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Application Guidelines for MEMS Compass

12 April 2013

AMS Application Team

Agenda

Educational part: What is compass? How magnetic compass works, My S Magnetometer used as a compass …

ST MEMS Magnetometers: Overview of the key product features

Hardware Design: Schematic, PCB design …

Embedded Software: Tilt-compensated compass, Calibration and Testing

Documentation & Support Tools

What is compass?

- Compass is a navigation instrument that measures direction relative to Earth surface

- There are 4 main directions: north, south, east and west

- Principle of operation
  - Magnetic compass – based on y rth’s magnetic field
  - Gyro compass – based on rotation of the Earth

- Traditional types of compass
  - Conventional magnetic compass – uses magnetized pointer
  - Gyro compass – uses rapidly spinning wheel
  - Dry compass – used by mariners in past

- New types of compass
  - Liquid compass – uses liquid to limit swing and wear out
  - GPS compass – based on information from GPS satellites
  - Solid state compass – based on magnetic field sensors e.g. MEMS sensors

LSM303D Applications [1/2]
Where compass is used …

- Consumer
  - E-compass application in hand held devices (Mobile phones, Tablets, Watches, …)
  - Remote controllers for TVs, STBs (Scrolling in the menu, 3D pointer, …)
    - Enhanced pointing
  - Gaming devices (Accessories for PCs, Tablets)
  - Gesture Monitoring

- Key parameters:
  - Price
  - Size 3x3mm or smaller
  - Resolution at least 8 mGauss
  - Power consumption 350uA
    - Acc. 50Hz ODR + Magn. 6Hz ODR

LSM303D Applications [2/2]
Where compass is used …

- Navigation
  - Monitoring and controlling movement of vehical, hand-held device, craft or a person from one place to another
    - Portable and fixed navigation systems
  - Dead reckoning

- Movement and Position detection
  - People, Animals and Goods Monitoring (y erly people monitoring, cow tracking, …)
  - Device special orientation

- Others
  - Mining - Finding direction underground, determining tunnelling
  - Astronomy - Compass used for establishing a local meridian
  - Building orientation – while Building churches and other houses in a prefered direction

- Key parameters:
  - Resolution – lower is better (down to 1 mGauss required)
  - Size (not so critical as for consumer applications)
  - Power consumption – lower is better. Acc. 50Hz ODR + Magn. 6Hz ODR goal is 200uA

E-compass is crucial component for Sensor Fusion Algorithms.

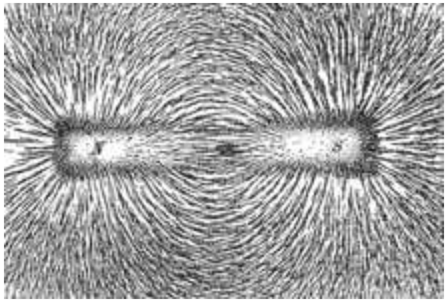
life.augmented

Magnetic Field

- **Magnetic field** is mathematical description of magnetic influence of electric currents and magnetic materials.

- It is specified by vector - direction and magnitude (strength). In literature it is denoted as **B** or **H.**

- Units
  - tesla (T) is SI unit
  - non-SI unit: gauss (G)



Src: http://www.wikipedia.org

1 T =10 000 G

- The **Earth's magnetic** field is about 0.2 to 0.6 G and has a component parallel to the Earth's surface that always points toward the magnetic north pole.

How a magnetic compass works

- **Compass** based on measurement of y arth’s magnetic field points to “**magnetic north**” – the North magnetic pole of the Earth.

- In **navigation**, maps and directions are related to geographical or “**true north**” – the Geographical North Pole**.**

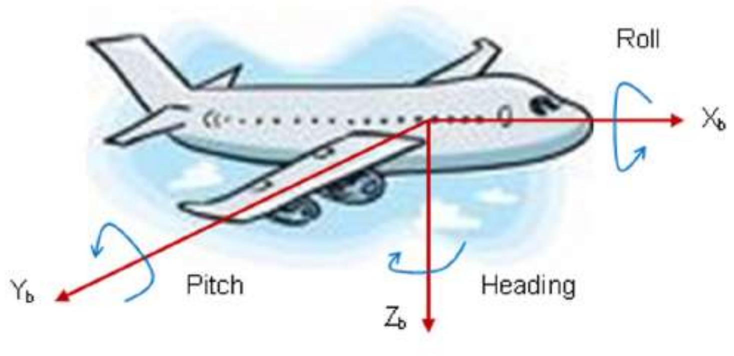
- Magnetic north and true north poles are not at the same location. The angle between directions to the two poles is called **magnetic declination**.

- Magnetic declination is in the range of ± 20º and can vary widely depending on where the compass is placed on y s surface. Lo magnetic declination is given on most maps to allow the map to be orientated with a compass.

- Positions of magnetic poles change over time (i.e. hundreds years ..)

MEMS magnetometer as a compass [1/2]

- Definition of attitude angles: Roll, Pitch and Heading (Yaw)



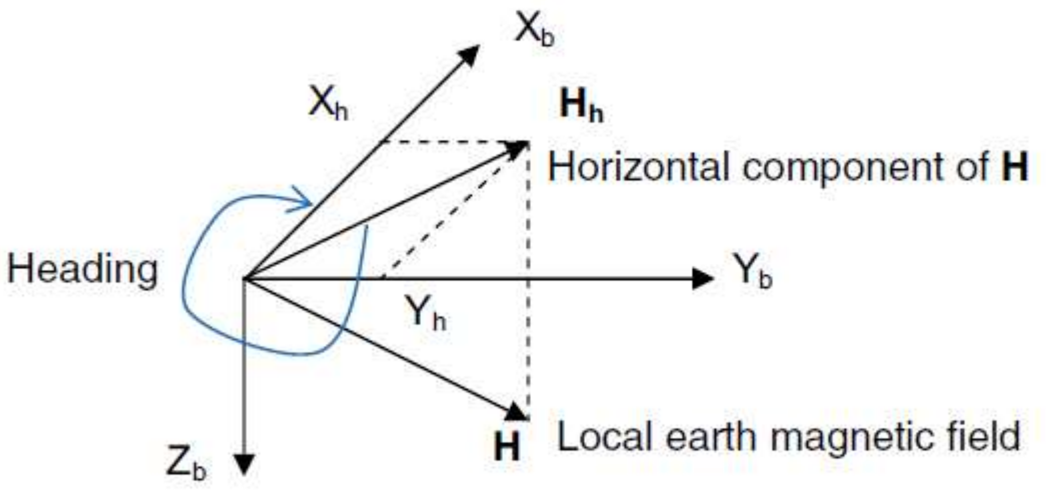
- The information shown by a compass is Heading.
- **Heading** is defined as the angle between the X_b axis and the magnetic north on the horizontal plane measured in a clockwise direction when viewing from the top of the device (or aircraft).

MEMS magnetometer as a compass [2/2]

- Local Earth magnetic field **H** has a fixed component H_h on the horizontal plane pointing to the y magnetic north.

- This component can be measured by the MEMS magnetic sensor sensing axes as X_h and Y_h. Then the heading angle is calculated as:

$$\text{Heading} = \arctan(Y_h / X_h)$$



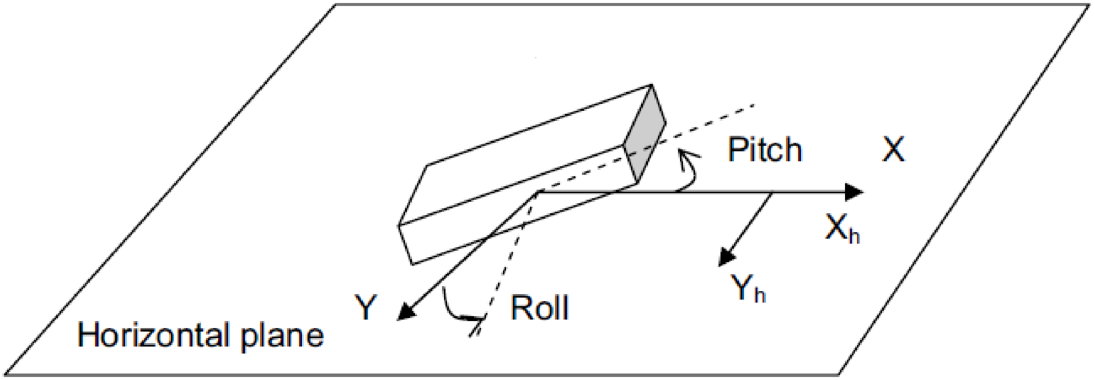
Tilt Compensation using Accelerometer

- **If a device is tilted, then the pitch and roll angles are not equal to 0°**.
- The magnetic sensor measurements XM, YM, and ZM need to be compensated to obtain X_h and Y_h by using accelerometer data.

$$X_h = XM \cdot \cos(Pitch) + ZM \cdot \sin(Pitch)$$

$$Y_h = XM \cdot \sin(Roll) \cdot \sin(Pitch) + YM \cdot \cos(Roll) - ZM \cdot \sin(Roll) \cdot \cos(Pitch)$$

- Compensation using accelerometer works well for tilt in **+/- 50° range**.



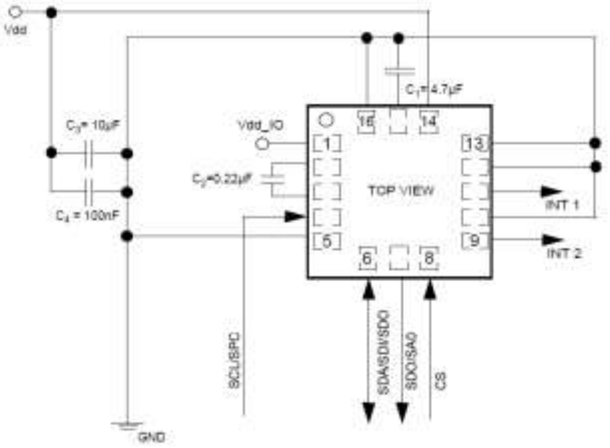
Key parameters for MEMS compass

- Magnetometer range: smaller – better, +/- 1 Gauss or higher
- Magnetometer resolution: higher – better

- The device should embed **accelerometer for tilt compensation**
- Accelerometer resolution: 2mg or better to achieve 0.2deg precision

LSM303D Key Features

Sensor Module: 3-Axis Accelerometer + 3-Axis Magnetometer



APPLICATION

- Compensated Compass
- Location Based Services
- Map Rotation
- Personal Navigation

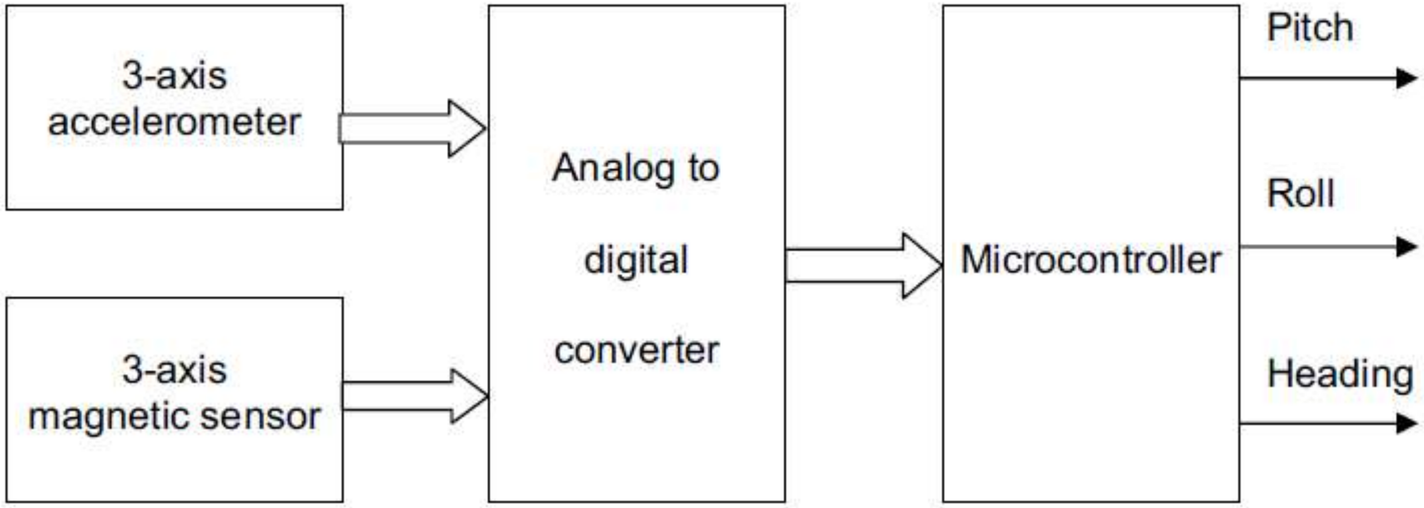
KEY FEATURES

- 3-axis accelerometer and 3-axis magnetometer
- ±2/±4/±8/±12 gauss magnetic field full-scale
- ±2/±4/±8/±16 g accelerometer full-scale
- Low accelerometer noise 150 ug/√Hz
- Low magnetometer noise 5 mgauss/RMS
- Analog supply voltage: 2.16 V to 3.6 V
- Digital supply voltage IOs: 1.71 V to Vdd
- Current consumption 300uA (A+M)
- 16-bit data out, FIFO for accelerometer
- Programmable interrupt generators for free-fall, motion detection and magnetic field detection
- Automatic Set/Reset internal functionality to cancel magnetic interference offset
- 3x3 mm LGA package

KEY ADVANTAGES

- High performance g-sensor with antialiasing filter embedded
- Offset bridge compensation of the magnetometer
- Compensation of the sensitivity drift over temperature for magnetometer
- Low noise, low current consumption

Building MEMS Compass Process



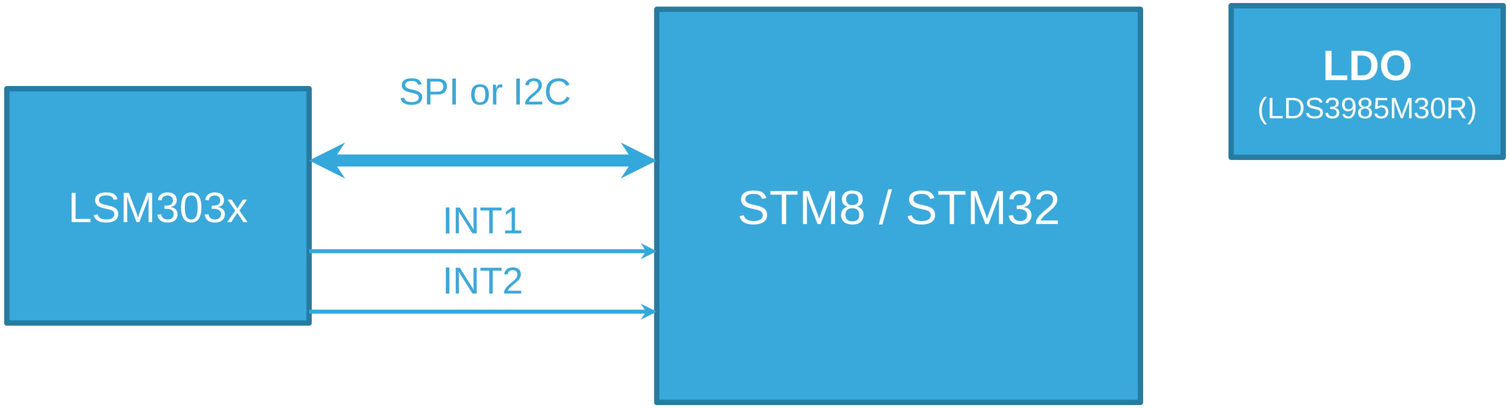
1. **Hardware design** to make sure the MCU can get clean raw data from the accelerometer and the magnetic sensor.
2. **Accelerometer calibration** to obtain parameters to convert accelerometer raw data to normalized values for pitch and roll calculation
3. **Magnetic sensor calibration** to obtain parameters to convert magnetic sensor raw data to normalized values for the heading calculation
4. MCU running **heading computation software**.
5. **Test the performance** of the electronic compass system.

Hardware Design

- Schematic aspects
- PCB design

Schematic Aspects

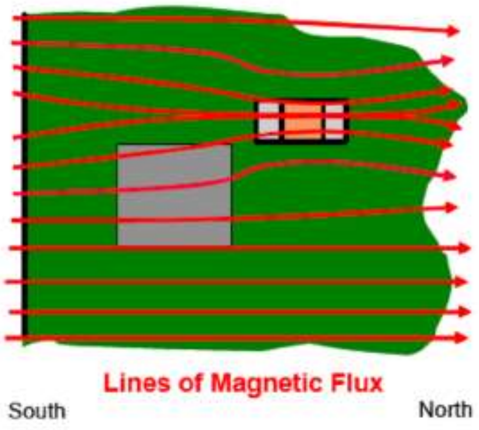
- Power supply
  - Separated VDD and VDD_IO lines (ultra low drop, low noise LDO)
  - Supply voltage range: 2.16 to 3.6V for VDD, VDD_IO 1.71 up to VDD
- 1 or 2 digital serial interfaces are used by ST 6D modules with magnetometer
  - LSM303D:
    - SPI 3-wire(CS, SPC, SDI/O) or 4-wire (CS, SPC, SDI, SDO)
    - I^{2}C (SCL, SSA) with slave address selectable by SA0 pin
    - CS pin is used to select between SPI and I^{2}C
  - LSM303DLxx
    - I^{2}C interface only
- Device setup and data acquisition is done by accessing registers
- INT1 and INT2 interrupts push-pull pins have programmable functionality



PCB Design [1/2]

Compass placement

- **Compass must be located in a magnetically quiet location**, far away from sources that could distort the y magnetic field from flowing cleanly through the circuitry:
  - Magnets
  - Speakers
  - Motors
  - Steel or ferrous metal shields
  - Batteries
  - Surface-mount electronic components containing the ferrous metal nickel: leave a couple od millimeters space between the nickel bearing components and the compass



PCB Design [2/2]

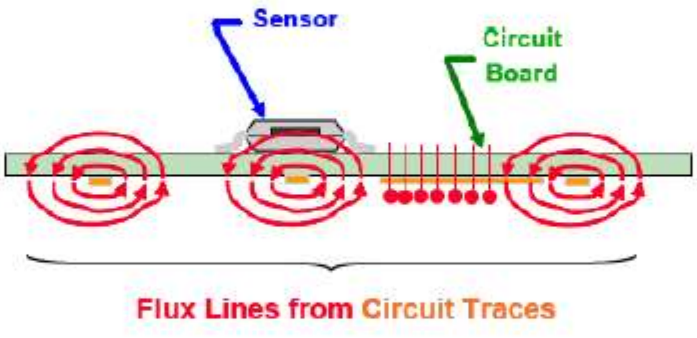
High Current Wiring Effect on Compass

- High currents in wiring and printed circuit traces can be culprits in causing errors in magnetic field measurements for compassing.

- **The magnetic sensors can not discern between y magnetic field and adjacent**.

- Conductor generated magnetic fields will add to y magnetic field making errors in compass heading computation.

- Keep currents higher than 10 mili-amperes a few millimeters further away from the sensor IC.



Embedded Software

- Accelerometer Calibration
- Magnetometer Calibration
- E-compass Application: Heading computation
- Testing the MEMS Compass: Verification of the calibration

Accelerometer Calibration [1/2]

- All ST MEMS **accelerometers are factory calibrated** – it is sufficient for most of the applications

- To reach a heading accuracy of below 2°, an easy calibration procedure is hereafter described.

- After the LSM303x is installed on PCB inside a device, **it is necessary to calibrate the accelerometer** part again by device's manufacturers in order to **determine the offset, the scale factor, and the misalignment** matrix with respect to the device body axes Xb/Yb/Zb.

- After the device is released to the market, **end users don't need to perform further accelerometer calibration** in field.

Accelerometer Calibration [2/2]

- Relationship between the normalized Ax1, Ay1, and Az1 and the accelerometer raw measurements Ax, Ay, and Az:

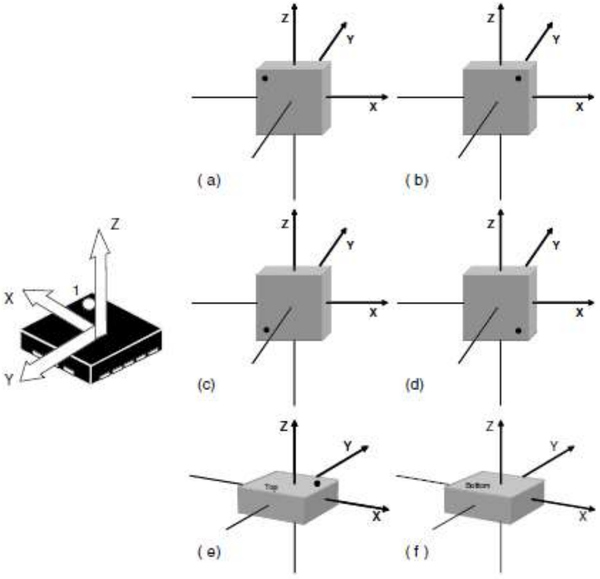
$$\begin{bmatrix} A_{x1} \\ A_{y1} \\ A_{z1} \end{bmatrix} = [A\_m]_{3x3} \begin{bmatrix} 1/A\_SC_x & 0 & 0 \\ 0 & 1/A\_SC_y & 0 \\ 0 & 0 & 1/A\_SC_z \end{bmatrix} \cdot \begin{bmatrix} A_x - A\_OS_x \\ A_y - A\_OS_y \\ A_z - A\_OS_z \end{bmatrix}$$

$$= \begin{bmatrix} ACC_{11} & ACC_{12} & ACC_{13} \\ ACC_{21} & ACC_{22} & ACC_{23} \\ ACC_{31} & ACC_{32} & ACC_{33} \end{bmatrix} \cdot \begin{bmatrix} A_x \\ A_y \\ A_z \end{bmatrix} + \begin{bmatrix} ACC_{10} \\ ACC_{20} \\ ACC_{30} \end{bmatrix}$$

- where [A_m] is a 3x3 misalignment matrix between the accelerometer sensing axes and the device body axes; A_SCi (i = x, y, z) is the scale factor and A_OSi is the offset

- **The goal of the accelerometer calibration is to determine the12 ACCxx parameters**.

- The calibration can be performed at 6 stationary positions:



Magnetometer Calibration Needs

- All **ST magnetometers are calibrated** in ST fab.

- **If no ferrous object** are on the PCB and other SMT devices are **sufficiently distant from the magnetometer, no calibration is necessary**. **<u>This is not the case usually!</u>**

- If ferrous object are close to the magnetometer an **Hard-Iron calibration** is necessary (rotation on the flat plane).

- If SMT devices are close to magnetometer an **Soft-Iron calibration** is necessary (pitch, roll and yaw rotations).

- Definition of terms
  - **Hard-Iron** magnetic materials – ferromagnetic materials with permanent magnetic fields (e.g. magnets, speakers). They are **time invariant.**
  - **Soft-Iron** magnetic materials – the items (e.g. current carrying traces on the PCB, steel shields, batteries or other magnetically soft materials) which can become magnetized and produce time varying magnetic field.

Magnetometer Calibration [1/4]

- The relationship between the normalized Mx1, My1, and Mz1 and the magnetic sensor raw measurements Mx, My, and Mz can be expressed as

$$\begin{bmatrix} M_{x1} \\ M_{y1} \\ M_{z1} \end{bmatrix} = [M\_m]_{3x3} \begin{bmatrix} 1/M\_SC_x & 0 & 0 \\ 0 & 1/M\_SC_y & 0 \\ 0 & 0 & 1/M\_SC_z \end{bmatrix} \cdot [M\_si]_{3x3} \begin{bmatrix} M_x - M\_OS_x \\ M_y - M\_OS_y \\ M_z - M\_OS_z \end{bmatrix}$$

$$= \begin{bmatrix} MR_{11} & MR_{12} & MR_{13} \\ MR_{21} & MR_{22} & MR_{23} \\ MR_{31} & MR_{32} & MR_{33} \end{bmatrix} \cdot \begin{bmatrix} M_x - MR_{10} \\ M_y - MR_{20} \\ M_z - MR_{30} \end{bmatrix}$$

- where [M_m] is a 3x3 misalignment matrix between the magnetic sensor sensing axes and the device body axes; M_SC_i (i = x, y, z) is the scale factor and M_OS_i is the offset caused by hard-iron distortion; [M_si] is a 3x3 matrix caused by soft-iron distortion.

- The goal of the magnetic sensor calibration is to determine the MRxx parameters.

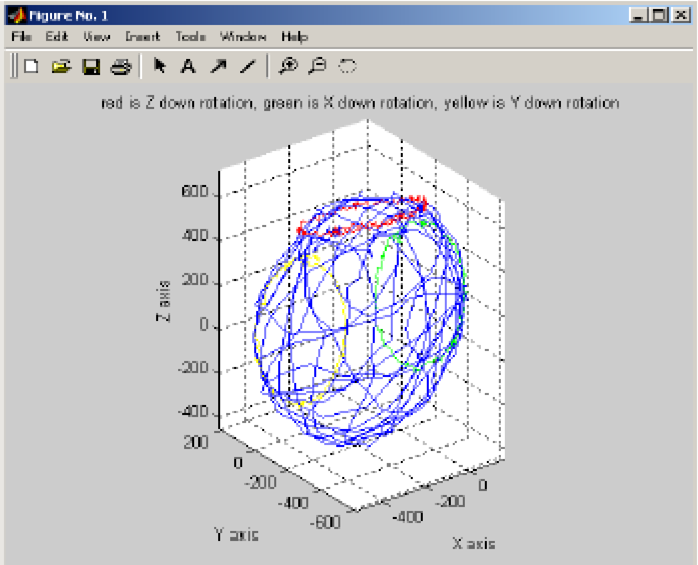
- **There are 3 steps for magnetic sensor calibration**.

Magnetometer Calibration [2/4]

Step 1: Soft-iron effect verification

- **It is always good to know if the device has soft-iron interference before choosing which model for the identification of the calibration parameters**, tilted ellipsoid, or non-tilted ellipsoid. This can be done by performing 3D rotations in a clean environmental area.

- An amount of 3D rotations data can be used for rough field calibration.



red is Z down rotation, green is X down rotation, yellow is Y down rotation

Magnetometer Calibration [3/4]

Step 2: Hard-iron, soft-iron and scale factor compensation

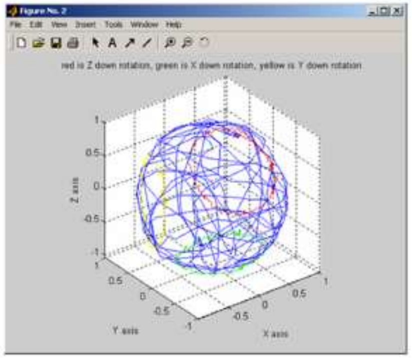
- **If there is soft-iron distortion**, the 3D rotations show a tilt ellipsoid which can be described as the following equation:

$$\frac{(x-x0)^2}{a^2}+\frac{(y-y0)^2}{b^2}+\frac{(z-z0)^2}{c^2}+\frac{(x-x0)(y-y0)}{d^2}+\frac{(x-x0)(z-z0)}{e^2}+\frac{(y-y0)(z-z0)}{f^2}=R^2$$

- where: x0, y0, z0 are the offsets M_OS_i (i = x, y, z) caused by hard-iron distortion; x, y, z are magnetic sensor raw data Mx, My and Mz; a, b, c are the semi-axes lengths; d, e, f are cross axis effect to make the ellipsoid tilted; R is a constant of the y h's magnetic field strength. Least square method based algorithm.

- **If there is no soft-iron distortion** inside the device, or the soft-iron effect is very small and can be ignored, then the ellipsoid from 3D rotations is not tilted. So the soft-iron matrix [M_si] is a 3x3 identity matrix and equation above can be simplified as:

$$\frac{(x-x0)^2}{a^2}+\frac{(y-y0)^2}{b^2}+\frac{(z-z0)^2}{c^2}=R^2$$



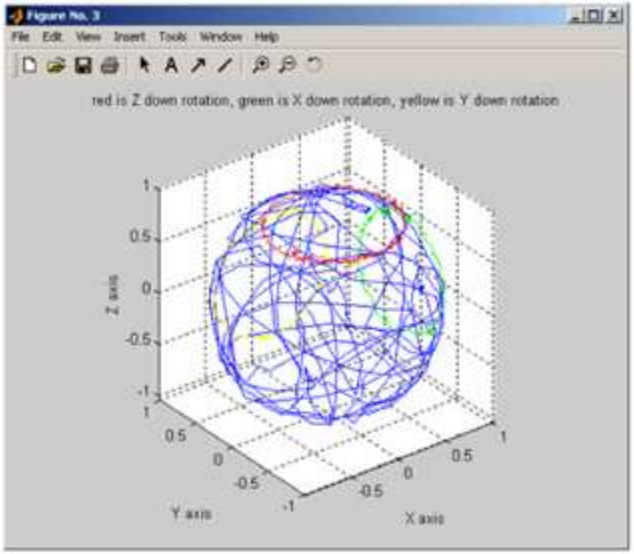
After soft-iron, hard-iron and scale compensations

Magnetometer Calibration [4/4]

Step 3: Misalignment error compensation

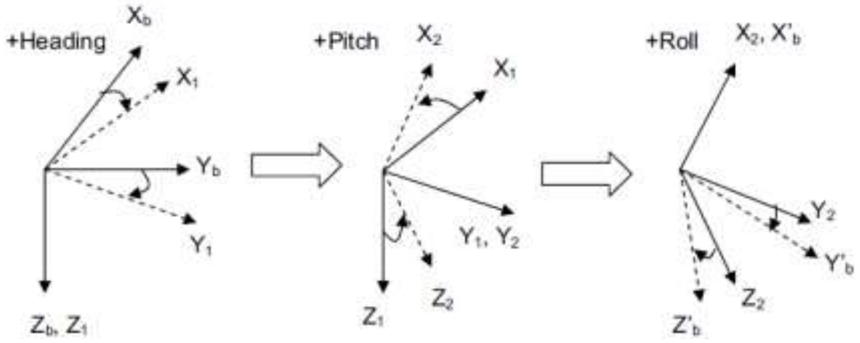
- **Misalignment error compensation is to align the magnetic sensor sensing axes to the device body axes** based on three 2D full round rotations. The vector dot-product method can be used to find each normalized vector that rotates, corrected, three 2D full round rotation circles to their corresponding body axes. The normalized vector means the magnitude is equal to 1.

- Applying the [M_m] 3x3 misalignment matrix to the above unit sphere and three 2D circles, the plot is shown below. Now three 2D full round rotations are aligned to the device body axes. For example, the red color Zb down rotation is parallel to Xb - Yb plane.



After misalignment compensation

E-Compass Application - Heading computation



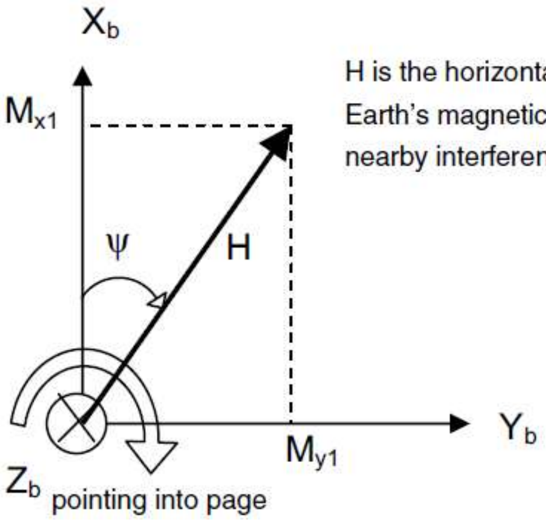
$$\text{Pitch} = \rho = \arcsin(-A_{x1})$$

$$\text{Roll} = \gamma = \arcsin(A_{y1} / \cos\rho)$$

$$|A| = \sqrt{A_{x1}^2 + A_{y1}^2 + A_{z1}^2} \quad \textit{is equal to 1}$$

where Ax1, Ay1, and Az1 are the normalized values after applying accelerometer calibration parameters into Ax, Ay, and Az raw data

For the **heading calculation**, 3-axis magnetic sensor measurements need to be normalized by applying **magnetic sensor calibration parameters** and then reflected onto the horizontal plane by **tilt compensation**:



H is the horizontal component of the Earth's magnetic field together with the nearby interference magnetic field

$$\text{Heading} = \psi = \arctan\left(M_{y2}/M_{x2}\right) \qquad \text{for } M_{x2} > 0 \text{ and } M_{y2} >= 0$$

$$= 180° + \arctan\left(M_{y2}/M_{x2}\right) \quad \text{for } M_{x2} < 0$$

$$= 360° + \arctan\left(M_{y2}/M_{x2}\right) \quad \text{for } M_{x2} > 0 \text{ and } M_{y2} <= 0$$

$$= 90° \qquad \text{for } M_{x2} = 0 \text{ and } M_{y2} < 0$$

$$M_{y2} > 0$$

$$M_{x2} = M_{x1}\cos\rho + M_{z1}\sin\rho$$

$$M_{y2} = M_{x1}\sin\gamma\sin\rho + M_{y1}\cos\gamma - M_{z1}\sin\gamma\cos\rho$$

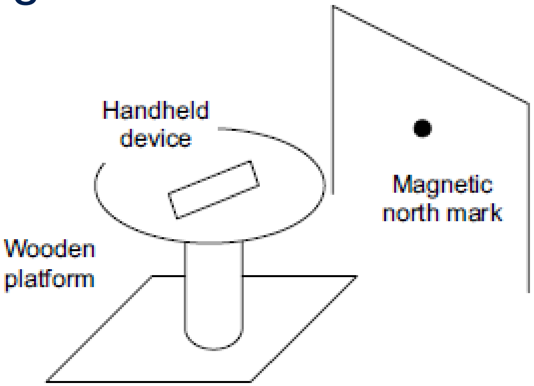
$$M_{z2} = -M_{x1}\cos\gamma\sin\rho + M_{y1}\sin\gamma + M_{z1}\cos\gamma\cos\rho$$

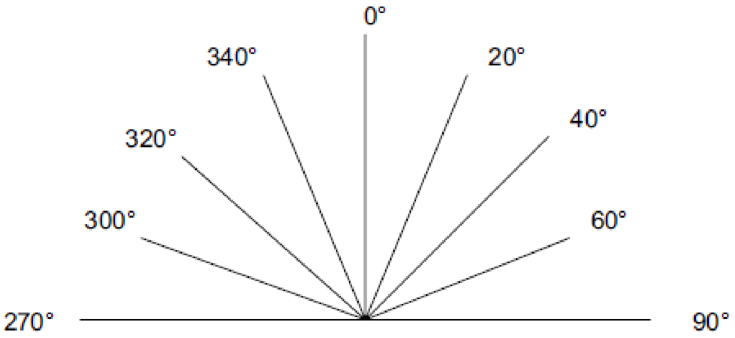
$$|M| = \sqrt{M_{x2}^2 + M_{y2}^2 + M_{z2}^2} \quad \text{should also be equal to 1}$$

where Mx1, My1, and Mz1 are the normalized magnetic sensor measurements after applying calibration parameters

Testing the MEMS Compass

- **After the calibration** parameters for the accelerometer and the magnetic sensor of the LSM303D have been determined, **it is necessary to check the performance of the electronic compass**. This could be carried out with accurate lab testing and rough field testing.





Lab testing

- Convenient setup for accurate lab testing is a wooden platform with 3 degrees of rotation freedom.
- Rotate the wooden platform horizontally clockwise or counterclockwise at a random angle which can be read from the marks on the platform.
- Then compare the compass heading output with the known heading angle.

Field testing

- In any physical situations outside the lab, rough field testing can be performed.
- A wooden table with a smooth surface is required. The surface does not have to be leveled.
- Draw some lines, for example, 20º apart on a white sheet of paper as shown.
- Align the left edge of the device to any line.
- Record the compass heading output value.

Documentation & Support Tools

- Datasheet, Application / Design Notes & Tips
- Evaluation Boards
- PC Graphical User Interface
- Technical Support

ST E-compass SW Libraries

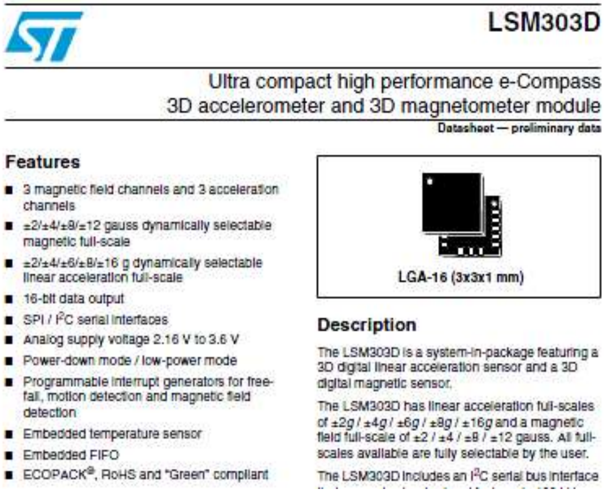
- ST has different SW solutions for tilt compensation and Magnetometer calibration for e-compass

Version	Features	Required Documentation
Tilt Compensation Library	• Needs Accel + Magnetometer data	Evaluation Agreement - LUA
Basic Calibration Library	• Needs only Magnetometer data • Very light at the computational point of view	Evaluation Agreement - LUA
iNEMO Engine Calibration Lite	• Needs only Magnetometer data • Needs less computation power • Calculates HI and SI corrections • It supports two functional mode: 1. Always on calibration (Background Calibration) 2. Triggered Calibration	Evaluation Agreement - LUA
iNEMO Engine Calibration (PRO version)	• Needs complete 9-axis data to Sensor Fusion • Has better performances but needs more resources • Uses Kalman filter theory to determine Offsets and “Gains” • Supports two functional mode: 1. Always on Calibration (Background Calibration) 2. Triggered Calibration	Evaluation Agreement - LUA End User Certificate - EUC

Documentation

http://www.emcu.it/MEMS/MEMS.html

- ST Compasses Product Website
- Application Note AN3192 for tilt-compensated compass implementation
- Technical Note TN0018 on PCB design and **package** surface mounting



LSM303D

Ultra compact high performance e-Compass
3D accelerometer and 3D magnetometer module

Datasheet — preliminary data

Features

- 3 magnetic field channels and 3 acceleration channels
- ±2/±4/±8/±12 gauss dynamically selectable magnetic full-scale
- ±2/±4/±6/±8/±16 g dynamically selectable linear acceleration full-scale
- 16-bit data output
- SPI / I^2C serial interfaces
- Analog supply voltage 2.16 V to 3.6 V
- Power-down mode / low-power mode
- Programmable interrupt generators for free-fall, motion detection and magnetic field detection
- Embedded temperature sensor
- Embedded FIFO
- ECOPACK®, RoHS and "Green" compliant

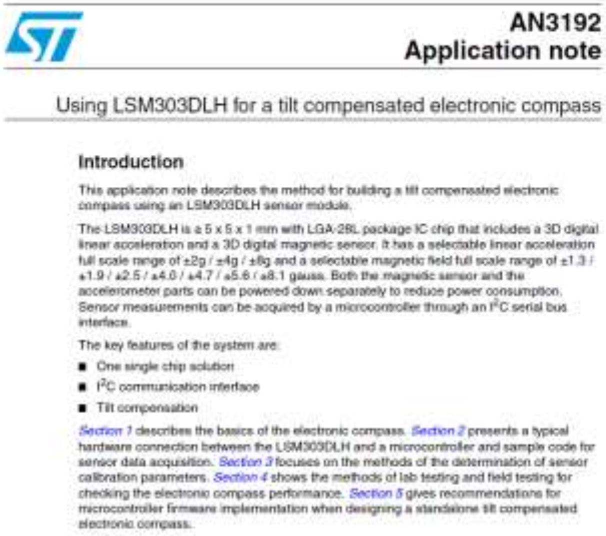
LGA-16 (3x3x1 mm)

Description

The LSM303D is a system-in-package featuring a 3D digital linear acceleration sensor and a 3D digital magnetic sensor.

The LSM303D has linear acceleration full-scales of ±2*g* / ±4*g* / ±6*g* / ±8*g* / ±16*g* and a magnetic field full-scale of ±2 / ±4 / ±8 / ±12 gauss. All full-scales available are fully selectable by the user.

The LSM303D includes an I^2C serial bus interface



AN3192
Application note

Using LSM303DLH for a tilt compensated electronic compass

Introduction

This application note describes the method for building a tilt compensated electronic compass using an LSM303DLH sensor module.

The LSM303DLH is a 5 x 5 x 1 mm with LGA-28L package IC chip that includes a 3D digital linear acceleration and a 3D digital magnetic sensor. It has a selectable linear acceleration full scale range of ±2g / ±4g / ±8g and a selectable magnetic field full scale range of ±1.3 / ±1.9 / ±2.5 / ±4.0 / ±4.7 / ±5.6 / ±8.1 gauss. Both the magnetic sensor and the accelerometer parts can be powered down separately to reduce power consumption. Sensor measurements can be acquired by a microcontroller through an I^2C serial bus interface.

The key features of the system are:

- One single chip solution
- I^2C communication interface
- Tilt compensation

Section 1 describes the basics of the electronic compass. *Section 2* presents a typical hardware connection between the LSM303DLH and a microcontroller and sample code for sensor data acquisition. *Section 3* focuses on the methods of the determination of sensor calibration parameters. *Section 4* shows the methods of lab testing and field testing for checking the electronic compass performance. *Section 5* gives recommendations for microcontroller firmware implementation when designing a standalone tilt compensated electronic compass.

Evaluation boards

STEVAL-MKI109V2

STM32-based MEMS motherboard compatible with ST MEMS adapters

- Firmware upgrades are possible via DFU
- Source codes available including low level drivers for STM32

Daughter boards available:

LSM303D
STEVAL-MKI133V1

LSM303DLHC
STEVAL-MKI106V1

Note: **Schematics** and **Gerber** files are available under evaluation boards webpages in internet

STM32F3 – Discovery Kit

New Discovery STM32 (M4) kit which embed 9-axis sensors:

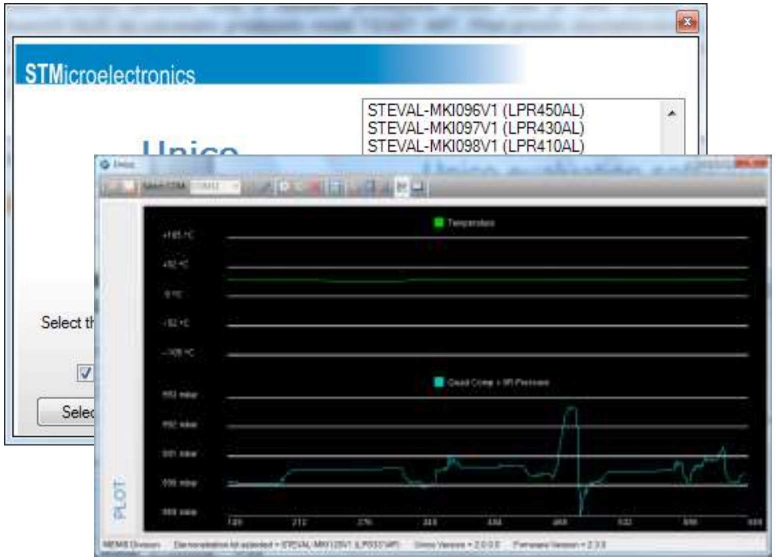
- **LSM303DLHC**
- **L3GD20**

Including **source codes** for a **compass.**

STM32F3DISCOVERY Web
Click to download

Unico Evaluation software

- **Unico** is Graphical User Interface (GUI) **for PC** (Windows based)
- Designated to be used with STEVAL-MKI109V2 and any MEMS adapter board
- Connection
  - USB
  - Bluetooth – with STEVAL-MKI132V1
- Compass in Unico
  - Register setup
  - Accelerometer and magnetometer data reading
  - Compass implemented in PC GUI



STEVAL-MKI096V1 (LPR450AL)
STEVAL-MKI097V1 (LPR430AL)
STEVAL-MKI098V1 (LPR410AL)

SOFTWARE PACKAGE
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  - Product and Application problems – answering detailed technical questions
- Providing
  - Design consulting (Schematic, PCB and Software)
  - Technical Trainings

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