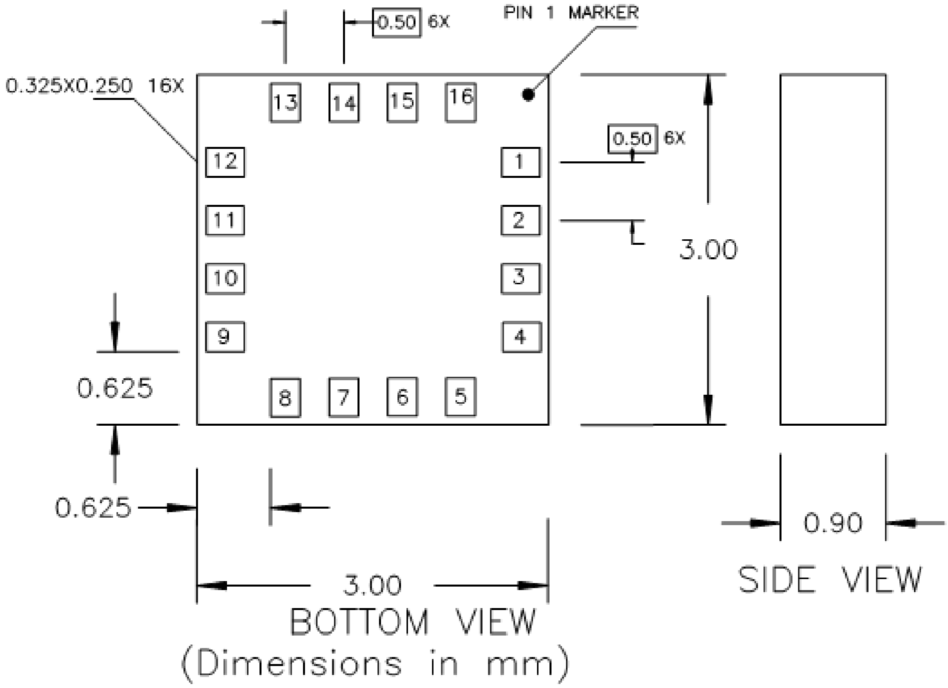
Table 1: Pin Configurations



Arrow indicates direction of magnetic field that generates a positive output reading in Normal Measurement configuration.

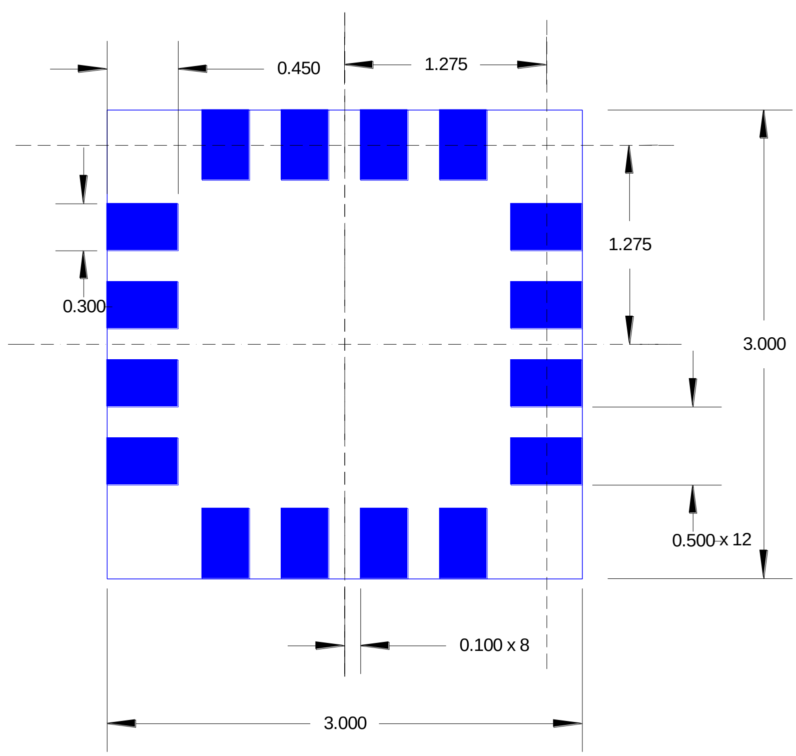
PACKAGE OUTLINES

PACKAGE DRAWING HMC5883L (16-PIN LPCC, dimensions in millimeters)



MOUNTING CONSIDERATIONS

The following is the recommend printed circuit board (PCB) footprint for the HMC5883L.



HMC5883 Land Pad Pattern
(All dimensions are in mm)

PCB Pad Definition and Traces

The HMC5883L is a fine pitch LCC package. Refer to previous figure for recommended PCB footprint for proper package centering. Size the traces between the HMC5883L and the external capacitors (C1 and C2) to handle the 1 ampere peak current pulses with low voltage drop on the traces.

Stencil Design and Solder Paste

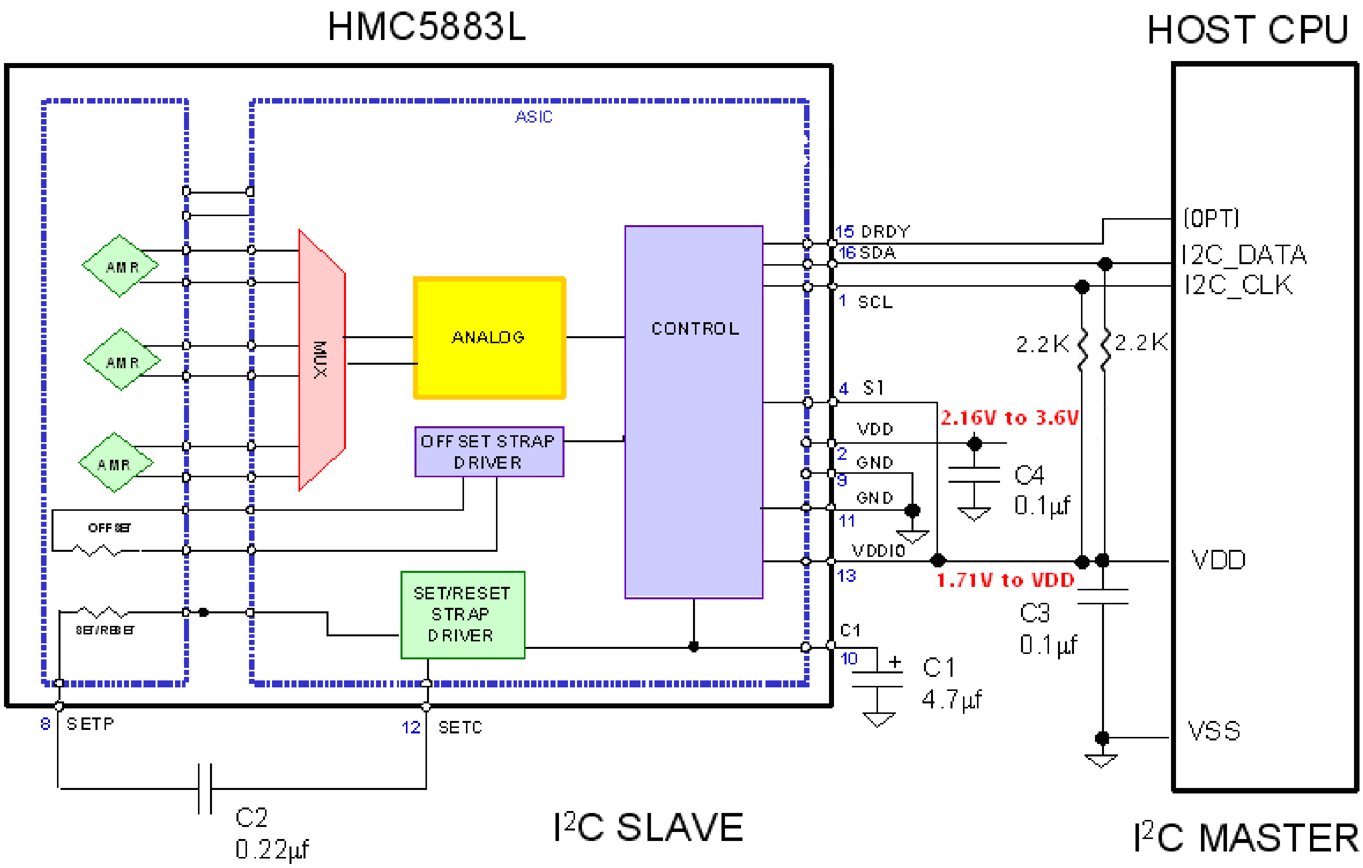
A 4 mil stencil and 100% paste coverage is recommended for the electrical contact pads.

Reflow Assembly

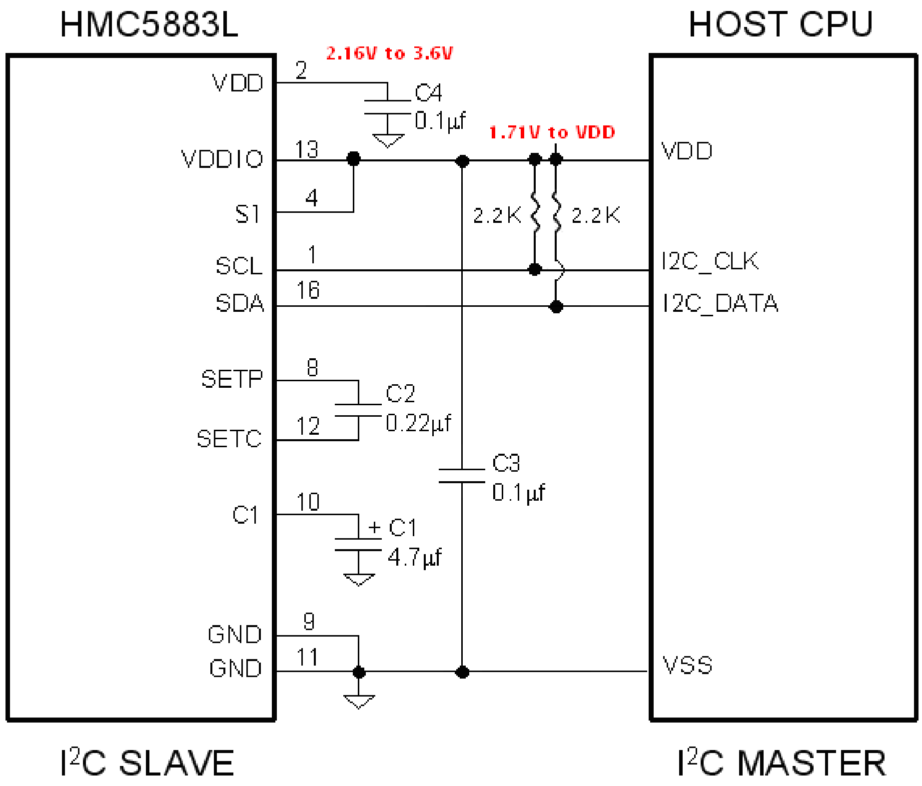
This device is classified as MSL 3 with 260°C peak reflow temperature. A baking process (125°C, 24 hrs) is required if device is not kept continuously in a dry (< 10% RH) environment before assembly. No special reflow profile is required for HMC5883L, which is compatible with lead eutectic and lead-free solder paste reflow profiles. Honeywell recommends adherence to solder paste manufacturer's guidelines.

INTERNAL SCHEMATIC DIAGRAM

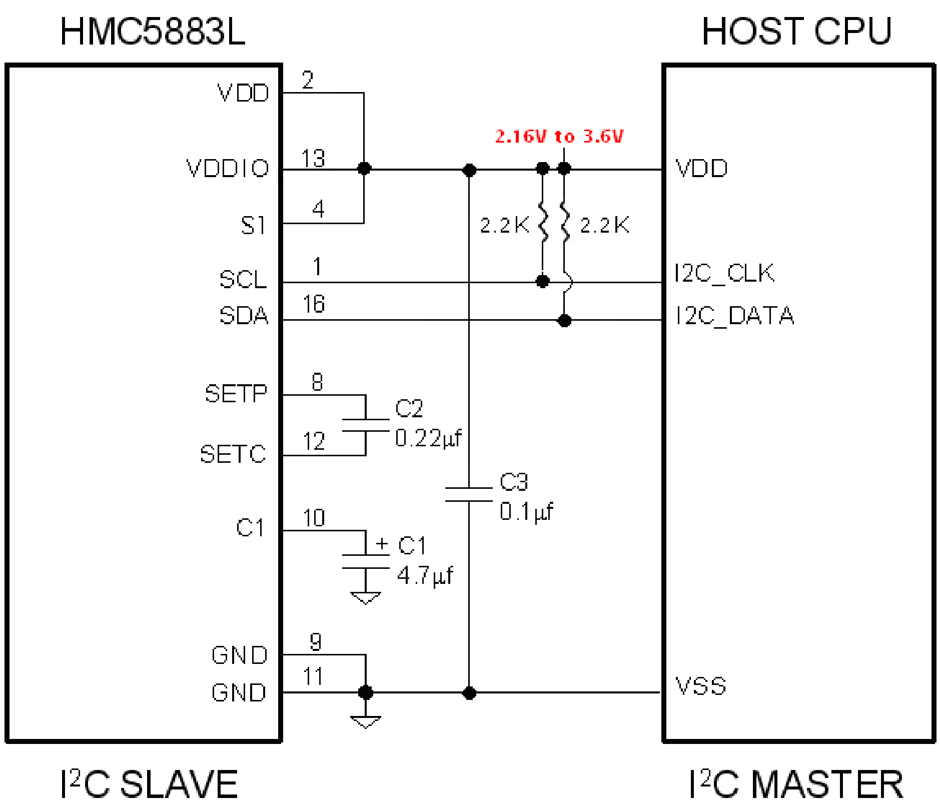
HMC5883L



DUAL SUPPLY REFERENCE DESIGN



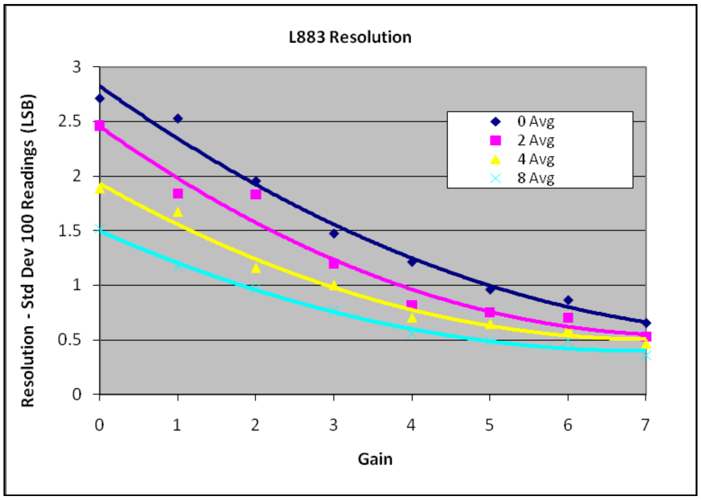
SINGLE SUPPLY REFERENCE DESIGN



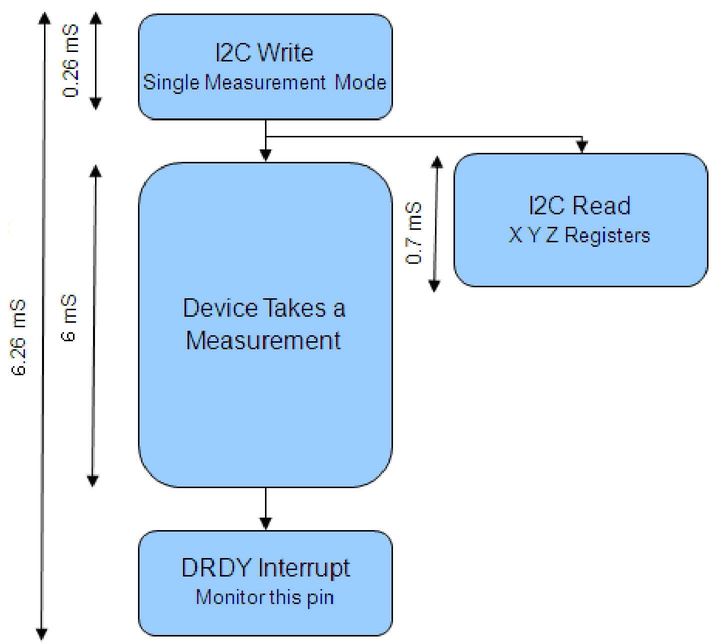
PERFORMANCE

The following graph(s) highlight HMC5883L's performance.

Typical Resolution



Typical Measurement Period in Single-Measurement Mode



** Monitoring of the DRDY Interrupt pin is only required if maximum output rate is desired.*

BASIC DEVICE OPERATION

Anisotropic Magneto-Resistive Sensors

The Honeywell HMC5883L magnetoresistive sensor circuit is a trio of sensors and application specific support circuits to measure magnetic fields. With power supply applied, the sensor converts any incident magnetic field in the sensitive axis directions to a differential voltage output. The magnetoresistive sensors are made of a nickel-iron (Permalloy) thin-film and patterned as a resistive strip element. In the presence of a magnetic field, a change in the bridge resistive elements causes a corresponding change in voltage across the bridge outputs.

These resistive elements are aligned together to have a common sensitive axis (indicated by arrows in the pinout diagram) that will provide positive voltage change with magnetic fields increasing in the sensitive direction. Because the output is only proportional to the magnetic field component along its axis, additional sensor bridges are placed at orthogonal directions to permit accurate measurement of magnetic field in any orientation.

Self Test

To check the HMC5883L for proper operation, a self test feature in incorporated in which the sensor is internally excited with a nominal magnetic field (in either positive or negative bias configuration). This field is then measured and reported. This function is enabled and the polarity is set by bits MS[n] in the configuration register A. An internal current source generates DC current (about 10 mA) from the VDD supply. This DC current is applied to the offset straps of the magneto-resistive sensor, which creates an artificial magnetic field bias on the sensor.

See SELF TEST OPERATION section later in this datasheet for additional details.

Power Management

This device has two different domains of power supply. The first one is VDD that is the power supply for internal operations and the second one is VDDIO that is dedicated to IO interface. It is possible to work with VDDIO equal to VDD; Single Supply mode, or with VDDIO lower than VDD allowing HMC5883L to be compatible with other devices on board.

I^{2}C Interface

Control of this device is carried out via the I^{2}C bus. This device will be connected to this bus as a slave device under the control of a master device, such as the processor.

This device is compliant with *I^{2}C-Bus Specification*, document number: 9398 393 40011. As an I^{2}C compatible device, this device has a 7-bit serial address and supports I^{2}C protocols. This device supports standard and fast modes, 100kHz and 400kHz, respectively, but does not support the high speed mode (Hs). External pull-up resistors are required to support these standard and fast speed modes.

Activities required by the master (register read and write) have priority over internal activities, such as the measurement. The purpose of this priority is to not keep the master waiting and the I^{2}C bus engaged for longer than necessary.

Internal Clock

The device has an internal clock for internal digital logic functions and timing management.

H-Bridge for Set/Reset Strap Drive

The ASIC contains large switching FETs capable of delivering a large but brief pulse to the Set / Reset strap of the sensor. This strap is largely a resistive load. There is no need for an external Set/Reset circuit. The controlling of the Set/Reset function is done automatically by the ASIC for each measurement. One half of the difference from the measurements taken after a set pulse and after a reset pulse will be put in the data output register for each of the three axes. By doing so, the sensor's internal offset and its temperature dependence is removed/cancelled for all measurements.

Charge Current Limit

The current that reservoir capacitor (C1) can draw when charging is limited for both single supply and dual supply configurations. This prevents drawing down the supply voltage (VDD).

MODES OF OPERATION

This device has several operating modes whose primary purpose is power management and is controlled by the Mode Register. This section describes these modes.

Continuous-Measurement Mode

During continuous-measurement mode, the device continuously makes measurements, at user selectable rate, and places measured data in data output registers. Data can be re-read from the data output registers if necessary; however, if the master does not ensure that the data register is accessed before the completion of the next measurement, the data output registers are updated with the new measurement. To conserve current between measurements, the device is placed in a state similar to idle mode, but the Mode Register is not changed to Idle Mode. That is, MD[n] bits are unchanged. Settings in the Configuration Register A affect the data output rate (bits DO[n]), the measurement configuration (bits MS[n]), when in continuous-measurement mode. All registers maintain values while in continuous-measurement mode. The I^2C bus is enabled for use by other devices on the network in while continuous-measurement mode.

Single-Measurement Mode

This is the default power-up mode. During single-measurement mode, the device makes a single measurement and places the measured data in data output registers. After the measurement is complete and output data registers are updated, the device is placed in idle mode, and the Mode Register *is* changed to idle mode by setting MD[n] bits. Settings in the configuration register affect the measurement configuration (bits MS[n])when in single-measurement mode. All registers maintain values while in single-measurement mode. The I^2C bus is enabled for use by other devices on the network while in single-measurement mode.

Idle Mode

During this mode the device is accessible through the I^2C bus, but major sources of power consumption are disabled, such as, but not limited to, the ADC, the amplifier, and the sensor bias current. All registers maintain values while in idle mode. The I^2C bus is enabled for use by other devices on the network while in idle mode.

REGISTERS

This device is controlled and configured via a number of on-chip registers, which are described in this section. In the following descriptions, *set* implies a logic 1, and *reset* or *clear* implies a logic 0, unless stated otherwise.

Register List
The table below lists the registers and their access. All address locations are 8 bits.

Address Location	Name	Access
00	Configuration Register A	Read/Write
01	Configuration Register B	Read/Write
02	Mode Register	Read/Write
03	Data Output X MSB Register	Read
04	Data Output X LSB Register	Read
05	Data Output Z MSB Register	Read
06	Data Output Z LSB Register	Read
07	Data Output Y MSB Register	Read
08	Data Output Y LSB Register	Read
09	Status Register	Read
10	Identification Register A	Read
11	Identification Register B	Read
12	Identification Register C	Read

Table2: Register List

Register Access

This section describes the process of reading from and writing to this device. The devices uses an address pointer to indicate which register location is to be read from or written to. These pointer locations are sent from the master to this slave device and succeed the 7-bit address plus 1 bit read/write identifier.

To minimize the communication between the master and this device, the address pointer updated automatically without master intervention. This automatic address pointer update has two additional features. First when address 12 or higher is accessed the pointer updates to address 00 and secondly when address 08 is reached, the pointer rolls back to address 03. Logically, the address pointer operation functions as shown below.

If (address pointer = 08) then address pointer = 03
Else if (address pointer >= 12) then address pointer = 0
Else (address pointer) = (address pointer) + 1

The address pointer value itself cannot be read via the I^2C bus.
Any attempt to read an invalid address location returns 0's, and any write to an invalid address location or an undefined bit within a valid address location is ignored by this device.

To move the address pointer to a random register location, first issue a "write" to that register location with no data byte following the commend. For example, to move the address pointer to register 10, send 0x3C 0x0A.

Configuration Register A

The configuration register is used to configure the device for setting the data output rate and measurement configuration. CRA0 through CRA7 indicate bit locations, with *CRA* denoting the bits that are in the configuration register. CRA7 denotes the first bit of the data stream. The number in parenthesis indicates the default value of that bit.

CRA7	CRA6	CRA5	CRA4	CRA3	CRA2	CRA1	CRA0
(1)	MA1(1)	MA0(1)	DO2 (1)	DO1 (0)	DO0 (0)	MS1 (0)	MS0 (0)

Table 3: Configuration Register A

Location	Name	Description
CRA7	CRA7	This bit must be cleared for correct operation.
CRA6 to CRA5	MA1 to MA0	Select number of samples averaged (1 to 8) per measurement output. 00 = 1; 01 = 2; 10 = 4; 11 = 8 (Default)
CRA4 to CRA2	DO2 to DO0	Data Output Rate Bits. These bits set the rate at which data is written to all three data output registers.
CRA1 to CRA0	MS1 to MS0	Measurement Configuration Bits. These bits define the measurement flow of the device, specifically whether or not to incorporate an applied bias into the measurement.

Table 4: Configuration Register A Bit Designations

The Table below shows all selectable output rates in continuous measurement mode. All three channels shall be measured within a given output rate. Other output rates with maximum rate of 160 Hz can be achieved by monitoring DRDY interrupt pin in single measurement mode.

DO2	DO1	DO0	Typical Data Output Rate (Hz)
0	0	0	0.75
0	0	1	1.5
0	1	0	3
0	1	1	7.5
1	0	0	15 (Default)
1	0	1	30
1	1	0	75
1	1	1	Not used

Table 5: Data Output Rates

MS1	MS0	Measurement Mode
0	0	Normal measurement configuration (Default). In normal measurement configuration the device follows normal measurement flow. The positive and negative pins of the resistive load are left floating and high impedance.
0	1	Positive bias configuration for X, Y, and Z axes. In this configuration, a positive current is forced across the resistive load for all three axes.
1	0	Negative bias configuration for X, Y and Z axes. In this configuration, a negative current is forced across the resistive load for all three axes..
1	1	This configuration is reserved.

Table 6: Measurement Modes

Configuration Register B

The configuration register B for setting the device gain. CRB0 through CRB7 indicate bit locations, with *CRB* denoting the bits that are in the configuration register. CRB7 denotes the first bit of the data stream. The number in parenthesis indicates the default value of that bit.

CRB7	CRB6	CRB5	CRB4	CRB3	CRB2	CRB1	CRB0
GN2 (0)	GN1 (0)	GN0 (1)	(0)	(0)	(0)	(0)	(0)

Table 7: Configuration B Register

Location	Name	Description
CRB7 to CRB5	GN2 to GN0	Gain Configuration Bits. These bits configure the gain for the device. The gain configuration is common for all channels.
CRB4 to CRB0	0	These bits must be cleared for correct operation.

Table 8: Configuration Register B Bit Designations

The table below shows nominal gain settings. Use the “Gain” column to convert counts to Gauss. Choose a lower gain value (higher GN#) when total field strength causes overflow in one of the data output registers (saturation).

GN2	GN1	GN0	Recommended Sensor Field Range	Gain (LSB/ Gauss)	Output Range
0	0	0	± 0.88 Ga	1370	0xF800–0x07FF (-2048–2047)
0	0	1	± 1.3 Ga	1090 (default)	0xF800–0x07FF (-2048–2047)
0	1	0	± 1.9 Ga	820	0xF800–0x07FF (-2048–2047)
0	1	1	± 2.5 Ga	660	0xF800–0x07FF (-2048–2047)
1	0	0	± 4.0 Ga	440	0xF800–0x07FF (-2048–2047)
1	0	1	± 4.7 Ga	390	0xF800–0x07FF (-2048–2047)
1	1	0	± 5.6 Ga	330	0xF800–0x07FF (-2048–2047)
1	1	1	± 8.1 Ga	230	0xF800–0x07FF (-2048–2047)

Table 9: Gain Settings

Mode Register

The mode register is an 8-bit register from which data can be read or to which data can be written. This register is used to select the operating mode of the device. MR0 through MR7 indicate bit locations, with *MR* denoting the bits that are in the mode register. MR7 denotes the first bit of the data stream. The number in parenthesis indicates the default value of that bit.

MR7	MR6	MR5	MR4	MR3	MR2	MR1	MR0
(1)	(0)	(0)	(0)	(0)	(0)	MD1 (0)	MD0 (1)

Table 10: Mode Register

Location	Name	Description
MR7 to MR2	0	These bits must be cleared for correct operation. Bit MR7 bit is set internally after each single-measurement operation.
MR1 to MR0	MD1 to MD0	Mode Select Bits. These bits select the operation mode of this device.

Table 11: Mode Register Bit Designations

MD1	MD0	Operating Mode
0	0	Continuous-Measurement Mode. In continuous-measurement mode, the device continuously performs measurements and places the result in the data register. RDY goes high when new data is placed in all three registers. After a power-on or a write to the mode or configuration register, the first measurement set is available from all three data output registers after a period of $2/f_{DO}$ and subsequent measurements are available at a frequency of f_{DO}, where f_{DO} is the frequency of data output.
0	1	Single-Measurement Mode (Default). When single-measurement mode is selected, device performs a single measurement, sets RDY high and returned to idle mode. Mode register returns to idle mode bit values. The measurement remains in the data output register and RDY remains high until the data output register is read or another measurement is performed.
1	0	Idle Mode. Device is placed in idle mode.
1	1	Idle Mode. Device is placed in idle mode.

Table 12: Operating Modes

Data Output X Registers A and B

The data output X registers are two 8-bit registers, data output register A and data output register B. These registers store the measurement result from channel X. Data output X register A contains the MSB from the measurement result, and data output X register B contains the LSB from the measurement result. The value stored in these two registers is a 16-bit value in 2's complement form, whose range is 0xF800 to 0x07FF. DXRA0 through DXRA7 and DXRB0 through DXRB7 indicate bit locations, with *DXRA* and *DXRB* denoting the bits that are in the data output X registers. DXRA7 and DXRB7 denote the first bit of the data stream. The number in parenthesis indicates the default value of that bit.

In the event the ADC reading overflows or underflows for the given channel, or if there is a math overflow during the bias measurement, this data register will contain the value -4096. This register value will clear when after the next valid measurement is made.

DXRA7	**DXRA6**	**DXRA5**	**DXRA4**	**DXRA3**	**DXRA2**	**DXRA1**	**DXRA0**
(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
DXRB7	**DXRB6**	**DXRB5**	**DXRB4**	**DXRB3**	**DXRB2**	**DXRB1**	**DXRB0**
(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)

Table 13: Data Output X Registers A and B

Data Output Y Registers A and B

The data output Y registers are two 8-bit registers, data output register A and data output register B. These registers store the measurement result from channel Y. Data output Y register A contains the MSB from the measurement result, and data output Y register B contains the LSB from the measurement result. The value stored in these two registers is a 16-bit value in 2's complement form, whose range is 0xF800 to 0x07FF. DYRA0 through DYRA7 and DYRB0 through DYRB7 indicate bit locations, with *DYRA* and *DYRB* denoting the bits that are in the data output Y registers. DYRA7 and DYRB7 denote the first bit of the data stream. The number in parenthesis indicates the default value of that bit.

In the event the ADC reading overflows or underflows for the given channel, or if there is a math overflow during the bias measurement, this data register will contain the value -4096. This register value will clear when after the next valid measurement is made.

DYRA7	**DYRA6**	**DYRA5**	**DYRA4**	**DYRA3**	**DYRA2**	**DYRA1**	**DYRA0**
(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
DYRB7	**DYRB6**	**DYRB5**	**DYRB4**	**DYRB3**	**DYRB2**	**DYRB1**	**DYRB0**
(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)

Table 14: Data Output Y Registers A and B

Data Output Z Registers A and B

The data output Z registers are two 8-bit registers, data output register A and data output register B. These registers store the measurement result from channel Z. Data output Z register A contains the MSB from the measurement result, and data output Z register B contains the LSB from the measurement result. The value stored in these two registers is a 16-bit value in 2's complement form, whose range is 0xF800 to 0x07FF. DZRA0 through DZRA7 and DZRB0 through DZRB7 indicate bit locations, with *DZRA* and *DZRB* denoting the bits that are in the data output Z registers. DZRA7 and DZRB7 denote the first bit of the data stream. The number in parenthesis indicates the default value of that bit.

In the event the ADC reading overflows or underflows for the given channel, or if there is a math overflow during the bias measurement, this data register will contain the value -4096. This register value will clear when after the next valid measurement is made.

DZRA7	DZRA6	DZRA5	DZRA4	DZRA3	DZRA2	DZRA1	DZRA0
(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
DZRB7	**DZRB6**	**DZRB5**	**DZRB4**	**DZRB3**	**DZRB2**	**DZRB1**	**DZRB0**
(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)

Table 15: Data Output Z Registers A and B

Data Output Register Operation

When one or more of the output registers are read, new data cannot be placed in any of the output data registers until all six data output registers are read. This requirement also impacts DRDY and RDY, which cannot be cleared until new data is placed in all the output registers.

Status Register

The status register is an 8-bit read-only register. This register is used to indicate device status. SR0 through SR7 indicate bit locations, with *SR* denoting the bits that are in the status register. SR7 denotes the first bit of the data stream.

SR7	SR6	SR5	SR4	SR3	SR2	SR1	SR0
(0)	(0)	(0)	(x)	(0)	(0)	LOCK (0)	RDY(0)

Table 16: Status Register

Location	Name	Description
SR7 to SR2	0	These bits are reserved. SR4 may be 0 or 1 depending on internal activity. Disregard activity on this bit.
SR1	LOCK	Data output register lock. This bit is set when this some but not all for of the six data output registers have been read. When this bit is set, the six data output registers are locked and any new data will not be placed in these register until one of three conditions are met: one, all six bytes have been read or the mode changed, two, the mode is changed, or three, the measurement configuration is changed.
SR0	RDY	Ready Bit. Set when data is written to all six data registers. Cleared when device initiates a write to the data output registers and after one or more of the data output registers are written to. When RDY bit is clear it shall remain cleared for a 250 μs. DRDY pin can be used as an alternative to the status register for monitoring the device for measurement data.

Table 17: Status Register Bit Designations

Identification Register A

The identification register A is used to identify the device. IRA0 through IRA7 indicate bit locations, with *IRA* denoting the bits that are in the identification register A. IRA7 denotes the first bit of the data stream. The number in parenthesis indicates the default value of that bit.

The identification value for this device is stored in this register. This is a read-only register.
Register values. ASCII value *H*

IRA7	IRA6	IRA5	IRA4	IRA3	IRA2	IRA1	IRA0
0	1	0	0	1	0	0	0

Table 18: Identification Register A Default Values

Identification Register B

The identification register B is used to identify the device. IRB0 through IRB7 indicate bit locations, with *IRB* denoting the bits that are in the identification register A. IRB7 denotes the first bit of the data stream.

Register values. ASCII value *4*

IRB7	IRB6	IRB5	IRB4	IRB3	IRB2	IRB1	IRB0
0	0	1	1	0	1	0	0

Table 19: Identification Register B Default Values

Identification Register C

The identification register C is used to identify the device. IRC0 through IRC7 indicate bit locations, with *IRC* denoting the bits that are in the identification register A. IRC7 denotes the first bit of the data stream.

Register values. ASCII value *3*

IRC7	IRC6	IRC5	IRC4	IRC3	IRC2	IRC1	IRC0
0	0	1	1	0	0	1	1

Table 20: Identification Register C Default Values

I^{2}C COMMUNICATION PROTOCOL

The HMC5883L communicates via a two-wire I^{2}C bus system as a slave device. The HMC5883L uses a simple protocol with the interface protocol defined by the I^{2}C bus specification, and by this document. The data rate is at the standard-mode 100kbps or 400kbps rates as defined in the I^{2}C Bus Specifications. The bus bit format is an 8-bit Data/Address send and a 1-bit acknowledge bit. The format of the data bytes (payload) shall be case sensitive ASCII characters or binary data to the HMC5883L slave, and binary data returned. Negative binary values will be in two's complement form. The default (factory) HMC5883L 8-bit slave address is 0x3C for write operations, or 0x3D for read operations.

The HMC5883L Serial Clock (SCL) and Serial Data (SDA) lines require resistive pull-ups (Rp) between the master device (usually a host microprocessor) and the HMC5883L. Pull-up resistance values of about 2.2K to 10K ohms are recommended with a nominal VDDIO voltage. Other resistor values may be used as defined in the I^{2}C Bus Specifications that can be tied to VDDIO.

The SCL and SDA lines in this bus specification may be connected to multiple devices. The bus can be a single master to multiple slaves, or it can be a multiple master configuration. All data transfers are initiated by the master device, which is responsible for generating the clock signal, and the data transfers are 8 bit long. All devices are addressed by I^{2}C's unique 7-bit address. After each 8-bit transfer, the master device generates a 9th clock pulse, and releases the SDA line. The receiving device (addressed slave) will pull the SDA line low to acknowledge (ACK) the successful transfer or leave the SDA high to negative acknowledge (NACK).

Per the I^2C spec, all transitions in the SDA line must occur when SCL is low. This requirement leads to two unique conditions on the bus associated with the SDA transitions when SCL is high. Master device pulling the SDA line low while the SCL line is high indicates the Start (S) condition, and the Stop (P) condition is when the SDA line is pulled high while the SCL line is high. The I^2C protocol also allows for the Restart condition in which the master device issues a second start condition without issuing a stop.

All bus transactions begin with the master device issuing the start sequence followed by the slave address byte. The address byte contains the slave address; the upper 7 bits (bits7-1), and the Least Significant bit (LSb). The LSb of the address byte designates if the operation is a read (LSb=1) or a write (LSb=0). At the 9th clock pulse, the receiving slave device will issue the ACK (or NACK). Following these bus events, the master will send data bytes for a write operation, or the slave will clock out data with a read operation. All bus transactions are terminated with the master issuing a stop sequence.

I^2C bus control can be implemented with either hardware logic or in software. Typical hardware designs will release the SDA and SCL lines as appropriate to allow the slave device to manipulate these lines. In a software implementation, care must be taken to perform these tasks in code.

OPERATIONAL EXAMPLES

The HMC5883L has a fairly quick stabilization time from no voltage to stable and ready for data retrieval. The nominal 6 milli-seconds with the factory default single measurement mode means that the six bytes of magnetic data registers (DXRA, DXRB, DZRA, DZRB, DYRA, and DYRB) are filled with a valid first measurement.

To change the measurement mode to continuous measurement mode, after the power-up time send the three bytes:

0x3C 0x02 0x00

This writes the 00 into the second register or mode register to switch from single to continuous measurement mode setting. With the data rate at the factory default of 15Hz updates, a 67 milli-second typical delay should be allowed by the I^2C master before querying the HMC5883L data registers for new measurements. To clock out the new data, send:

0x3D, and clock out DXRA, DXRB, DZRA, DZRB, DYRA, and DYRB located in registers 3 through 8. The HMC5883L will automatically re-point back to register 3 for the next 0x3D query. All six data registers must be read properly before new data can be placed in any of these data registers.

SELF TEST OPERATION

To check the HMC5883L for proper operation, a self test feature in incorporated in which the sensor offset straps are excited to create a nominal field strength (bias field) to be measured. To implement self test, the least significant bits (MS1 and MS0) of configuration register A are changed from 00 to 01 (positive bias) or 10 (negetive bias), e.g. 0x11 or 0x12.

Then, by placing the mode register into single-measurement mode (0x01), two data acquisition cycles will be made on each magnetic vector. The first acquisition will be a set pulse followed shortly by measurement data of the external field. The second acquisition will have the offset strap excited (about 10 mA) in the positive bias mode for X, Y, and Z axes to create about a ±1.1 gauss self test field plus the external field. The first acquisition values will be subtracted from the second acquisition, and the net measurement will be placed into the data output registers.

Since self test adds ~1.1 Gauss additional field to the existing field strength, using a reduced gain setting prevents sensor from being saturated and data registers overflowed. For example, if the configuration register B is set to 0x60 (Gain=3), values around +766 LSB (1.16 Ga * 660 LSB/Ga) will be placed in the X and Y data output registers and around +713 (1.08 Ga * 660 LSB/Ga) will be placed in Z data output register. To leave the self test mode, change MS1 and MS0 bit of the configuration register A back to 00 (Normal Measurement Mode), e.g. 0x10.

SCALE FACTOR CALIBRATION

Using the self test method described above, the user can scale sensors' sensitivity to match each other. Since placing device in positive bias mode (or alternatively negative bias mode) applies a known artificial field on all three axes, the resulting ADC measurements in data output registers can be used to scale the sensors. For example, if the expected self test value for X-axis is 766 and the actual value is 750 then a scale factor of (766/750) should be multiplied to all future readings of X-axis. Doing so for all three axes will ensure their sensitivity are well matched,

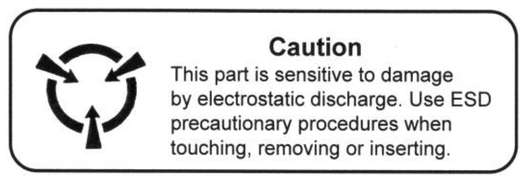
The built-in self test can also be used to periodically compensate the scaling errors due to temperature variations. A compensation factor can be found by comparing the self test outputs with the ones obtained at a known temperature. For example, if the self test output is 750 at room temperature and 700 at the current temperature then a compensation factor of (750/700) should be applied to all current magnetic readings. A temperature sensor is not required using this method.

EXTERNAL CAPACITORS

The two external capacitors should be ceramic type construction with low ESR characteristics. The exact ESR values are not critical but values less than 200 milli-ohms are recommended. Reservoir capacitor C1 is nominally 4.7 µF in capacitance, with the set/reset capacitor C2 nominally 0.22 µF in capacitance. Low ESR characteristics may not be in many small SMT ceramic capacitors (0402), so be prepared to up-size the capacitors to gain Low ESR characteristics.

ORDERING INFORMATION

Ordering Number	Product
HMC5883L-TR	Tape and Reel 4k pieces/reel



CAUTION: ESDS CAT. 1B

FIND OUT MORE

For more information on Honeywell's Magnetic Sensors visit us online at www.honeywell.com/magneticsensors or contact us at 800-323-8295 (763-954-2474 internationally).

The application circuits herein constitute typical usage and interface of Honeywell product. Honeywell does not warranty or assume liability of customer-designed circuits derived from this description or depiction.

Honeywell reserves the right to make changes to improve reliability, function or design. Honeywell does not assume any liability arising out of the application or use of any product or circuit described herein; neither does it convey any license under its patent rights nor the rights of others.

U.S. Patents 4,441,072, 4,533,872, 4,569,742, 4,681,812, 4,847,584 and 6,529,114 apply to the technology described

Honeywell
12001 Highway 55
Plymouth, MN 55441
Tel: 800-323-8295
www.honeywell.com/magneticsensors

Form # 900405 Rev B
October 2010
©2010 Honeywell International Inc.

Honeywell

Applications of Magnetoresistive Sensors in Navigation Systems

Michael J. Caruso
Honeywell Inc.

ABSTRACT

Most navigation systems today use some type of compass to determine heading direction. Using the earth's magnetic field, electronic compasses based on magnetoresistive (MR) sensors can electrically resolve better than 0.1 degree rotation. Discussion of a simple 8-point compass will be described using MR sensors. Methods for building a one degree compass using MR sensors will also be discussed. Compensation techniques are shown to correct for compass tilt angles and nearby ferrous material disturbances.

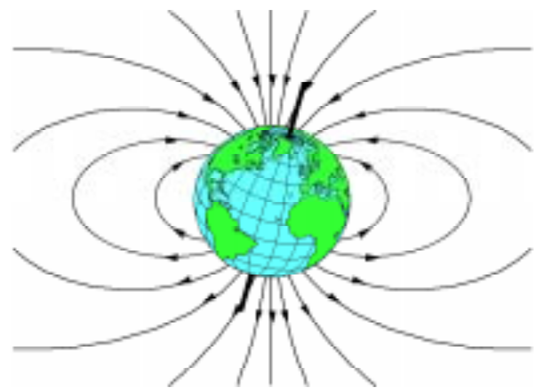


Figure 1 - Earth's Magnetic Field vs. True North

INTRODUCTION

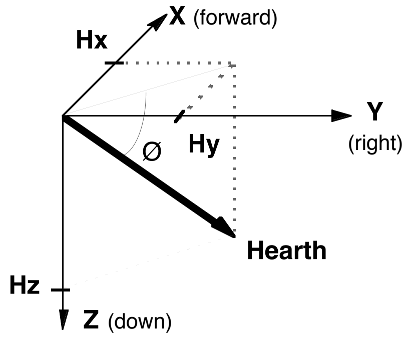
The magnetic compass has been used in navigation for centuries. The inventor of the compass is not known, though evidence suggests that the Chinese were using lodestone—a magnetic iron ore—over 2000 years ago to indicate horizontal directions. It appears that Mediterranean seamen of the 12th century were the first to use a magnetic compass at sea [1]. Today, the balanced needle compass is only a slight variation of this early discovery. Advances in technology have led to the solid state electronic compass based on MR magnetic sensors and acceleration based tilt sensors. Electronic compasses offer many advantages over conventional "needle" type or gimbaled compasses such as: shock and vibration resistance, electronic compensation for stray field effects, and direct interface to electronic navigation systems. Two types of compasses will be discussed in this paper—a basic eight-point compass and a one-degree compass.

EARTH'S MAGNETIC FIELD

The earth's magnetic field intensity is about 0.5 to 0.6 gauss and has a component parallel to the earth's surface that always point toward magnetic north. This is the basis for all magnetic compasses. The key words here are "parallel to the earth's surface" and "magnetic north".

The earth's magnetic field can be approximated with the dipole model shown in Figure 1. This figure illustrates that the earth's field points down toward north in the northern hemisphere, is horizontal and pointing north at the equator, and point up toward north in the southern hemisphere. In all cases, the direction of the earth's field is always pointing to magnetic north. It is the components of this field that are parallel to the earth's surface that are used to determine compass direction. The angle of the magnetic field to the surface of the earth is called the dip, or inclination, angle (see Figure 2). In the northern hemisphere, the dip angle is roughly 70° down toward the north. Only the X and Y components of the earth's field is used when determining the azimuth, or compass direction. The vertical portion of the earth's magnetic field is ignored.

The term magnetic north refers to the earth's magnetic pole position and differs from true, or geographic, north by about 11.5 degrees. True north is at the earth's rotational axis and is referenced by the meridian lines found on maps. At different locations around the globe magnetic north and true north can differ by ±25 degrees, or more as shown in Figure 3. This difference is called the declination angle and can be determined from a lookup table based on the geographic location.



$$|Hearth| = \sqrt{Hx^2 + Hy^2 + Hz^2}$$

Ø = Dip or inclination angle

Figure 2 - Earth's Field in X, Y, Z Coordinates

The key to accurately finding a compass heading, or azimuth, is a two step process: 1) determine the Hx and Hy horizontal components of the earth's magnetic field and 2) add or subtract the proper declination angle to correct for true north.

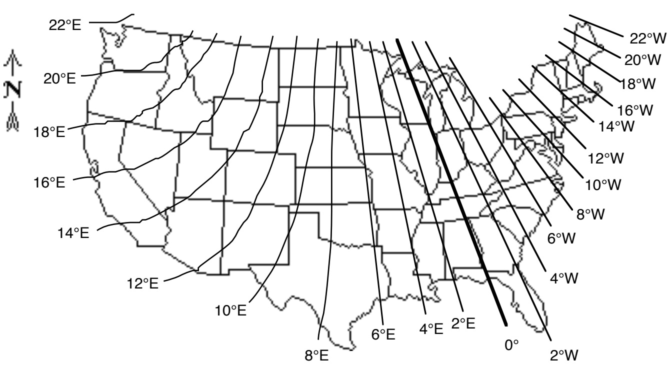


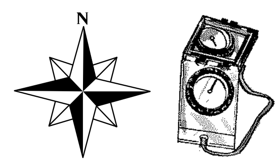
Figure 3 - Declination Angle To Correct For True North

BASICS OF MAGNETIC SENSING

Today, there are several types of electronic compasses to chose from: fluxgate, magnetoresistive, magnetoinductive, and others. A common type of magnetic compass for navigation systems is the fluxgate sensor. The fluxgate sensor consists of a set of coils around a core with excitation circuitry that is capable of measuring magnetic fields with less than 1 milligauss resolution. These sensors provide a low cost means of magnetic field detection; they also tend to be bulky, somewhat fragile, and have a slow response time. Sometimes, fluxgate sensors in motion can have a reading response time of 2-3 seconds. This reading delay may be unacceptable when navigating a high speed vehicle or an unmanned plane.

Another type of magnetic sensor is the magnetoresistive (MR) sensor. This sensor is made up of thin strips of permalloy (NiFe magnetic film) whose electrical resistance varies with a change in applied magnetic field. These sensors have a well defined axis of sensitivity and are mass produced as an integrated circuit. Recent MR sensors show sensitivities below 0.1 milligauss, come in small solid state packages, and have a response time less than 1 microsecond. These MR sensors allow reliable magnetic readings in moving vehicles at rates up to 1,000 times a second.

A magnetoresistive sensor will be used in the remainder of this paper to detect both the sign and magnitude of the earth's field as a voltage output. The sensor will also detect any stray field or field anomaly superimposed onto the earth's field. The magnetic sensor output will have an X, Y, and Z component referenced to the magnetic sensor, or compass, package. For our navigational reference: the X component will be in the forward looking direction, the Y component to the right, and the Z component will be down as shown in Figure 2.



COMPASS DESIGN

There are many forms of compasses used in navigation systems. Two forms will be discussed here that use magnetoresistive magnetic sensors—the eight point compass and the one-degree compass.

EIGHT-POINT COMPASS—A simple eight point compass depicts the cardinal points (N, S, E, W) and the midway points (NE, NW, SE, SW). This type of compass may be used for basic automotive use where the driver needs to know the general direction of travel. For this application, the magnetic sensor can be reduced to a two-axis sensor using only the X and Y axis. An automobile usually travels on a level surface, barring any hills or potholes, so that the X and Y sensors will directly measure the earth's Hx and Hy magnetic fields. The compass can be mounted on the dashboard with the X axis pointing straight ahead and the Y axis to the left. For now, ignore the magnetic effect of the car on the earth's field.

The compass design can be broken into eight regions to indicate the cardinal directions. To analyze the magnetoresistive sensor response, plot the X and Y outputs while the car travels in a circle as indicated in Figure 4. Knowing that the earth's magnetic field is always pointing toward the north, start the analysis with the X axis (and the car) directly pointing north. The X output will be at its maximum value while the Y output will be zero—since no part of the earth's field is pointing to the left, or west. As the car turns clockwise toward the east, the X axis will diminish to zero while the Y axis will decrease to its maximum negative value. With the car continuing its clockwise turn to point due south, the X axis will decrease to its most negative value while the Y axis will return to zero. This effect is illustrated in Figure 4 and shows the complete circular cycle for the X and Y axis outputs. The X and Y outputs of the magnetometer can be modeled by the cos(Ø) and sin(Ø) functions where Ø is the azimuth, referenced to magnetic north.

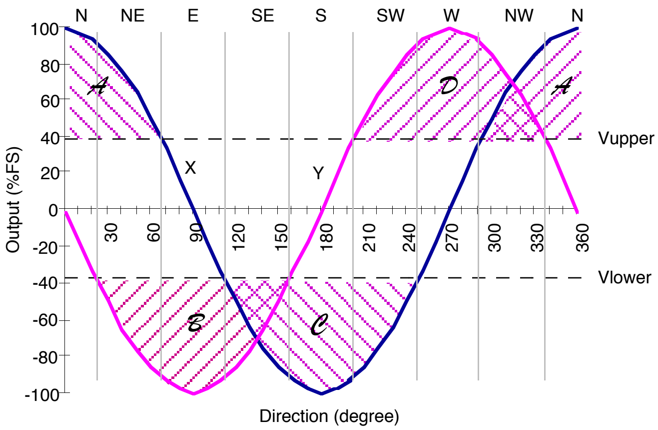


Figure 4 - Magnetic Outputs X And Y For 360° Rotation

The X and Y curves in Figure 4 can be split into eight regions representing the four cardinal and four midway points. A combination of these curves can be formed to represent each region. Two crossover points, Vupper and Vlower, are necessary to distinguish the boundaries of the eight compass direction headings. The crossover points can be determined by knowing the full scale (FS) values for X and Y as:

Vupper = 100*sin(22.5°) (%FS) = 38 %FS (1)
Vlower = -100*sin(22.5°) (%FS) = -38 %FS

Voltage comparators can be used to detect Vupper and Vlower levels to divide the X and Y curves into four regions: A, B, C, and D. The eight points of the compass can be determined by combining the A, B, C, and D using Boolean logic gates, four comparators, and a two axis magnetic sensor as shown in Figure 5. This circuit requires a two axis magnetometer with a signal sensitivity of 1-2 milligauss. Magnetic hysteresis and linearity must be less than 1-2%FS with good repeatability. There are three limitations to consider while using this design: 1) there is no tilt compensation so the compass must be held level, 2) there should be no nearby ferrous material to create magnetic distortions, and 3) the declination angles are difficult to add to this design. These limitations will be addressed in the one-degree compass discussion below.

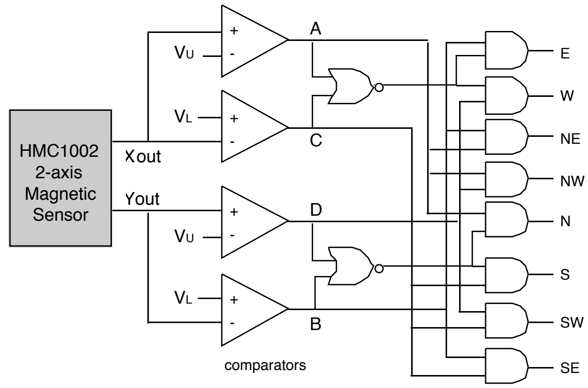


Figure 5 - Eight Point Compass Circuit

ONE-DEGREE COMPASS—Some navigation systems require more than just an eight point compass. For instance, the Global Positioning System (GPS) has led to a sophisticated tracking of vehicle position on video maps with accuracy better than 10 meters. These systems rely on telemetry contact from four satellites, sometimes aided by a system radio tower. It is essential to keep a line of sight with these satellites for position determination. Backup systems are required in cities and tunnels to maintain a course of direction during short blackouts. This is where a more accurate compass can help in GPS based navigation systems. During the loss of GPS signals, knowing the vehicle's speed and heading direction can maintain proper vehicle tracking. Gyros can be used to maintain direction but a lower cost MR based compass is preferred. For these systems, a compass accuracy of one degree is desirable.

To achieve a one degree accurate compass requires a magnetic sensor that can reliably resolve angular changes to 0.1 degrees. The sensors must also exhibit low hysteresis (<0.05%FS), a high degree of linearity (< 0.5%FS error) and be repeatable. The magnetic fields in the X and Y plane will typically be in the 200 to 300 milligauss range—more at the equator, less at the poles. Using the relationship:

Azimuth = arcTan (y/x) (2)

the required magnetometer resolution can be estimated. To resolve a 0.1° change in a 200milligauss field would require a magnetic sensitivity of better than 0.35 milligauss. Solid state MR sensors are available today that reliably resolve 0.07 milligauss signals giving a five times margin of detection sensitivity.

Using the simple magnetic sensor shown in Figure 6, the azimuth can be calculated by using the X and Y outputs in a horizontal plane. To account for the tangent function being valid over 180° and not allowing the y=0 division calculation, the following equations can be used:

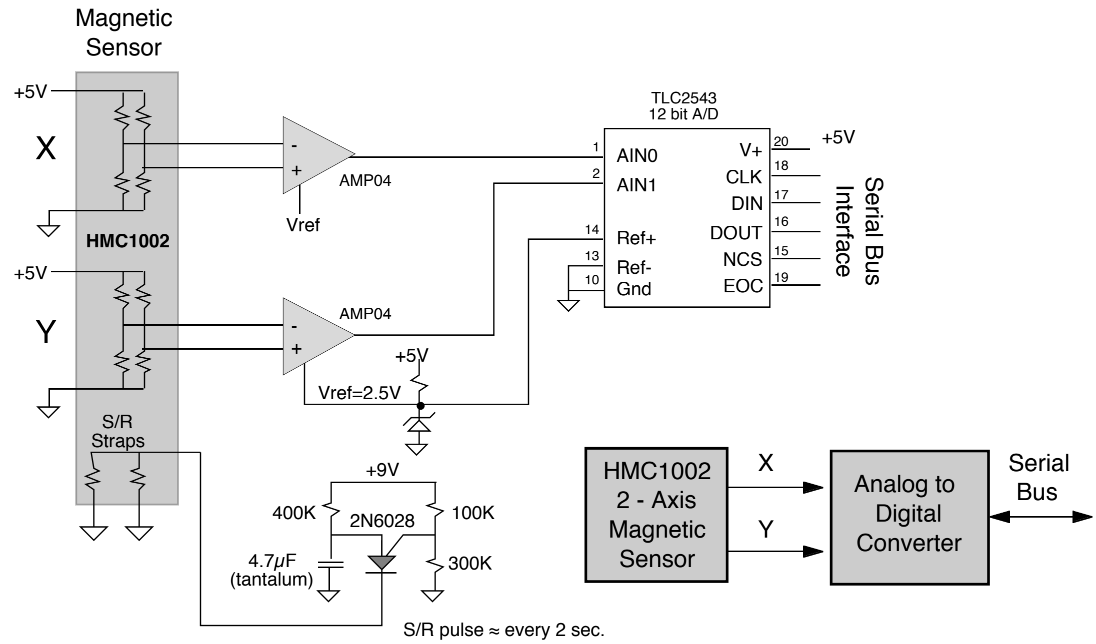


Figure 6 - One Degree Compass System without Tilt Compensation

---

Azimuth (x=0, y<0) = 90.0 (3)
Azimuth (x=0, y>0) = 270.0
Azimuth (x<0) = 180 - [arcTan(y/x)]*180/π
Azimuth (x>0, y<0) = - [arcTan(y/x)]*180/π
Azimuth (x>0, y>0) = 360 - [arcTan(y/x)]*180/π

The set/reset (S/R) circuit shown in Figure 6 is a current pulse generator used to eliminate the effects of past magnetic effects and temperature drift [4]. The serial bus output can readily interface to a low cost microprocessor for azimuth computation. Equations (3) provide continuous azimuth angles from 0° to 360° in the forward direction relative to magnetic north (H_{North}), see Figure 7. In this example, there is no compensation for tilt and nearby ferrous distortion effects on the azimuth.

COMPENSATING FOR TILT—Most often compasses are not confined to a flat and level plane. They are often hand held, attached to an aircraft, or on a vehicle in an uneven terrain. This makes it more difficult to determine the azimuth, or heading direction, since the compass is not always horizontal to the earth's surface. Errors introduced by tilt angles can be quite large depending on the amount of the Dip angle. A typical method for correcting the compass tilt is to use an inclinometer, or tilt sensor, to determine the roll and pitch angles. The terms roll and pitch are commonly used in aviation: ROLL refers to the rotation around the X, or forward direction, and PITCH refers to the rotation around the y, or left-right, direction (see Figure 8).

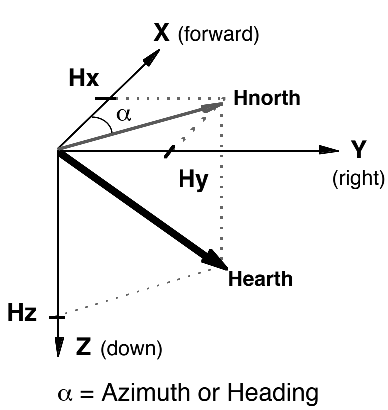


Figure 7 - Azimuth Defined In The X-Y Plane

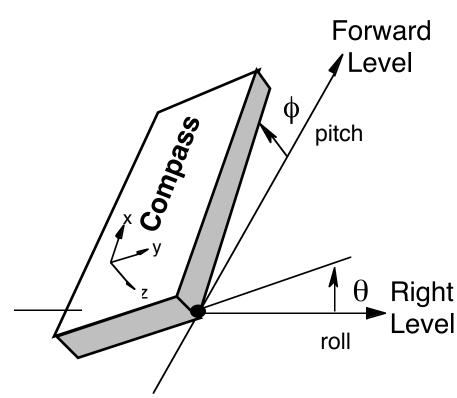


Figure 8 - Compass Tilt Referenced To The Earth's Horizontal Plane

Common liquid filled tilt sensors resemble a glass "thimble" that uses electrodes to monitor the fluid movement as the sensor changes angles. Newer solid state accelerometer tilt sensors are available that measure the earth's gravitational field by means of an electromechanical circuit [5]. The output of these devices are an electrical signal equivalent to the angle of tilt. During compass assembly, the tilt sensor directions must be carefully aligned with the X,Y,Z magnetic axis. Several manufacturers offer these tilt sensors as stand alone circuit boards that provide the roll and pitch angles as outputs.

To compensate a compass for tilt, knowing the roll and pitch is only half the battle. The magnetometer must now rely on all three magnetic axes (X, Y, Z) so that the earth's field can be fully rotated back to a horizontal orientation. In Figure 8, a compass is shown with roll (θ) and pitch (ϕ) tilt angles referenced to the right and forward level directions of the observer or vehicle. The X, Y, and Z magnetic readings can be transformed back to the horizontal plane (X_H, Y_H) by applying the rotational equations shown below:

$$X_H = X^*\cos(\phi) + Y^*\sin(\theta)^*\sin(\phi) - Z^*\cos(\theta)^*\sin(\phi)$$

$$Y_H = Y^*\cos(\theta) + Z^*\sin(\theta) \qquad (4)$$

$$\text{Azimuth} = \arctan(Y_H / X_H)$$

Once the X and Y magnetic readings are in the horizontal plane, equations (3) can be used to determine the azimuth. For speed in processing the rotational operations, a sine and cosine lookup table can be stored in program memory to minimized computation time.

A block diagram for a tilt compensated compass is shown in Figure 9 with a serial bus interface. After the azimuth is determined, the declination correction can be applied to find true north according to the geographic region of operation.

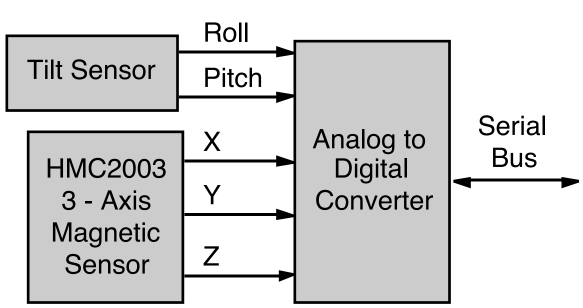


Figure 9- Tilt Compensated Compass System

COMPENSATING FOR NEARBY FERROUS EFFECTS—When a compass is operating in a open area in the absence of any ferrous metals there is no distortion effects on the earth's magnetic field. In reality, though, compasses are mounted in vehicles, aircraft, and platforms that most likely have ferrous materials nearby. The effects of ferrous metals (iron, nickel, steel, cobalt) will distort, or bend, the earth's field which will alter the compass heading. These effects can be thought of as a magnetic field that is added to the earth's field. If the compass is securely mounted in the vehicle, the ferrous effects can be accounted for and removed from the magnetic readings.

Figure 10 illustrates the X and Y magnetic readings when the compass is turning around in a circle in a horizontal plane. In this example, there is no ferrous interference with the earth's field. The readings are taken from Honeywell's HMR2300 Smart Digital Magnetometer where each count represents 67 microgauss. The earth's field magnitude in the X and Y plane reads 2800 counts which is approximately 190 milligauss. When the X and Y readings are plotted with each other they form a circle centered about the 0,0 point. An azimuth can be determined for each reading using equations (3) as show in Figure 10. This plot shows a sine and cosine output response for the X and Y directions during rotation.

If the magnetometer is mounted in a car, the effect of the engine and car body would distort the earth's magnetic field. Driving the car in a circle would produce the curves shown in Figure 11. Note here that the X,Y plot is not a circle (slightly ellipsoid) and that it is offset from the 0,0 point by -480 and -795 counts. This offset and ellipsoid effect are a result of the fixed distortion of the car on the earth's magnetic field. This distortion can be determined systematically and applied to subsequent X,Y readings to eliminated the effects of the car.

To compensate for the vehicle's distortion, two scale factors Xsf and Ysf can be determined to change the ellipsoid response to a circle. Offset values Xoff and Yoff can then be calculated to center the circle around the 0,0 origin. The X,Y values used to compute the azimuth when compensating for the vehicle's distortion are:

$$\text{Xvalue} = \text{Xsf} * \text{Xreading} + \text{Xoff} \qquad (5)$$

$$\text{Yvalue} = \text{Ysf} * \text{Yreading} + \text{Yoff}$$

Here, the scale factors Xsf and Ysf scale each reading to change the ellipsoid to a circle and Xoff and Yoff values shift the center back to the 0,0 origin. The result of this compensation is shown in Figure 12 and should be compared to the 'no interference' curves in Figure 10.

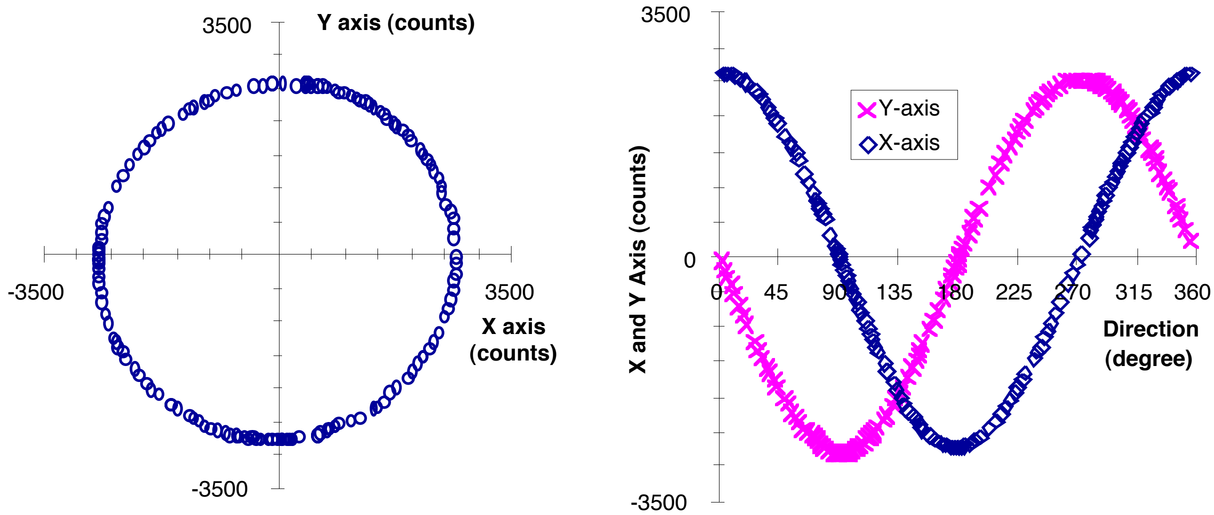


Figure 10 - No Interference Of Magnetometer Readings For 360° Rotation In Level Plane

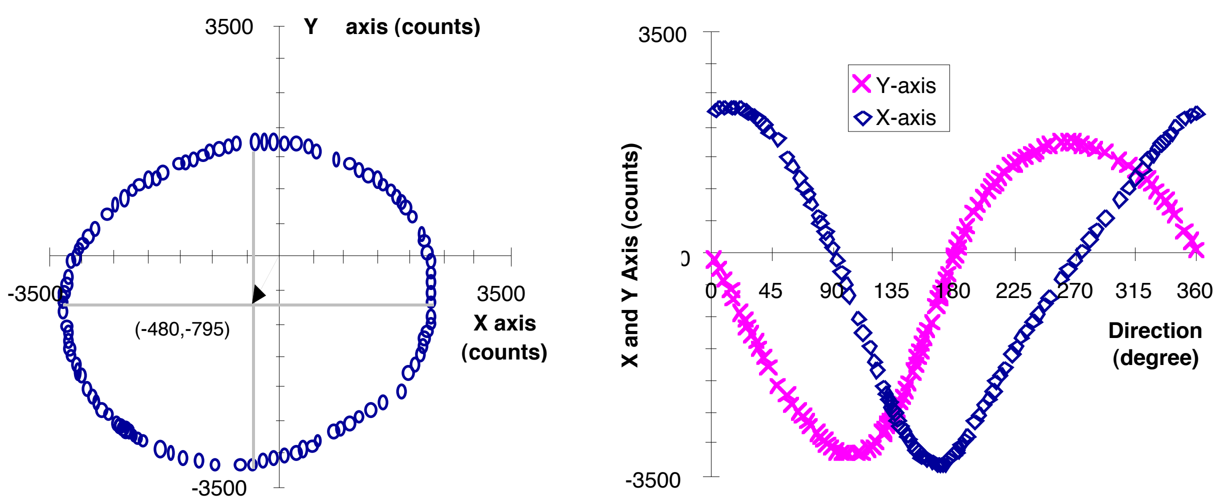


Figure 11 - Car Engine/Body Interference Of Magnetometer Readings For 360° Rotation In Level Plane

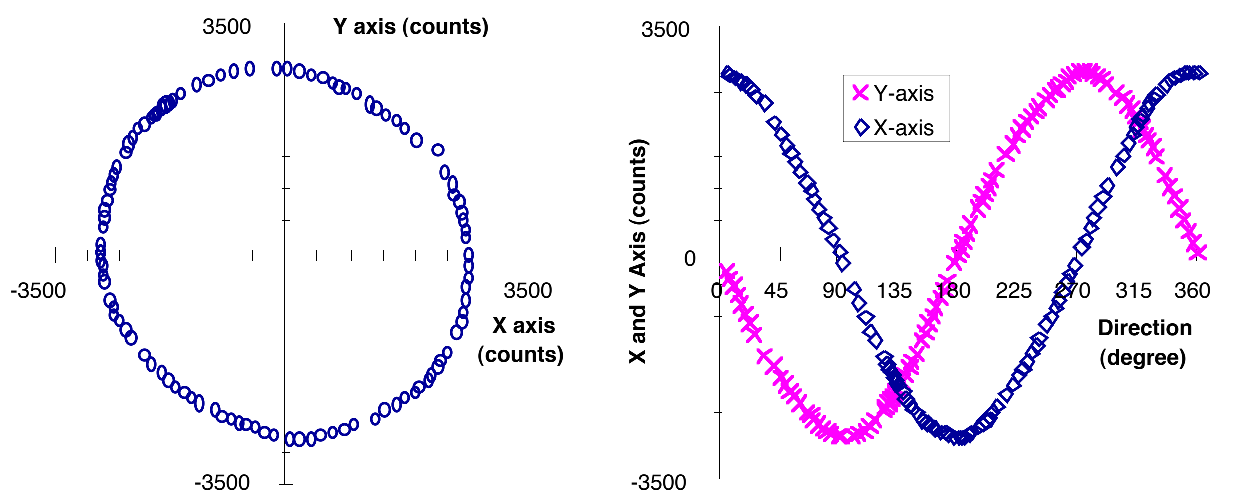


Figure 12 - Car Engine/Body Compensation Of Magnetometer Readings For 360° Rotation In Level Plane

A simple calibration method can be used to determine the offset and scale factor values:

- Mount the compass in the car and drive the car in a circle on a horizontal surface.
- Find the maximum and minimum values of the X and Y magnetic readings.
- Using these four values determine the X and Y scale factors (Xsf, Ysf) and the zero offset values (Xoff, Yoff).

Xsf = 1 or (Ymax - Ymin) / (Xmax - Xmin) (6)
whichever is greater

Ysf = 1 or (Xmax - Xmin) / (Ymax - Ymin)
whichever is greater

Xoff = [(Xmax - Xmin)/2 - Xmax] * Xsf (7)

Yoff = [(Ymax - Ymin)/2 - Ymax] * Ysf

The following example will show how the compensation values are determined. A compass is mounted in a car that has traveled a circle in a vacant parking lot. The magnetic X and Y counts (15,000 counts=1 gauss) from the magnetometer are scanned and the minimum and maximum readings are:

Xmin = -3298 Xmax = 2338

Ymin = -3147 Ymax = 1763

Set the X scale factor (Xsf) to one since (Ymax - Ymin)/(Xmax - Xmin)< 1, according to equation (5). Next, determine the Y scale factor (Ysf) by dividing the X reading span by the Y reading span.

Xsf = 1

Ysf = (Xmax - Xmin) / (Ymax - Ymin) = 1.15

Calculate the offset correction values by taking one-half the difference of the max. minus min. readings and apply the scale factors, Xsf and Ysf.

Xoff = [(Xmax - Xmin)/2 - Xmax] * Xsf = 480

Yoff = [(Ymax - Ymin)/2 - Ymax] * Ysf = 795

Store these values and apply them to every tilt compensated reading—X_H and Y_H. The Xvalue and Yvalue numbers used in the azimuth calculations, equations (3), to determine compass heading are:

Xvalue = X_H + 480

Yvalue = 1.15 * Y_H + 795

CONCLUSION

Compass headings are determined from the earth's magnetic fields in a horizontal plane. In a compass system each magnetometer reading must first be corrected for tilt. Then each reading must be compensated for the effects of nearby ferrous materials. Once the compass reading is tilt compensated and nearby ferrous material corrected, the declination angle should be applied to adjust magnetic north to true north.

Magnetoresistive sensors provide a solid state solution for building compass navigation systems. Their high sensitivity and good repeatability, along with small size, results in a high accuracy and easy to integrate magnetic sensor. There are many other techniques than the ones shown here for tilt and ferrous distortion compensation. The method for compensation depends on the application requirements: accuracy, resolution, speed, size, and cost.

REFERENCES

[1] Grant, George A., and Klinkert, John, The Ship's Compass, 2d ed. (1970).

[2] Barber, G.W., and Aarott,A.S., History and Magnetics of Compass Adjusting, IEEE Trans. Magn. Nov. 1988.

[3] Olson, Gregory J., et al, Nongimbaled Solid-State Compass, Solid-State Sensor and Actuator Workshop, June, 1994.

[4] Set/Reset Pulse Circuits for Magnetic Sensors, Honeywell Applications Note, AN-201.

[5] A Dual Axis Tilt Sensor Based on Micromachined Accelerometers, Mike Horton, Charles Kitchin, Sensors Magazine, April, 1996.

Unit conversion from SI to Gaussian:

1 Tesla= 10^4 gauss = 10^9 gamma = 7.96×10^5 A/m,

1 nTesla = 10 μgauss = 1 gamma = 7.96×10^{-4} A/m

Honeywell

Solid State Electronics Center
Honeywell Inc.
12001 State Highway 55
Plymouth, MN 55441 2-98 900212

Helping You Control Your World

Applications of Magnetic Sensors for Low Cost Compass Systems

Michael J. Caruso
Honeywell, SSEC

Abstract—A method for heading determination is described here that will include the effects of pitch and roll as well as the magnetic properties of the vehicle. Using solid-state magnetic sensors and a tilt sensor, a low-cost compass system can be realized. Commercial airlines today use attitude and heading reference systems that cost tens of thousands of dollars. For general aviation, or small private aircraft, this is too costly for most pilots' budget. The compass system described here will provide heading, pitch and roll outputs accurate to one degree, or better. The shortfall of this low-cost approach is that the compass outputs are affected by acceleration and turns. A solution to this problem is presented at the end of this paper.

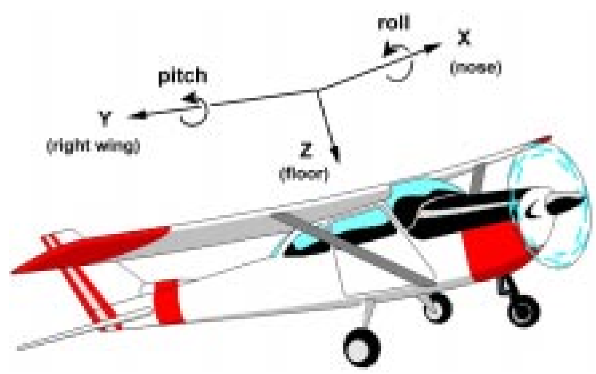


Figure 1—Coordinate direction (X,Y,Z) and attitude orientation (roll,pitch) on an aircraft.

BACKGROUND

The Earth's magnetic field intensity is about 0.5 to 0.6 gauss and has a component parallel to the Earth's surface that always point toward magnetic north. This field can be approximated with a dipole model—the field points down toward north in the Northern Hemisphere, is horizontal and pointing north at the equator, and point up toward north in the Southern Hemisphere. In all cases, the horizontal direction of the Earth's field is always pointing toward magnetic north and is used to determine compass direction.

Aircraft convention defines the attitude parameters in terms of three angles: heading, pitch and roll (see Figure 1). These angles are referenced to the local horizontal plane. That is, the plane perpendicular to the earth's gravitational vector. Heading is defined as the angle in the local horizontal plane measured clockwise from a true North (earth's polar axis) direction. Pitch is defined as the angle between the aircraft's longitudinal axis and the local horizontal plane (positive for nose up). Roll is defined as the angle about the longitudinal axis between the local horizontal plane and the actual flight orientation (positive for right wing down).

The local horizontal plane is defined as the plane normal to the earth's gravity vector (see Figure 2). If a compass was sitting in the local horizontal plane, then the roll and pitch angles would be zero and the heading would be calculated as:

$$\text{Heading} = \arcTan (Yh/Xh) \qquad (1)$$

where Xh and Yh represent the earth's horizontal magnetic field components. As the aircraft is rotated, the heading would sweep 0° to 360° referenced to magnetic north. If the compass were now tilted, the tilt angles (roll and pitch) and all three magnetic field components (X,Y,Z) must be used in order to calculate heading [1].

TILT DETERMINATION

One method to determine the roll and pitch angles is to use a tilt sensor that senses the direction of gravity. Common tilt measuring devices include accelerometers, electrolytic (fluid) based tilt sensors, and gimbaled mechanical structures. Another method to determine the local horizontal plane is to use a gyroscope to maintain a known inertial reference orientation at all times.

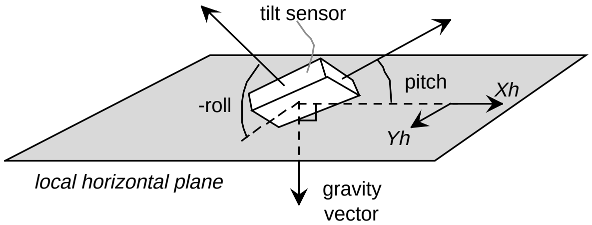


Figure 2—Tilt sensor angles are referenced to the local horizontal plane defined by gravity.

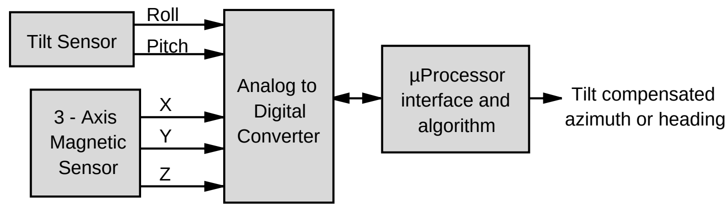


Figure 3—Compass system block diagram.

Gyroscopes (gyros) are instruments used to measure precise angular motion. Several techniques are used to achieve this such as spinning wheels, vibrating structures, and ring lasers. The output signal is proportional to the angular rate of turn. A key consideration when using gyros is the output drift with time. With periodic correction, the drift can be compensated for and provide very high levels of accuracy for roll, pitch, and heading. Gyros are standard in navigation instrument on commercial aircraft and will operate well under accelerating conditions. When compared to tilt sensors, though, gyros tend to be bulky and expensive and will not be considered here.

Tilt sensors come in many types and sizes. The gimbaled tilt device usually has two rings mounted at right angles to each other much like a dual pendulum. A magnetic sensor, or compass, inside of the gimbaled structure will remain suspended in the local horizontal plane for various roll and pitch angles. The mechanical structure of the gimbal makes it susceptible to shock and vibration and can often take seconds for it to become stable after movement. Gimbaled compasses only require two axes of magnetic sensing since the roll and pitch angles are never present in a steady-state condition. However, since the magnetic sensors change orientation with the compass platform, these compasses cannot compensate for the ferrous effects of its surroundings.

Low cost tilt sensors like the two-axis electrolytic and dual axis accelerometer measure the roll and pitch angle directly. Liquid filled electrolytic tilt sensors, resembling a glass “thimble”, use electrodes to monitor the fluid movement as the sensor changes angles. Solid state accelerometer tilt sensors measure the Earth’s gravitational field by means of an electromechanical circuit [2]. These sensors are similar in that they have two single axis components that measure the angle deviations from the local horizontal plane. Signal conditioning circuits are used to create an output signal proportional to the angle of tilt. These sensors are considered strapdown devices since they have no moving or pendulous parts and are desirable for vehicle applications [3].

COMPASS SYSTEM

If a strapdown compass is required to output heading for any orientation then, as a minimum, a compass system must have a three-axis magnetic sensor and a two-axis tilt (see Figure 3). The heading calculation relies on all three magnetic components (X,Y,Z) so the compass orientation can be mathematically rotated to the horizontal plane. Then, the Xh and Yh components can be calculated to determine the heading value from equation (1).

In Figure 2, a compass is shown with roll (θ) and pitch (ϕ) tilt angles referenced to the right and forward level directions. The X, Y, and Z magnetic readings can be transformed to the horizontal plane (Xh, Yh) by applying the rotation equations shown in equation (2). If these equations are not used, then appreciable errors will result in the heading calculations as shown in Figure 4.

$$
\begin{aligned}
Xh &= X*\cos(\phi) + Y*\sin(\theta)*\sin(\phi) - Z*\cos(\theta)*\sin(\phi) \\
Yh &= Y*\cos(\theta) + Z*\sin(\theta) \qquad (2)
\end{aligned}
$$

Once the magnetic components are found in the horizontal plane, equation (1) can be used to determine heading. To minimize processing time, a sine and cosine lookup table can be stored in program memory. To account for the arcTan limits, the heading calculations must account for the sign of the Xh and Yh readings as shown in (3).

$$
\begin{aligned}
\text{Heading for } (Xh<0) &= 180 - \arctan(Yh/Xh) \\
\text{for } (Xh>0, Yh<0) &= -\arctan(Yh/Xh) \\
\text{for } (Xh>0, Yh>0) &= 360 - \arctan(Yh/Xh) \\
\text{for } (Xh=0, Yh<0) &= 90 \\
\text{for } (Xh=0, Yh>0) &= 270 \qquad (3)
\end{aligned}
$$

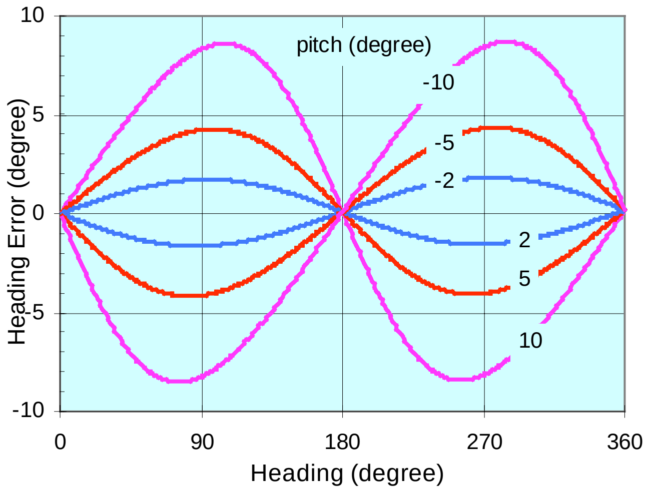


Figure 4—Heading errors due to pitch without tilt compensation (Dip Angle =40°).

COMPASS ERROR ANALYSIS

If a compass system has a requirement of better than one degree of accuracy, then it is important to break down the error contributed by the tilt sensor and the magnetic sensor and determine what level of signal processing is required. Specifically, heading accuracy is affected by:

- ✔ A/D converter resolution
- ✔ Magnetic sensor errors
- ✔ Temperature effects
- ✔ Nearby ferrous materials
- ✔ Compass tilt errors
- ✔ Variation of the earth's field

A/D Converter Resolution—To achieve a one-degree accurate compass requires a magnetic sensor that can reliably resolve angular changes to 0.1°. The sensors must also exhibit low hysteresis (<0.08%FS), a high degree of linearity (<0.05%FS) and be repeatable. The magnetic fields in the X and Y horizontal plane will typically be in the 200 mgauss range—more at the equator, less near the poles.

Using the standard heading relationship of equation (1), the required A/D converter resolution for the magnetic sensors can be estimated. If the magnetometer error, or uncertainty, is allowed to be 0.1° then:

$$\begin{aligned} &\textit{if:} \quad \text{Error} = 0.1° = \arctan(Yh/Xh) \\ &\textit{then:} \quad Yh/Xh = 1/573 \end{aligned} \qquad (4)$$

This implies that a ratio change of 1 part in 573 will result in a 0.1° difference. If X and Y were read with a nine-bit A/D converter there would be only a 1:512 bit resolution. This means that a 9+ bit A/D converter is needed to meet the 0.1° error budget for an (X,Y) magnetic field change of 200 mgauss. Since the (X,Y) magnetic fields measure ±200 mgauss for a complete heading sweep, the A/D converter range should be doubled, to 10+ bits. To allow for hard iron correction and larger horizontal fields—like at the equator—this range should be quadrupled to ±800 mgauss. Now the A/D converter resolution should be 12+ bits, or 12.163 bits to be more exact.

A 12 bit A/D converter can be used to provide a 0.1° resolution in a 200 mgauss horizontal field. This implies that the sensor must be able to resolve a 0.39 mgauss field over a span of ±800 mgauss (1.6 gauss/4096 counts).

Magnetic Sensor Errors—Solid state magneto-resistive (MR) sensors available today can reliably resolve <0.07 mgauss fields [4-7]. This is more than a five times margin over the 0.39 mgauss field required to achieve 0.1° resolution.

Other magnetic sensor specifications should support field measurement certainty better than 0.5° to maintain an overall 1° heading accuracy. These include the sensor noise, linearity, hysteresis, and repeatability errors.

Any gain and offset errors of the magnetic sensor will be compensated for during the hard iron calibration (discussed later) and will not be considered in the error budget.

MR sensors can provide a total error of less than 0.5 mgauss, which corresponds to a 0.14° heading error as shown in Table 1.

Parameter	**Spec Limit (1)**	**Field Error**	**Heading Error**
Noise (BW=10Hz)	85 ugauss	85 ugauss	<0.01°
Linearity	0.05 %FS	0.2 mgauss	0.06°
Hysteresis	0.08 %FS	0.32 mgauss	0.09°
Repeatabilit y	0.08 %FS	0.32 mgauss	0.09°
	Total rms error	***0.49 mgauss***	***0.14°***

(1) Typical specs for HMC1021/22 MR sensors; FS=400 mgauss

Table 1—Error budget for an MR magnetic sensor

Temperature Effects—The temperature coefficient (tempco) of the sensor will also affect the heading accuracy. There are two characteristics of temperature to consider—the offset drift with temperature and the sensitivity tempco. The sensitivity tempco will appear as a change in output gain of the sensor over temperature (Figure 5). MR sensors generally have sensitivity tempcos that are well correlated, or matched—especially sensors with two (X,Y) axes in the same package. The matching tempcos imply that the output change over temperature of the X axis will track the change in output of the Y axis. This effect will cancel itself since it is the *ratio* of Y over X that is used in the heading calculation [Azimuth = arcTan(Y/X)]. For example, as the temperature changes the Y reading by 12%, it also changes the X reading by 12% and the net change is canceled. The only consideration is then the dynamic input range of the A/D converter.

The magnetic sensor offset drift with temperature is not correlated and may in fact drift in opposite directions. This will have a direct affect on the heading and can cause appreciable errors. There are many ways to compensate for temperature offset drifts using digital and analog circuit techniques. A simple method to compensate for temperature offset drifts in MR sensors is to use a switching technique referred to as set/reset switching. This technique cancels the sensor temperature offset drift, and the dc offset voltage as well as the amplifier offset voltage and its temperature drift.

The transfer curves for a MR magnetic sensor after it has been set, and then reset, is shown in Figure 6. The set/reset modes are achieved by using an ac coupled driver to generate a bi-directional current

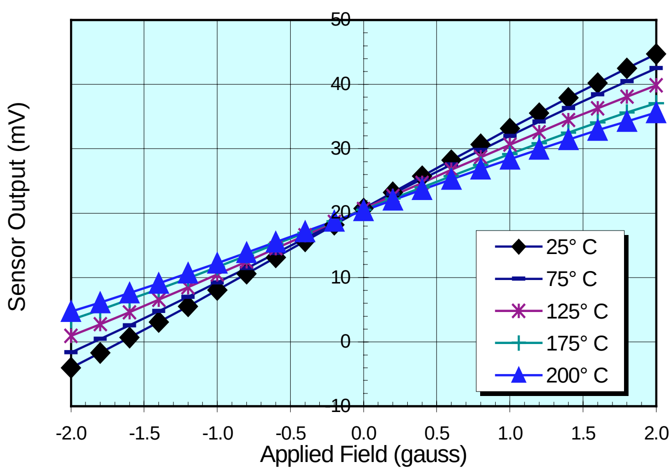


Figure 5—Magnetic sensor output temperature variation has a pivot point at zero applied field.

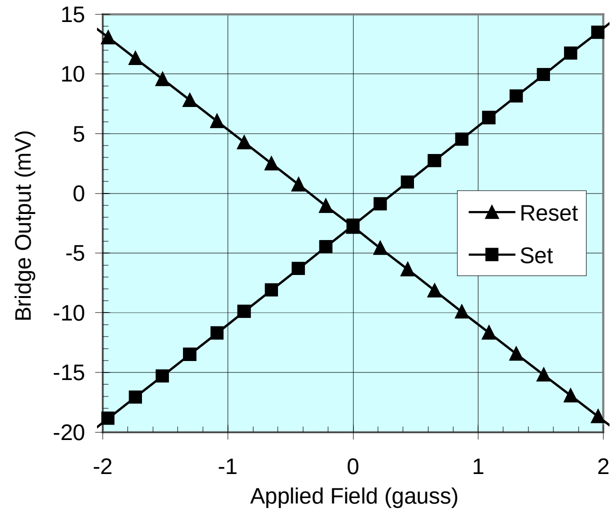


Figure 6—Set and reset output transfer curves.

pulse [7]. The two curves result from an inversion of the gain slope with a common crossover point at the offset voltage. For the sensor in Figure 6, the sensor offset is –3 mV. This from the resistor mismatch during the manufacture process. This offset is not desirable and can be eliminated using the set/reset switching technique described below. Other methods of offset compensation are described in ref. [8].

The sensor offset (Vos) can be eliminated by using a simple subtraction technique. First apply a set pulse, measure Happlied and store it as Vset—Figure 7. Then apply a reset pulse and store that reading as Vreset. Subtract these two readings to eliminate Vos:

$$Vset = S * Happlied + Vos \tag{5}$$

$$Vreset = -S * Happlied + Vos \tag{6}$$

$$Vset - Vreset = S * 2 * Happlied \tag{7}$$

The sensor sensitivity (S) is expressed in mV/gauss. Note that equation (7) has no Vos term. This method also eliminates the amplifier offset as well. Another benefit is that the temperature drift of the sensor offset and the amplifier is eliminated! Now, a low cost amplifier can be used without concern for its offset effects. This is a powerful technique and is easy to implement if the readings are controlled by a low cost microprocessor.

Using this technique to reduce temperature effects can drop the overall variation in magnetic readings to less than 0.01%/°C. This amounts to less than 0.29° effect on the heading accuracy over a 50°C temperature change.

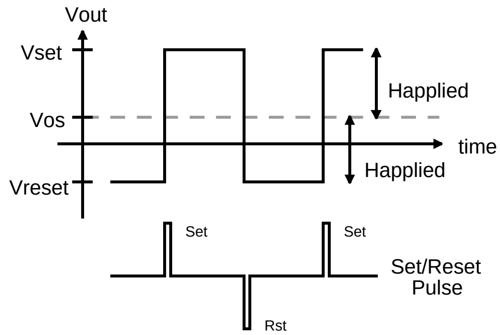
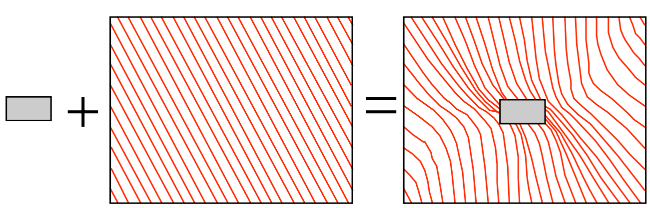


Figure 7—Set and reset effect on sensor output (Vout) show the peak-to-peak level is 2*Happlied.

Nearby Ferrous Materials—Another consideration for heading accuracy is the effects of nearby ferrous materials on the earth's magnetic field [9-11]. Since heading is based on the direction of the earth's horizontal field (Xh,Yh), the magnetic sensor must be able to measure this field without influence from other nearby magnetic sources or disturbances. The amount of disturbance depends on the material content of the platform and connectors as well as ferrous objects moving near the compass.

When a ferrous object is placed in a uniform magnetic field it will create disturbances as shown in Figure 8. This object could be a steel bolt or bracket near the compass or an iron door latch close to the compass. The net result is a characteristic distortion, or anomaly, to the earth's magnetic field that is unique to the shape of the object.

Before looking at the effects of nearby magnetic disturbances, it is beneficial to observe an ideal output curve with no disturbances. When a two-axis (X,Y) magnetic sensor is rotated in the horizontal plane, the output plot of Xh vs. Yh will form a circle centered at the (0,0) origin (see Figure 9). If a heading is calculated at each point on the circle, the result will be a linear sweep from 0° to 360°.



Ferrous Object + Uniform Magnetic Field = Field Disturbance

Figure 8–Ferrous object disturbance in uniform field.

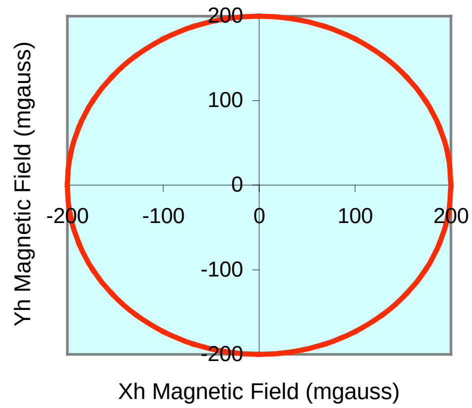


Figure 9—Magnetic sensor outputs (X,Y) rotated horizontally in the earth's field with no disturbances.

The effect of a magnetic disturbance on the heading will be to distort the circle shown in Figure 9. Magnetic distortions can be categorized as two types—hard iron and soft iron effects. Hard iron distortions arise from permanent magnets and magnetized iron or steel on the compass platform. These distortions will remain constant and in a fixed location relative to the compass for all heading orientations. Hard iron effects add a constant magnitude field component along each axes of the sensor output. This appears as a shift in the origin of the circle equal to the hard iron disturbance in the Xh and Yh axis (see Figure 10). The effect of the hard iron distortion on the heading is a one-cycle error and is shown in Figure 11.

To compensate for hard iron distortion, the offset in the center of the circle must be determined. This is usually done by rotating the compass and platform in a circle and measure enough points on the circle to determine this offset. Once found, the (X,Y) offset can be stored in memory and subtracted from every reading. The net result will be to eliminate the hard iron disturbance from the heading calculation; as if it were not present[1].

The soft iron distortion arises from the interaction of the earth's magnetic field and any magnetically soft material surrounding the compass. Like the hard iron materials, the soft metals also distort the earth's magnetic field lines. The difference is the amount of distortion from the soft iron depends on the compass orientation. Soft iron influence on the field values measured by X and Y sensors are depicted in Figure 12. Figure 13 illustrates the compass heading errors associated with this effect—also known as a two cycle error.

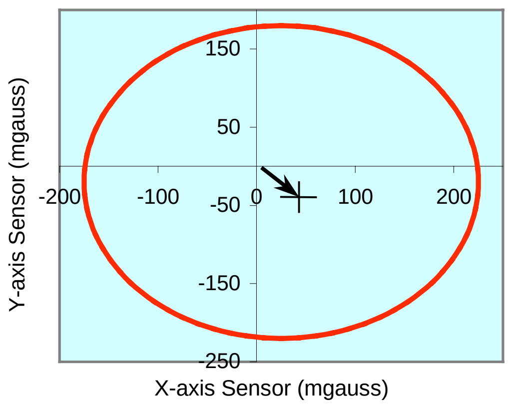


Figure 10— Hard iron offsets when rotated horizontally in the earth's field.

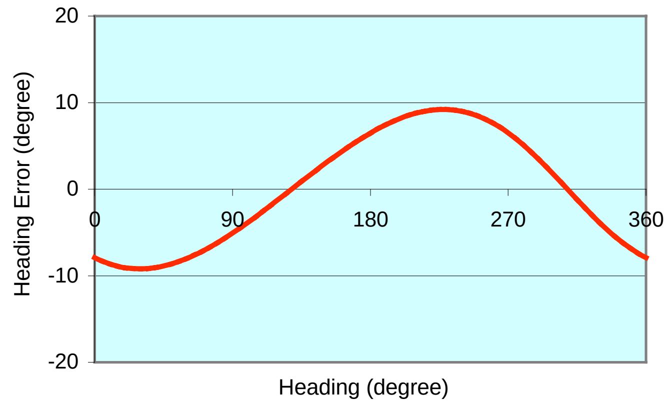


Figure 11— Heading error due to hard iron effects known as single-cycle errors.

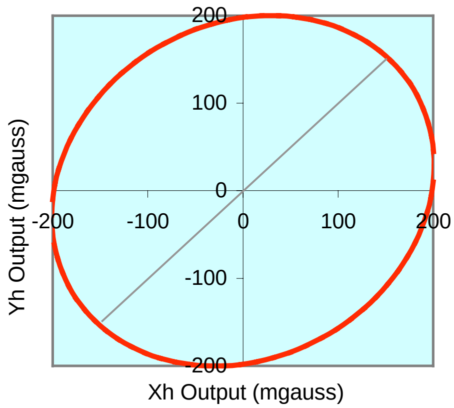


Figure 12—Soft iron distortion when rotated horizontally in the earth's field.

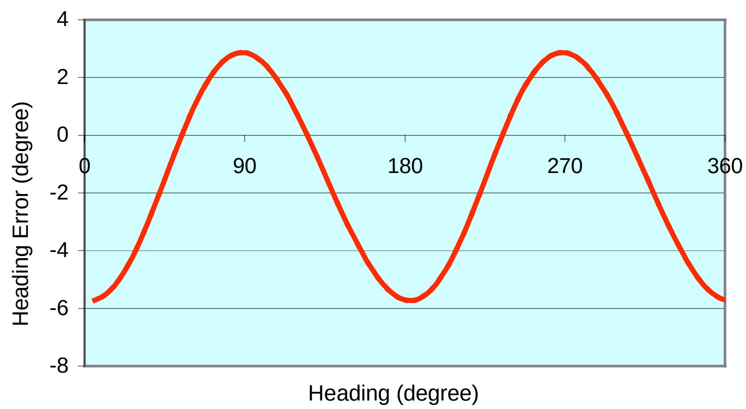


Figure 13— Heading error due to soft iron effects known as two-cycle errors.

Compensating for soft iron effects is a bit more difficult than for hard iron effects. This involves a bit more calculation than a simple subtraction. One way to remove the soft iron effect is to rotate the reading by 45°, scale the major axis to change the ellipse to a circle, then rotate the reading back by 45°. This will result in the desired circular output response shown in Figure 9.

Most ferrous material in vehicles tend to have hard iron characteristics. The best approach is to eliminate any soft iron materials near the compass and deal with the hard iron effects directly. It is also recommended to degauss the platform near the compass prior to any hard/soft iron compensation.

Some compass manufacturers provide calibration methods to compensate for the hard and soft iron effects. Each calibration method is associated with a specified physical movement of the compass platform in order to sample the magnetic space surrounding the compass. The calibration procedure can be as simple as pointing the host in three known directions, or as complicated as moving in a complete circle with pitch and roll, or pointing the host in 24 orientations including variations in tilt. It is impossible for a marine vessel to perform the 24-point calibration, but easy for a hand-held platform. If the compass is only able to sample the horizontal field components during calibration, then there will be uncompensated heading errors with tilt. Heading error curves can be generated for several known headings to improve heading accuracy [10,11].

Hard and soft iron distortions will vary from location to location within the same platform. The compass has to be mounted permanently to its platform to get a valid calibration. A particular calibration is only valid for that location of the compass. If the compass is reoriented in the same location, then a new calibration is required. A gimbaled compass can not satisfy these requirements and hence the advantage of using a strapdown, or solid state, magnetic sensor. It is possible to use a compass without any calibration if the need is only for repeatability and not accuracy.

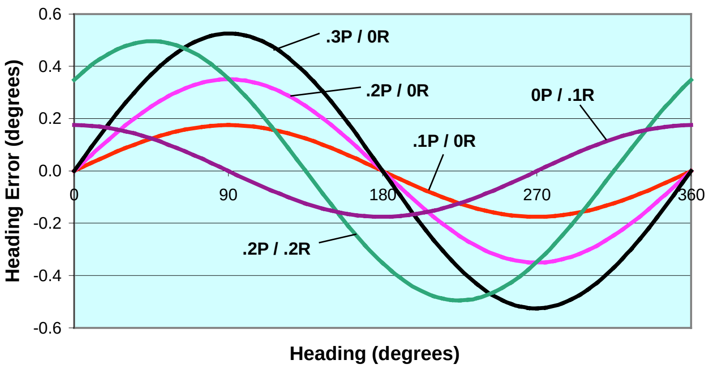


Figure 14—Heading error due to roll and pitch tilt errors (.2P/.2R = .2° error in pitch and roll).

Compass Tilt Errors—Heading errors due to the tilt sensor depend somewhat on geographic location. At the equator, tilt errors are less critical since the earth's field is strictly in the horizontal plane. This provides larger Xh and Yh readings and little Z component correction [ref. Equation (2)]. Near the magnetic poles, tilt errors are extremely important—since there is less Xh,Yh field and more Z component. Tilt errors are also dependent on the heading [ref. Figure 4].

Tilt sensors also have offset, gain errors, and temperature effects that need to be accounted for. These will not be compensated for during hard/soft iron calibration, as in the case for the magnetic sensors. The offset error can be zeroed out after installation and will include any platform leveling error. Also, temperature drifts, linearity, repeatability, hysteresis and cross-axis effects are important. The tilt sensor usually contributes the largest percentage of error to the heading calculation.

For a one degree compass, a tilt sensor with 0.1° resolution is desired. The total error introduced by the tilt sensor should be less than 0.5°. The curve in Figure 14 shows the effect on heading for various tilt sensor errors. In this Figure, a pitch error of 0.3° and no roll error can contribute a 0.5° error alone.

Variation of the Earth's Field—The final consideration for heading accuracy is the variation, or declination, angle. It is well known that the earth's magnetic poles and its axis of rotation are not at the same geographical location. They are about 11.5° rotation from each other. This creates a difference between the true north, or grid north, and the magnetic north, or direction a magnetic compass will point. Simply it is the angular difference between the magnetic and true north expressed as an Easterly or Westerly variation. This difference is defined as the variation angle and is dependent on the compass location—sometimes being as large as 25°. To account for the variation simply add, if Westerly, or subtract, if Easterly, the variation angle from the corrected heading computation.

The variation angles have been mapped over the entire globe. For a given location the variation angle can be found by using a geomagnetic declination map or a GPS (Global Positioning System) reading and an IGRF model. The International Geomagnetic Reference Field (IGRF) is a series of mathematical models describing the earth's field and its time variation [12-14]. After heading is determined, the variation correction can be applied to find true north according to the geographic region of operation.

COMPASS INSTALLATION

The performance of a compass will greatly depend on its installation location. A compass depends on the earth's magnetic field to provide heading. Any distortions of this magnetic field by other sources should be compensated for in order to determine an accurate heading. 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 from 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, disturbances generated by the motion of magnetic metals, or unpredictable electrical current in a nearby wire. Magnetic shielding can be used for large field disturbances from motors or speakers. The best way to reduce disturbances is distance. Also, never enclose the compass in a magnetically shielded metallic housing.

ACCELERATION EFFECTS

Any acceleration of the compass will effect the tilt or accelerometer outputs and will result in heading errors. An aircraft making a turn will cause the tilt sensors to experience the centripetal force in addition to gravity and the compass heading 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 more than those of a strapdown magnetic compass.

CONCLUSION

A low cost compass has been discussed here having a one degree accuracy requirement. At the heart of the compass is a three-axis MR magnetic sensor and a two-axis electrolytic tilt sensor. Other circuits include a 12 to 14 bit A/D converter, signal conditioning electronics and a microprocessor. The error budget for heading accuracy breaks down as:

Magnetic sensor error	0.14°
Temperature effects	0.29°
Signal conditioning	0.05°
Tilt sensor error	0.50°
Total Error	0.98°

The effects of nearby magnetic distortions can be calibrated out of the compass readings once it is secured to the platform. Caution must be taken in finding a compass location that is not too near varying magnetic disturbances and soft iron materials. Shielding effects from speakers and high current conductors near the compass may be necessary.

Variations in the earth's field from a true north heading can be accounted for if the geographical location of the compass is known. This can be achieved by using a map marked with the deviation angles to find the correct heading offset variation; or use a GPS system and the IGRF reference model to compute the variation angle.

Low cost compasses of the type described here are susceptible to temporary heading errors during accelerations and banked turns. The heading accuracy will be restored once these accelerations diminish. With a strapdown compass there is no accuracy drift to worry about since the heading is based on the true earth's magnetic field. They tend to be very rugged to shock and vibration effects and consume very low power and are small in size.

REFERENCES

[1] M.J. Caruso, "Application of Magnetoresistive Sensors in Navigation Systems", *Sensors and Actuators 1997*, SAE SP-1220, (Feb. 1997) 15-21.

[2] M. Horton, C. Kitchin, "A Dual Axis Tilt Sensor Based on Micromachined Accelerometers", *Sensors*, (April 1996).

[3] Olson, Gregory J., et al, "Nongimbaled Solid-State Compass", Solid-State Sensor and Actuator Workshop, June, 1994.

[4] B.B. Pant, "Magnetoresistive Sensors", *Scientific Honeyweller*, vol. 8, no.1, (Fall 1987) 29-34.

[5] J.E. Lenz, G.F.Rouse, L.K. Strandjord, B.B.Pant, A.Metze, H.B.French, E.T.Benser, D.R.Krahn, "A Highly Sensitive Magnetoresistive Sensors", Solid State Sensors and Actuator Workshop, 1992.

[6] J.Goetz, T.Bratland, M.Caruso, "Designing with Magnetoresistive Sensors", Sensor Expo Workshop, Philadelphia, October, 1996.

[7] Sensor Products Data Sheet, "1 and 2 Axis Magnetoresistive Microcircuits", Honeywell SSEC, 5/99, <www.magneticsensors.com>.

[8] M.J.Caruso, T.Bratland, C.H.Smith, R.Schneider, "A New Perspective on Magnetic Field Sensing", *Sensors Expo Proceedings*, October 1998, 195-213.

[9] M.J.Caruso, L.S. Withanawasam, "Vehicle Detection and Compass Applications using AMR Magnetic Sensors", *Sensors Expo Proceedings*, May 1999, 477-489.

[10] C.A. Lund, *Compasses in Small Craft"*, Glasgow, Scotland: Brown, Son & Ferguson, Ltd., 1983, 39-62.

[11] W. Denne, *Magnetic Compass Deviation and Correction*, Glasgow, Scotland: Brown, Son & Ferguson, Ltd., 1998.

[12] Y. Zhao, *Vehicle Location and Navigation Systems*, Norwood, MA: Artech House, Inc, 1997, Chapter 3.

[13] National Geomagnetic Information Center, website URL http://geomag.usgs.gov/

[14] National Geophysical Data Center, website URL http://www.ngdc.noaa.gov/

Unit conversion from SI to Gaussian:

79.6 A/m = 1 oersted
1 gauss = 1 oersted (in free air)
1 gauss = 10^{-4} tesla = 10^{5} gamma
1 nanotesla = 10 microgauss = 1 gamma