THE PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA

Ministry of Higher Education and Scientific Research

Ecole Nationale Polytechnique

المدرسة الوطنية المتعددة التقنيات
Ecole Nationale Polytechnique

Electronics Department

Master report

in the fullfillment of the requirements for the Master degree in Electronics Engineering

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MATLAB-based Method for Magnetometer Calibration

Mouaadh KELLAL

Supervised by
Dr. Rabah SADOUN

Publicly presented and discussed on 18/06/2016

Jury members

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ملخص

المستشعرات المغناطيسية جزء أساسي من أي نظام مرجعي لتحديد حركة و اتجاه الأجسام. وصول تقنية جهزة الاستشعار. MEMS المنخفضة التكلفة جعل من استعمالها أكثر انتشارا من أي وقت مضى، انطلاقا من تطبيقات في الطائرات بدون طيار للهواة و وصولا إلى تطبيقات في مجال صناعة المركبات.

أغلب المستشعرات المغناطيسية منخفضة التكلفة المتوفرة في السوق هي ذات جودة استهلاكية. هذا يجعل الحاجة إلى طريقة بسيطة للمعايرة أكثر إلحاحا خاصة و أن المعايرة تمثل تقدم خيارا للتوفيق بين السعر المتدني و دقة المعطيات.

في هذه المذكرة نقدم طريقة لمعايرة المستشعرات المغناطيسية باستعمال MATLAB و نناقشها، مع عرض النتائج التجريبية و التطبيقات الممكنة.

الكلمات المفتاحية : مستشعر مغناطيسي، معايرة، MATLAB ، مستشعر MEMS ، المحيط المغناطيسي.

Résumé

Les magnétomètres sont des composants essentiels de n'importe quel système de référence d'attitude et de cap. L'arrivée de la technologie de capteurs MEMS à bas coût permettait l'utilisation répandu des magnétomètres dans diverses applications allant des drones amateurs à l'industrie automobile.

La majorité des magnétomètres MEMS à bas coût disponibles sur le marché sont des capteurs de bas de gamme. Cela rend le besoin d'une méthode simple de calibration plus pertinant car elle offre un compromis entre le prix et précision.

Dans ce mémoire, une méthode de calibration de magnétomètre sur MATLAB est proposée et discutée, ainsi que les données expérimentales et les applications possibles de cette méthode.

Mots clés : Magnétomètre, calibration, MATLAB, Capteur MEMS, environnement magnétique.

Abstract

Magnetometers are essential components of any reliable Attitude and Heading Reference System. The advent of low-cost MEMS based sensor technology made their use more widespread than ever with applications ranging from hobbyist drones to automotive industry.

Most low-cost MEMS magnetometers available on the market fall into consumer grade sensors. This makes the need for simple calibration techniques more relevant as it provides a means of trading cost for improved performance and accuracy.

In this thesis, a MATLAB-based method for magnetometer calibration is proposed and discussed along with experimental data and possible applications.

Key words : Magnetometer, calibration, MATLAB, MEMS sensor, magnetic environment.

Contents

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Introduction

Magnetometers are used for a wide range of industrial and scientific applications. Nowadays, most consumer sensors are low-cost MEMS based sensors. These sensor offer a great advantage in terms of cost compared with their high end counterparts. As a trade off between price and performance is often expected, these sensors prove less precise than high end sensors and require, therefore, special handling to improve their performance.

With the absence of factory calibration in low-cost MEMS-based magnetometer, simple and reliable methods of calibration are more relevant than ever.

A simple MATLAB-based calibration method is presented and discussed in this thesis. Necessary notions are also introduced along with experimental data.

This work encompasses 8 chapters including the conclusion. In chapter 2, the notion of sensor calibration is presented and discussed along with its purpose. Sources of errors in sensor measurements are also listed.

MEMS sensors, IMUs and magnetometers are introduced in chapter 3. Magnetometers' operating principle is detailed.

Chapter 4 will provide general information about the earth magnetic field and explain the underlying causes of magnetic disturbances.

In chapter 5, the hardware and software used in the calibration system design is presented and detailed. This chapter will also discuss the data logging process.

Chapter 6 will clarify the calibration procedure and detail the MATLAB routines utilized in this application.

An experimental scenario is attempted in chapter 7 and numerical data are presented.

The different components of this work are summarized in the conclusion. The outlook of this work and suggested fields of application are also discussed.

Chapter 1

Sensor calibration and error sources

1.1 Introduction

In this chapter, we will define sensor calibration and discuss its purpose. The sources of error in measurements are also listed in general.

1.2 Sensor calibration

1.2.1 Definition of calibration

The formal definition of calibration by the International Bureau of Weights and Measures is the following: "Operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties (of the calibrated instrument or secondary standard) and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication. [1]

1.2.2 Sensor calibration

Sensor calibration is a method of improving sensor performance by removing structural errors in the sensor outputs. Structural errors are differences between a sensors expected output and its measured output, which show up consistently every time a new measurement is taken.

Any of these errors that are repeatable can be calculated during calibration, so that during actual end-use the measurements made by the sensor can be compensated in real-time to digitally remove any errors. Calibration presents a means of providing enhanced performance by improving the overall accuracy of the underlying sensors [2].

1.3 Purpose of calibration

A device that has been calibrated is able to measure in the scale most appropriate for the job, so the information is reliable. The use of the proper units in calibration assures that the instrument is measuring what is intended.

Calibration is essential for guaranteeing that measurements are consistent in several ways. When making decisions, it is important to know that information is dependable even when it is collected over a period of time or by different operators. Also, location should not impact measurement readings, so calibrations are needed to ensure consistency among different geographic areas.

Once an instrument is calibrated, it must be cared for in order to retain that calibration. For example, it should not be exposed to environmental conditions for which it was not designed. Also, the device should be monitored to make certain the calibration remains steady [3].

Magnetometers are especially prone to errors as they're very sensitive to local variations in earth magnetic field. The importance of magnetometer calibration is more apparent when magnetic measurements are used along other measurements as a reference. Such is the case of Attitude and Heading Reference Systems that use magnetometers as a means of boosting the systems ability to estimate orientation parameters.

1.3.1 Approaches of calibration

Sensors can be calibrated using two approaches:

Comparing against a reference sensor This approach is based on comparing output values of the sensor that is to be calibrated against a reference sensor. Reference sensors (or standards) are sophisticated, factory calibrated sensors. They are regularly maintained to ensure that their output values are as close as possible to the true value of the measured physical quantity.

The difference between the sensor value and the standard value is then subtracted from the sensor value to align it with the standard.

Single sensor calibration This approach does not require any standard sensor for the uncalibrated sensor to be compared against. It relies on assumptions that the physical quantity measured by the sensor should respect certain conditions (Symmetry in space, mean value,etc...). The sensor output values are then adjusted to fit the assumed criteria.

In this document, the proposed calibration method is a single sensor calibration approach. It relies on certain properties of earth magnetic field that are detailed in Chapter 3.

1.4 Sources of errors in measurement systems

Definition of error Measurement error is defined as the difference between the distorted information and the undistorted information about a measured product, expressed in its measurands. In short, an error is defined as the real value at the output of a measurement system minus ideal value at the input of a measurement system.

$$\Delta = x_r - r_i$$

where Δ is the error of measurement, x_r is the real untrue measurement value, and x_i is the ideal true measurement value.

A measurement under ideal conditions has no errors. Real measurement results, however, will always contain measurement errors of varying magnitudes. A systematic (clearly defined process) and systemic (all encompassing) approach is needed to identify every source of error that can arise in a given measuring system. It is then necessary to decide their magnitude and impact on the prevailing operational conditions.

1.4.1 Types of errors

Systematic error (bias) is a permanent deflection in the same direction from the true value. It can be corrected. Bias and long-term variability are controlled by monitoring measurements against a check standard over time.

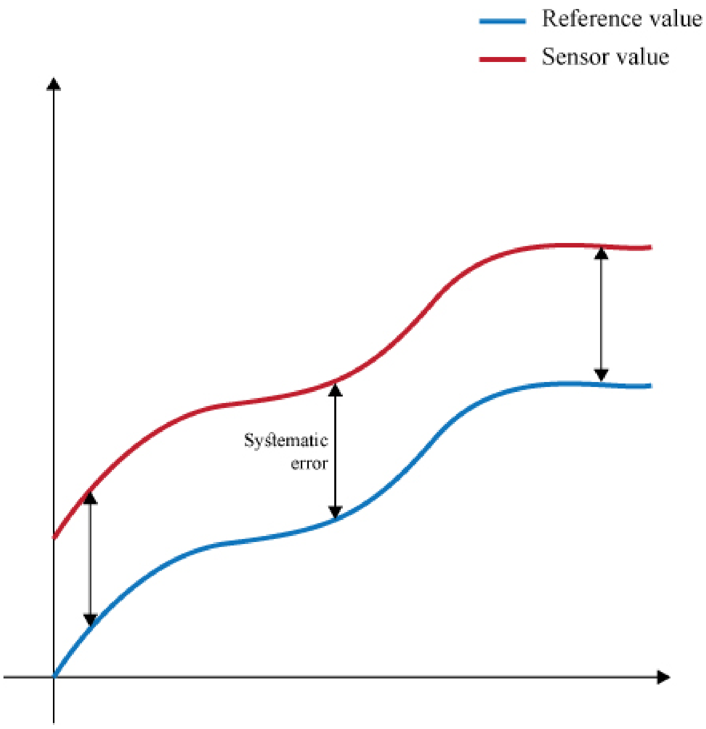


Figure 1.1: Systematic error

Random error is a short-term scattering of values around a mean value. It cannot be corrected on an individual measurement basis. Random errors are expressed by statistical methods.

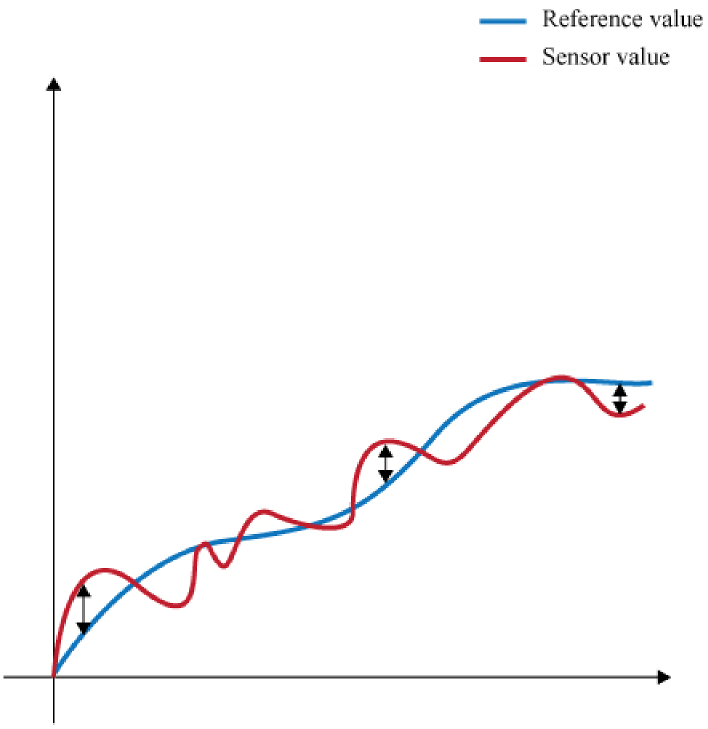


Figure 1.2: Random error

1.4.2 Error sources

Systematic errors or bias are repeatable errors existing with the specified source; these can be adjusted out or compensated for. The terms ‘bias’ and ‘systematic error’ have the same meaning. Bias is defined in the International Vocabulary of Metrology, VIM, as the difference between the measurement result and its unknown ‘true value’. It can often be estimated and/or eliminated by calibration to a reference standard

1.4.2.1 Lack of resolution

Resolution is the ability of the measurement system to detect and faithfully indicate small enough changes in the characteristic of the measurement result.

1.4.2.2 Lack of linearity

A test of linearity starts by establishing a plot of the measured values versus corresponding values of the reference standards. This obtains an indication of whether or not the points fall on a straight line with slope equal to 1, which indicates linearity.

Non-linearities of sensors can be caused by the following facts:

- sensor is not properly calibrated at the lower and upper ends of the operating range,
- errors in the values at the maximum or minimum range,
- worn sensor,
- internal design problems (in, say the electronic units of the sensor).

1.4.2.3 Hysteresis

Hysteresis is a retardation of the effect when the forces acting upon a body are changed (as in viscosity or internal friction); for example, a lagging in the values of resulting magnetization in a magnetic material (as iron) because of a changing magnetizing force. Hysteresis represents the history dependence of a physical system under real environmental conditions [4].

1.5 Conclusion

This chapter introduced the fundamental notions involved in calibration. These notions help to recognize our calibration problem and categorize it.

The proposed magnetometer calibration method corrects only the systematic errors that a magnetometer may suffer from. It is a single sensor calibration technique as there is no need for any standard to compare with.

Chapter 2

Magnetometers and IMU

2.1 Introduction

Magnetometers are one of the many types of sensors available. Most magnetometers are nowadays based on MEMS technology.

Magnetometers are often used for Attitude and Heading Reference Systems as part of Inertial Measurement Units.

In this chapter, MEMS sensors are presented in general. Inertial Measurement Units are introduced along with their applications. Finally, the inner workings of magnetometer sensors are explained in detail.

2.2 MEMS technology

Micro-Electro-Mechanical Systems, or MEMS, is a technology that in its most general form can be defined as miniaturized mechanical and electro-mechanical elements (i.e., devices and structures) that are made using the techniques of microfabrication. The critical physical dimensions of MEMS devices can vary from well below one micron on the lower end of the dimensional spectrum, all the way to several millimeters.

Likewise, the types of MEMS devices can vary from relatively simple structures having no moving elements, to extremely complex electromechanical systems with multiple moving elements under the control of integrated microelectronics. The one main criterion of MEMS is that there are at least some elements having some sort of mechanical functionality whether or not these elements can move.

While the functional elements of MEMS are miniaturized structures, sensors, actuators, and microelectronics, the most notable (and perhaps most interesting) elements are the microsensors and microactuators. Microsensors and microactuators are appropriately categorized as “transducers”, which are defined as devices that convert energy from one form to another. In the case of microsensors, the device typically converts a measured mechanical signal into an electrical signal [5].

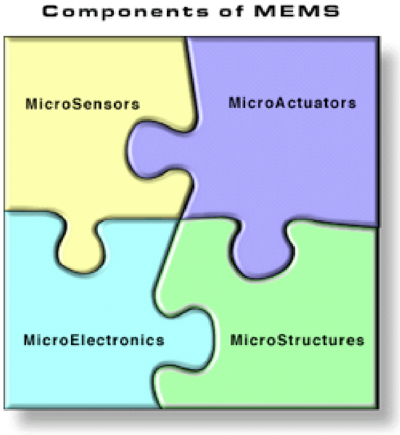


Figure 2.1: Components of MEMS

Motion sensing has been one of the first applications to embrace MEMS Based technology thanks to their small size and reliable performance. MEMS sensors for motion sensing are often packaged in one unit known as Inertial Measurement Unit.

2.3 Inertial Measurement Unit

An inertial measurement unit (IMU) is an electronic device that measures and reports a body's specific force, angular rate, and sometimes the magnetic field surrounding the body, using a combination of accelerometers and gyroscopes with respect to a local frame of reference, sometimes also magnetometers. IMUs are typically used to maneuver aircraft, including unmanned aerial vehicles (UAVs), among many others, and spacecraft, including satellites and landers [6].

An inertial measurement unit works by detecting the current rate of acceleration using one or more accelerometers, and detects changes in rotational attributes like pitch, roll and yaw using one or more gyroscopes. And some also include a magnetometer, mostly to assist calibration against orientation drift.

Inertial navigation systems contain IMUs which have angular and linear accelerometers (for changes in position); some IMUs include a magnetic element (for maintaining an absolute angular reference).

Angular accelerometers measure how the vehicle is rotating in space. Generally, there is at least one sensor for each of the three axes: pitch (nose up and down), yaw (nose left and right) and roll (clockwise or counter-clockwise from the cockpit).

Linear accelerometers measure non-gravitational accelerations of the vehicle. Since it can move in three axes (up & down, left & right, forward & back), there is a linear accelerometer for each axis.

2.3.1 Accelerometers

MEMS-based accelerometers are available with different technologies. The most common are based on capacitors.

MEMS-based accelerometer with capacitors is typically a structure that uses two capacitors formed by a moveable plate held between two fixed plates (figure 2.3). Under zero net force the two capacitors are equal but a change in force will cause the moveable plate to shift closer to one of the fixed plates, increasing the capacitance, and further away from the other fixed reducing that capacitance. This difference in capacitance is detected and amplified to produce a voltage proportional to the acceleration. The dimensions of the structure are of the order of microns [7].

(a) Xsens MTi - High end IMU (b) MPU-9250 - Low-cost IMU

Figure 2.2: Examples of MEMS IMU

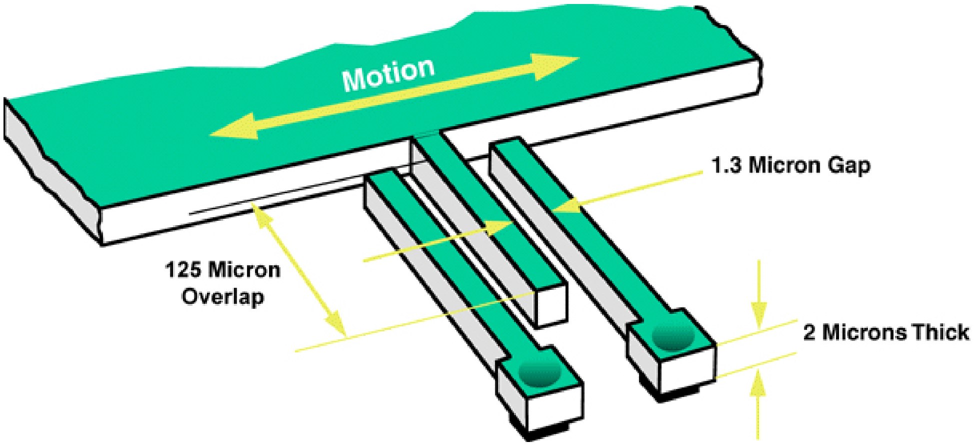


Figure 2.3: Working principle of capacitive accelerometers

2.3.2 Gyroscopes

To fully describe the motion of a body in 3-D space, rotational motion as well as translational motion must be measured. Sensors which measure angular rates with respect to an inertial frame of reference are called gyroscopes. If the angular rates are mathematically integrated this will provide the change in angle with respect to an initial reference angle. Traditionally, these rotational measurements are made using the angular momentum of a spinning rotor.

MEMS gyroscopes however encompass a vibrating element that relies on the principle of conservation of motion to detect changes in angular rate.

One of the many classes is tuning fork gyroscopes. it contain a pair of masses that are driven to oscillate with equal amplitude but in opposite directions. When rotated, the Coriolis force creates an orthogonal vibration that can be sensed by a variety of mechanisms.

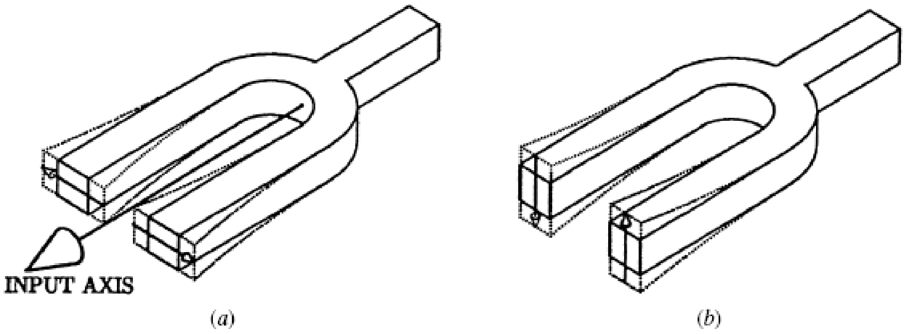


Figure 2.4: Working principle of Vibratory Coriolis Gyroscopes (a) input mode, (b) output mode

2.3.3 Magnetometers

Magnetometers will be explained in greater details in the following section.

2.4 Magnetometers

A MEMS-based magnetometer or magnetic field sensor is a small-scale microelectromechanical (MEMS) device for detecting and measuring magnetic fields. Many of these operate by detecting effects of the Lorentz force: a change in voltage or resonant frequency may be measured electronically, or a mechanical displacement may be measured optically.

2.4.1 Working principle

Several magnetic sensing approaches are used by magnetometer manufacturers, but there are essentially four methods, each with its own pros and cons. These include Hall effect, giant magnetoresistance (GMR), magnetic tunneling junction (MTJ) sensing, and anisotropic magnetoresistance (AMR).

2.4.1.1 Hall effect

The most common magnetometer method is the Hall effect method. It works on the principle that a voltage can be detected across a thin metallic element, when the element is placed in a strong magnetic field perpendicular to the element's plane (Figure 2.5).The detected voltage is referred to as the Hall voltage.

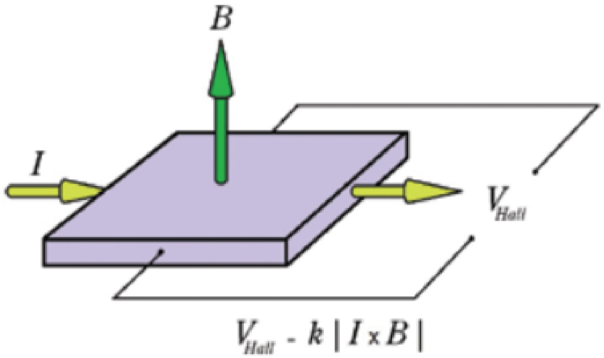


Figure 2.5: The Hall effect

The Hall-effect method has some drawbacks. Compared to other methods, it produces a smaller output signal and has comparatively low sensitivity and temperature stability. But it is relatively small in size, dissipates little power, and is low cost. A Hall effect magnetometer's sensitivity can be increased with a magnetic-flux concentrator, but this increases the overall footprint of the sensor. The concentrator also introduces potential nonlinearity and hysteresis effects, and reduces usable magnetic field range.

2.4.1.2 Giant magneto-resistance

The GMR effect discovered in the late 1980s is actually a quantum effect. GMR sensors utilize the quantum nature of electrons that have two spin states, up and down. Conducting electrons with spin direction parallel to the sensor film's magnetic orientation move easily and thus produce low electrical resistance. In its simplest form, GMR is achieved by using four-layer structure that consists of two thin-film ferromagnets separated by a conductor. The fourth layer is an antiferromagnetic field that is used to pin or inhibit the rotation of the magnetization of the ferromagnetic layers. This structure is essentially a spin valve (Figure 2.6).

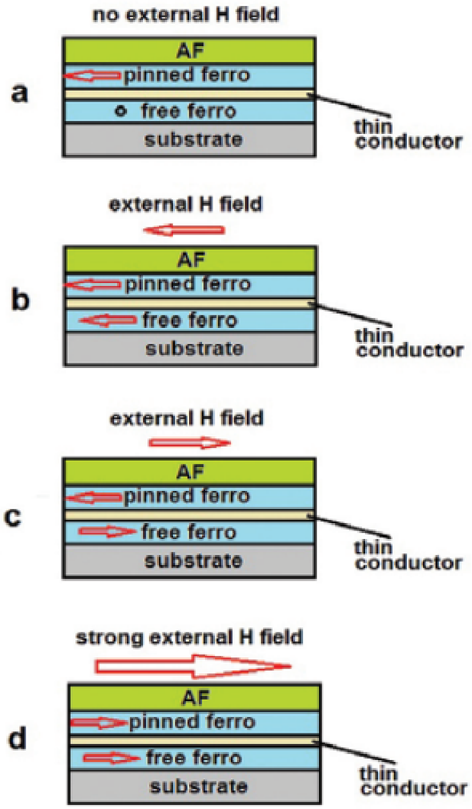


Figure 2.6: The GMR effect

In a GMR spin valve, when H = 0, the magnetization of the free ferromagnetic layer is perpendicular to the magnetization of the pinned ferromagnet and R = R(0) (a). When H is parallel to the magnetization of the pinned ferromagnet, a low-resistant state results and R <R(0) (b). When H is directed opposite to the magnetization of the pinned ferromagnet, a high-resistant state results and R> R(0) (c). Making H large enough unpins the pinned ferromagnet and R <R(0) (d).

GMR magnetometer sensors exhibit high sensitivity levels, produce large signals, are highly temperature-stable, and are physically small in size. They're also said to be low in power dissipation [8].

2.4.1.3 Lorentz force

This type of sensor relies on the mechanical motion of the MEMS structure due to the Lorentz force acting on the current-carrying conductor in the magnetic field (figure 2.7).

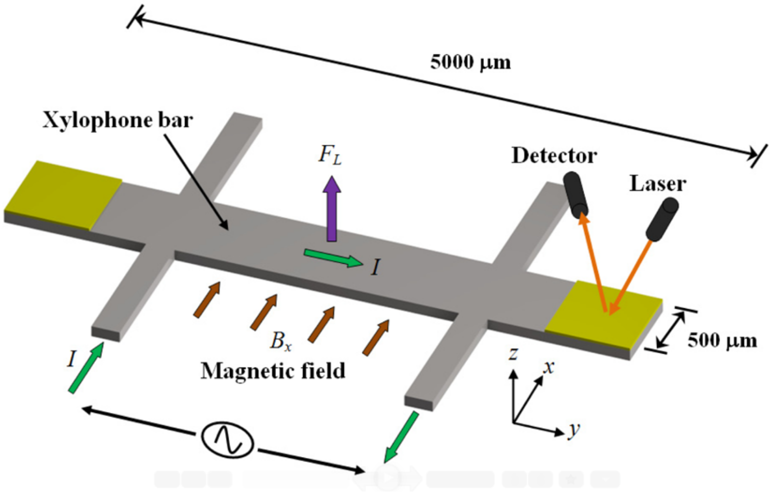


Figure 2.7: Lorentz force magnetometer with optical detection

The mechanical motion of the micro-structure is sensed either electronically or optically. The mechanical structure is often driven to its resonance in order to obtain the maximum output signal. Piezoresistive and electrostatic transduction methods can be used in the electronic detection. Displacement measurement with laser source or LED source can also be used in the optical detection [9].

2.4.2 Applications

Magnetometers are used in a wide range of industrial and scientific applications, including:

- Military applications
- Defense and aerospace
- Oil and gas exploration
- Health care monitoring, etc...

Perhaps one of the most widespread use of magnetometers is in AHRS (Attitude and Heading Reference Systems). They are used besides accelerometers and gyroscopes as part of an IMU with the purpose of providing a reliable means of orientation estimation. Magnetometers are specifically used to mitigate yaw drift.

2.5 Conclusion

This chapter presented MEMS based sensors, more specifically those that make IMUs. Magnetometers were detailed, with their working principles and applications.

In this work, magnetometers are discussed in the context of IMUs, specifically for AHRS as a main application. In this context, magnetometers are used to detect earth magnetic fields for the purpose of drift cancellation. These magnetometers are therefore 3D magnetometers.

Chapter 3

Earth's magnetic field and magnetic distortion

3.1 Introduction

In the context of this thesis, magnetometers are primarily used for the purpose of earth magnetic field detection.

This chapter is to introduce earth magnetic field and explain its underlying causes. It will also discuss the sources of local magnetic field distortions and disturbances.

3.2 Earth's magnetic field

The Earth's magnetic field is similar to that of a bar magnet tilted 11 degrees from the spin axis of the Earth. The problem with that picture is that the Curie temperature of iron is about 770 C . The Earth's core is hotter than that and therefore not magnetic. So this could not be the reason for the Earth's magnetic field.

Magnetic fields surround electric currents, so a reasonable explanation would be that circulating electric currents in the Earth's molten metallic core are the origin of the magnetic field. A current loop gives a field similar to that of the earth. The magnetic field magnitude measured at the surface of the Earth is about half a Gauss and dips toward the Earth in the northern hemisphere. The magnitude varies over the surface of the Earth in the range 0.3 to 0.6 Gauss.

The Earth's magnetic field is attributed to a dynamo effect of circulating electric current, but it is not constant in direction. Rock specimens of different age in similar locations have different directions of permanent magnetization. Evidence for 171 magnetic field reversals during the past 71 million years has been reported.

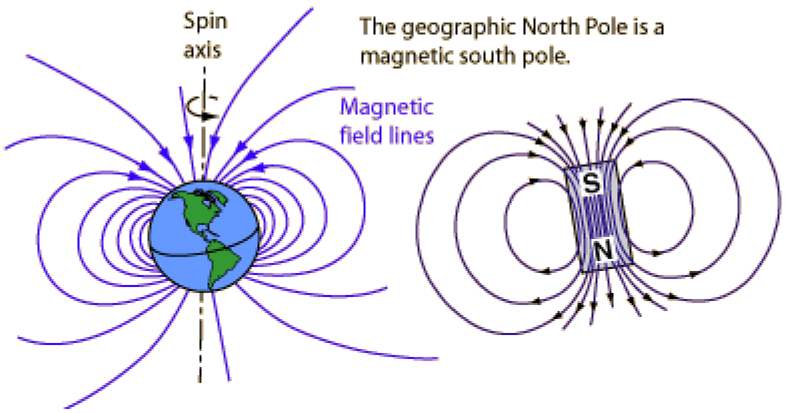


Figure 3.1: Earth's magnetic field

Interaction of the terrestrial magnetic field with particles from the solar wind sets up the conditions for the aurora phenomena near the poles [10].

On a local scale, Earth's magnetic field can be represented by a vector of a constant amplitude and direction.

3.3 Distortion of magnetic field

Distortions of the earth's magnetic field are a result of external magnetic influences generally classified as either a hard- or soft-iron effect. If no distorting effects are present, rotating a magnetometer through a minimum of 360° around two perpendicular axes and plotting the resulting data as y,z axes vs. x axis will result in a sphere centered around (0, 0, 0).

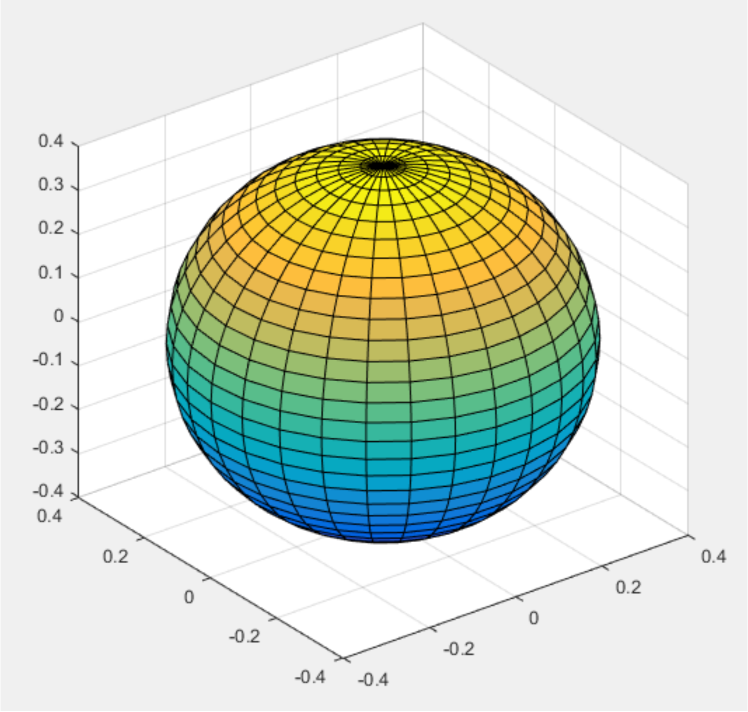


Figure 3.2: Sphere centered at (0, 0, 0)

However, the presence of hard- and/or soft-iron effects may produce a perturbation of the circle as a simple offset from (0, 0) in the case of a hard-iron effect, or deform the circle to produce an ellipse in the case of a soft-iron effect. It is also possible that both effects will be exhibited simultaneously.

It is also important to recognize that effective compensation of hard- and soft-iron distortions is dependent upon the distorting material(s) rotating/moving with the sensor. An example would be mounting the sensor in an aircraft; any materials that are part of the aircraft that exhibit a distorting effect would move as the aircraft and mounted sensor move, and it would generally be possible to compensate for the associated hard- and soft-iron effects. In contrast, it is much more difficult—if not impossible—to compensate for distorting effects exhibited by material external to the aircraft/sensor platform. Thus, it is important to understand not only how compensation may be applied, but also to recognize those conditions under which effective compensation techniques are not possible.

3.3.0.1 Hard-Iron Distortion

Hard-iron distortion is produced by materials that exhibit a constant, additive field to the earth's magnetic field, thereby generating a constant additive value to the output of each of the magnetometer axes. A speaker magnet, for example, will produce a hard-iron distortion. As long as the orientation and position of the magnet relative to the sensor is constant the field and associated offsets will also be constant. A hard-iron distortion can be visibly identified by an offset of the origin of the ideal sphere from (0, 0, 0).

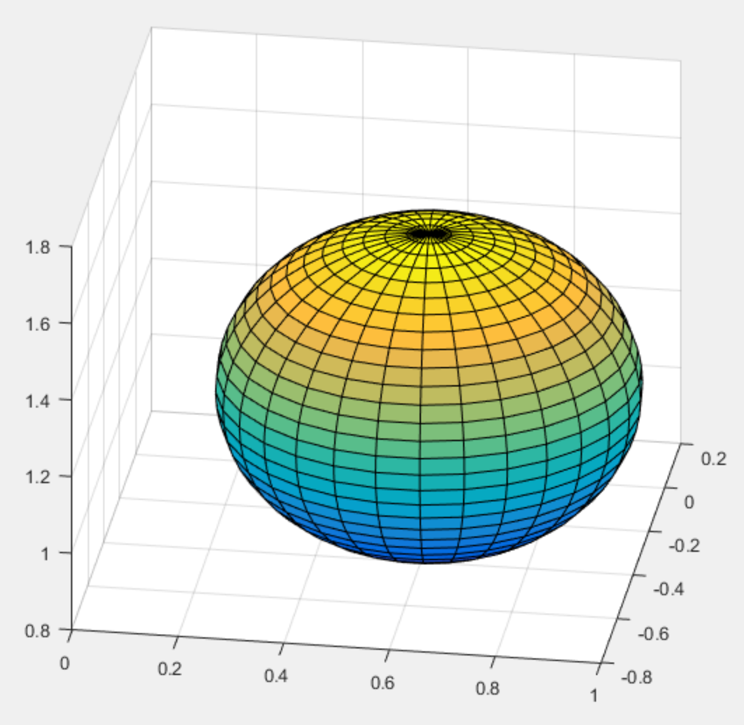


Figure 3.3: Hard-iron distortion effect

3.3.0.2 Soft-Iron Distortion

Unlike hard-iron distortion where the magnetic field is additive to the earth's field, soft-iron distortion is the result of material that influences, or distorts, a magnetic field—but does not necessarily generate a magnetic field itself, and is therefore not additive. Iron and nickel, for example, will generate a soft-iron distortion. While hard-iron distortion is constant regardless of orientation, the distortion produced by soft-iron materials is dependent upon the orientation of the material relative to the sensor and the magnetic field.

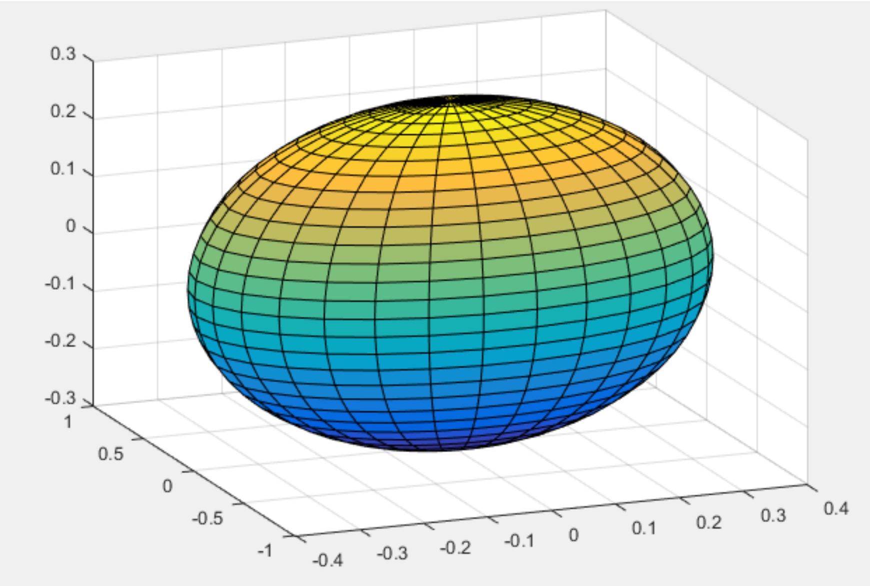


Figure 3.4: Soft-iron distortion effect

3.4 Conclusion

In this chapter, we saw that a magnetometer measuring Earth's magnetic field can be subject to distortions from different sources.

The aim of this thesis is to compensate for the above mentioned hard-iron and soft-iron distortions.

In the next chapter, the data-logging system will be presented.

Chapter 4

Data-logging system setup

4.1 Introduction

A data logging system has been developed to collect magnetic data from the magnetometer that is to be calibrated. This system is based on an ARM Mbed microcontroller that plays the role of an interface between the sensor and the data logging application running on a PC.

4.2 System architecture

The role of the data logging system is to format magnetic data output by the magnetometer module into a file that is easily read by MATLAB for later processing.

The developed system makes use of an ARM Mbed microcontroller to retrieve magnetic data from the sensor module and send it over Serial USB to the data logging application on a Windows PC. The data logging application receives the magnetic data over the USB port and saves it in a .csv file.

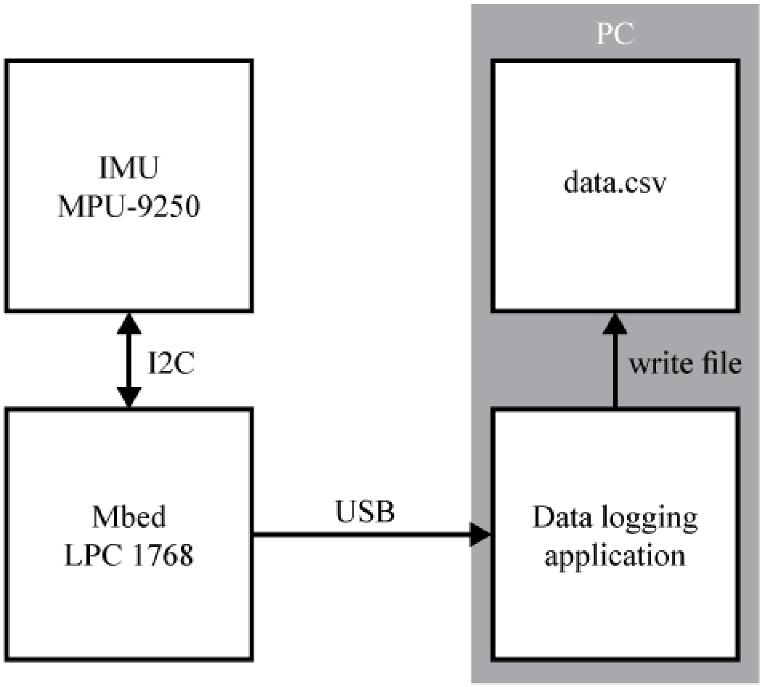


Figure 4.1: Data logging system architecture

4.3 MPU-9250 IMU module

MPU-9250 is a multi-chip module (MCM) consisting of two dies integrated into a single QFN package. One die houses the 3-Axis gyroscope and the 3-Axis accelerometer. The other die houses the AK8963 3-Axis magnetometer from Asahi Kasei Microdevices Corporation. Hence, the MPU-9250 is a 9-axis MotionTracking device that combines a 3-axis gyroscope, 3-axis accelerometer, 3-axis magnetometer and a Digital Motion Processor™ (DMP) all in a small 3x3x1mm package available as a pin-compatible upgrade from the MPU-6515. With its dedicated I2C sensor bus, the MPU-9250 directly provides complete 9-axis MotionFusion™ output. The MPU-9250 MotionTracking device, with its 9-axis integration, on-chip MotionFusion™, and run-time calibration firmware, enables manufacturers to eliminate the costly and complex selection, qualification, and system level integration of discrete devices, guaranteeing optimal motion performance for consumers [11].

Figure 4.2: MPU-9250 on a Drotek breakout board

We are particularly interested in the AK8963 magnetometer.

AK8963 magnetometer AK8963 is 3-axis electronic compass IC with high sensitive Hall sensor technology.Small package of AK8963 incorporates magnetic sensors for detecting terrestrial magnetism in the X-axis,Y-axis, and Z-axis, a sensor driving circuit, signal amplifier chain, and an arithmetic circuit for processing thesignal from each sensor. Self test function is also incorporated [12].

The communication between the Mbed microcontroller and the MPU-9250 is done through I2C protocol.

I2C is a serial protocol for two-wire interface to connect low-speed devices like microcontrollers, EEPROMs, A/D and D/A converters, I/O interfaces and other similar peripherals in embedded systems. Each I2C slave device needs an address.

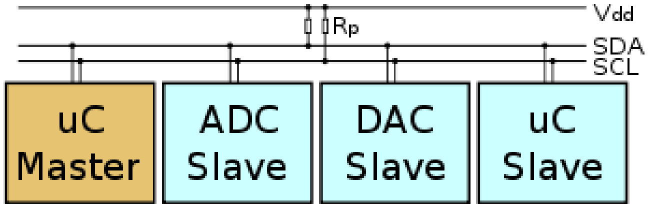


Figure 4.3: I2C protocol

I2C Interface I2C uses only two wires: SCL (serial clock) and SDA (serial data). Both need to be pulled up with a resistor to +Vdd. There are also I2C level shifters which can be used to connect to two I2C buses with different voltages [13].

4.4 Mbed LPC1768 microcontroller

The mbed Microcontrollers are a series of ARM microcontroller development boards designed for rapid prototyping.

The mbed NXP LPC1768 Microcontroller in particular is designed for prototyping all sorts of devices, especially those including Ethernet, USB, and the flexibility of lots of peripheral interfaces and FLASH memory. It is packaged as a small DIP form-factor for prototyping with through-hole PCBs, stripboard and breadboard, and includes a built-in USB FLASH programmer [14].

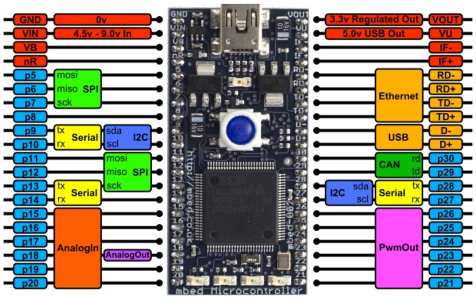


Figure 4.4: Mbed LPC1768

Features

- High performance ARM® Cortex™-M3 Core
- 96MHz, 32KB RAM, 512KB FLASH
- Ethernet, USB Host/Device, 2xSPI, 2xI2C, 3xUART, CAN, 6xPWM, 6xADC, GPIO
- Lightweight Online Compiler
- High level C/C++ SDK
- Cookbook of published libraries and projects

The mbed microcontroller interfaces with the application on PC via USB serial communication.

4.4.1 Code running on mbed microcontroller

The code running on the Mbed platform iterates the following steps:

- Read magnetometer data
- Put the data in the following format: $MagX, MagY, MagZ$ in ASCII
- Add a *newline* character to the data line and send it over USB

Similar operation is detailed in the PFE thesis.

4.5 Data acquisition and logging

To log the magnetic data received from the Mbed microcontroller, a simple console application was developed. The application's main functionality is reading the data on the USB port and writing them in a CSV file format. Figure 4.5 explains the execution process.

CSV file format CSV is a simple file format used to store tabular data, such as a spreadsheet or database. Files in the CSV format can be imported to and exported from programs that store data in tables, such as Microsoft Excel or OpenOffice Calc. CSV stands for "comma-separated values" [15].

4.6 Conclusion

In this chapter, the magnetic data logging system was presented along with its component. This system provides the MATLAB routine with data in a MATLAB compatible format. The next chapter will explain the calibration process and the MATLAB routine used to process and visualize the data.

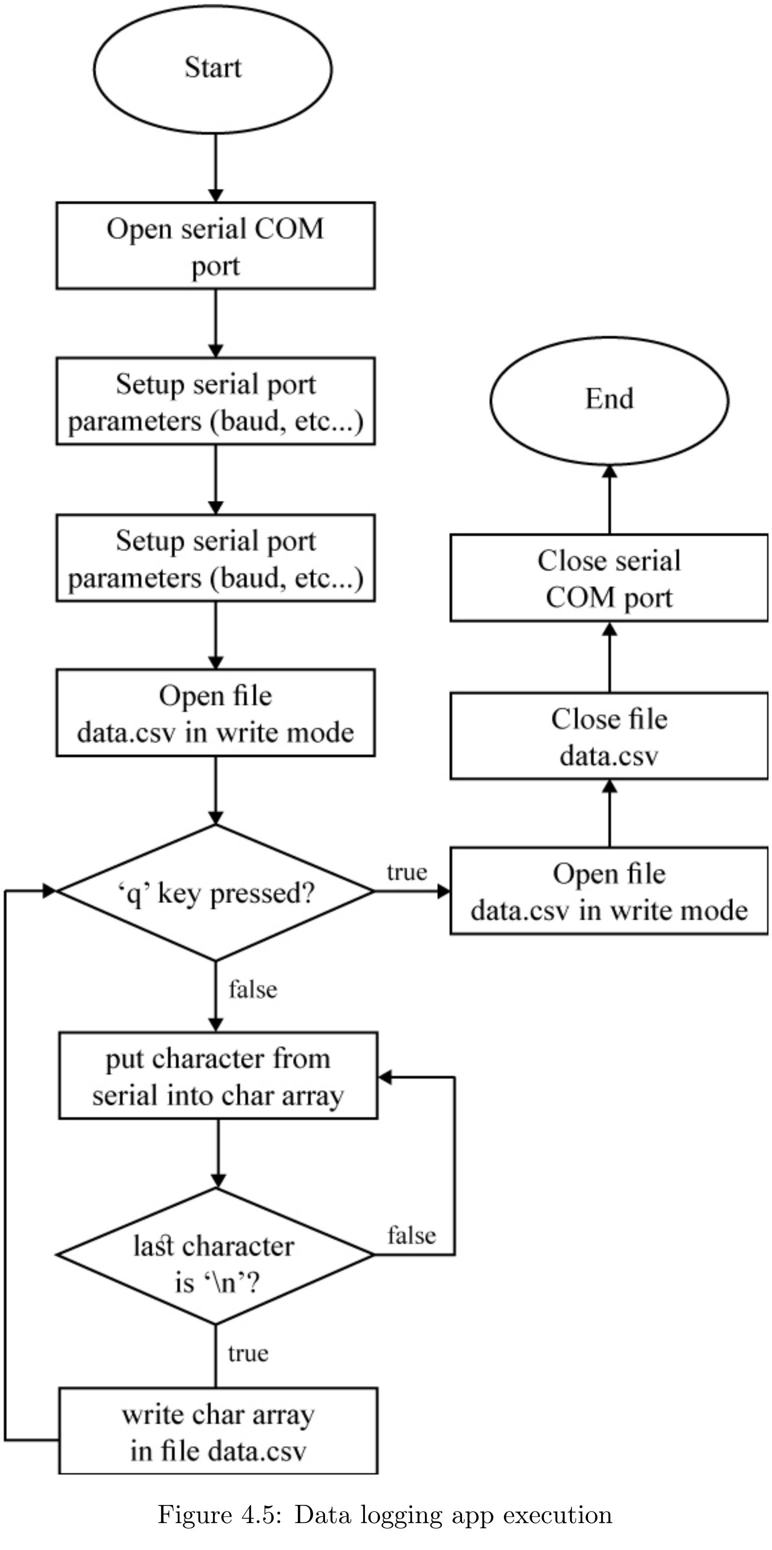


Figure 4.5: Data logging app execution

Chapter 5

Calibration Process

5.1 Introduction

In this chapter, we will use the system introduced in the previous chapter to log magnetometer data and process them on MATLAB with the purpose of establishing a calibration process. The tools used in this process are explained and detailed.

5.2 Magnetic environment construction

In order to calibrate a magnetic sensor, magnetic data from the sensor must be collected. This data is used to construct the magnetic environment of the said sensor.

The magnetic environment is the set of point in 3D space described by the values $(MagX, MagY, MagZ)$ where $MagX$ is the value of the magnetic field on the X axis as perceived by the said magnetometer. A complete magnetic environment construction is achieved when the sensor is turned 360° around 3 mutually perpendicular axes.

A common practise to construct the magnetic environment around a magnetometer is to move the latter in 8 shaped figure on 3 mutually perpendicular planes.

The CSV data file is opened on MATLAB with magnetic data stored in arrays: X, Y and Z. A scatter plot of the 3 arrays in 3D space gives the following (figure 5.1

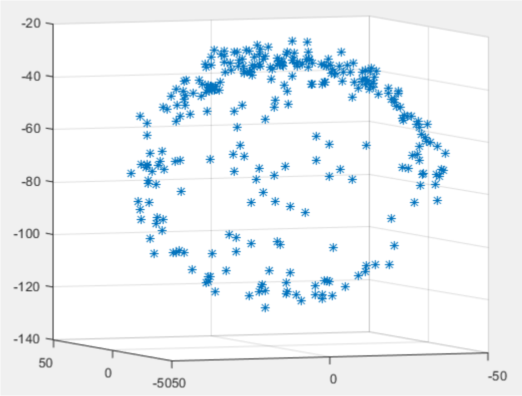


Figure 5.1: A scatter plot of the magnetic environment as seen by the magnetometer

5.3 Ellipsoid fitting

The purpose of constructing the magnetic environment is to be able to approximate it to an ellipsoid, and thus spot its center and semi-radii.

Doing so graphically is a challenging and unreliable way. It is therefore necessary to make use of an approximation algorithm to calculate the closest ellipsoid to the 3D scatter points.

Many approaches of fitting an ellipsoid to a 3D scatter exist but Least Square methods are the most commonly used thanks to their simplicity and computational efficiency [**ellip**].

Least square fitting algorithms are based on the idea of minimizing the sum of the squares of the distances between individual points of the scatter and the surface of the ellipsoid. Ellipsoid parameters (center, radii, R-rotation matrix) are calculated so that the sum of the squares is the smallest possible.

An excellent MATLAB sktech is available on the MATLAB file exchange plaform [16]. This sketch uses a least square method to find the best ellipsoidal approximation surface of any 3D set of points.

```
function [ center, radii, evecs, v, chi2 ] = ellipsoid_fit( X, equals )
```

The *ellipsoid_fit* function takes 2 parameters:

- X: Data set coordinates, n x 3 matrix or three n x 1 vectors
- *equals*: a flag to define fitting constraints (spherical, aligned, etc...)

The output of the function is:

- *center*: ellipsoid center coordinates $[x_c;\ y_c;\ z_c]$
- *radii*: ellipsoid radii $[a;\ b;\ c]$
- *evecs*: the radii directions as columns of the 3x3 matrix
- v: the 10 parameters describing the ellipsoid / conic algebraically:

$$Ax^2 + By^2 + Cz^2 + 2Dxy + 2Exz + 2Fyz + 2Gx + 2Hy + 2Iz + J = 0$$

- $chi2$: residual sum of squared errors

5.4 Bias and scale compensation

As mentionned in Chapter 4, the calibration process aims to compensate the hard-iron and soft-iron distortions.

Offset compensation The hard-iron distortion is characterized by an offset from the center. To compensate this offense, subtracting the calculated ellipsoid center from sensor magnetic vector data will suffise:

$$MagX_c = MagX - x_c$$

$$MagY_c = MagY - y_c$$

$$MagZ_c = MagZ - z_c$$

Where $MagX_c$ is the hard-iron calibrated data and $MagX$ is the uncalibrated data. $[x_c;\ y_c;\ z_c]$ are the coordinates of the ellipsoid center [17].

Soft-iron effect compensation For the sake of simplicity, only the case where *evecs* is equal to the 3D canonical basis is considered (no rotation).

In these circumstances, only a rescaling of the magnetometer data is necessary to reproduce a perfect sphere.

A scaling factor σ is calculated for each based on the ellipsoid radii:

$$\sigma_x = \frac{R}{a}$$

$$\sigma_y = \frac{R}{b}$$

$$\sigma_z = \frac{R}{c}$$

Where R is the radius on the major axis.

$$R = Max(a, b, c)$$

Rescaling is achieved by multiplying each component of magnetic data by its respective scaling factor:

$$MagX_c = MagX\sigma_x$$

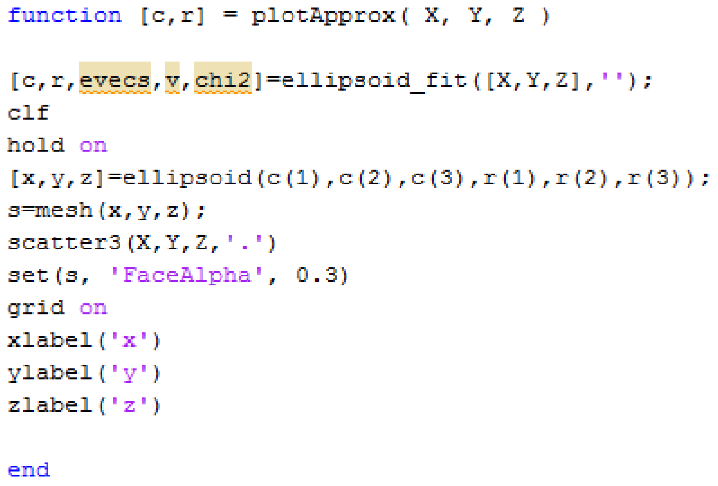
$$MagY_c = MagY\sigma_y$$

$$MagZ_c = MagZ\sigma_z$$

In general, uncalibrated magnetometer data suffers from both hard-iron and soft-iron distortions. When compensating for distortion, it is important first to correct the hard-iron offset and then apply the soft-iron rescaling.

The order of compensation does matter.

5.5 Data visualization



```
function [c,r] = plotApprox( X, Y, Z )

[c,r,evecs,v,chi2]=ellipsoid_fit([X,Y,Z],'');
clf
hold on
[x,y,z]=ellipsoid(c(1),c(2),c(3),r(1),r(2),r(3));
s=mesh(x,y,z);
scatter3(X,Y,Z,'.')
set(s, 'FaceAlpha', 0.3)
grid on
xlabel('x')
ylabel('y')
zlabel('z')

end
```

ellipsoid_fit is used to calculate the necessary ellipsoid parameters. These parameters and then used with the MATLAB function *ellipsoid* to generate a point set describing the ellipsoid. This set is then plotted using the function *mesh*. The returned 3D surface handler is used to change the ellipsoid opacity to allow the scatter to be visible in the same time as the ellipsoid (figure 5.2).

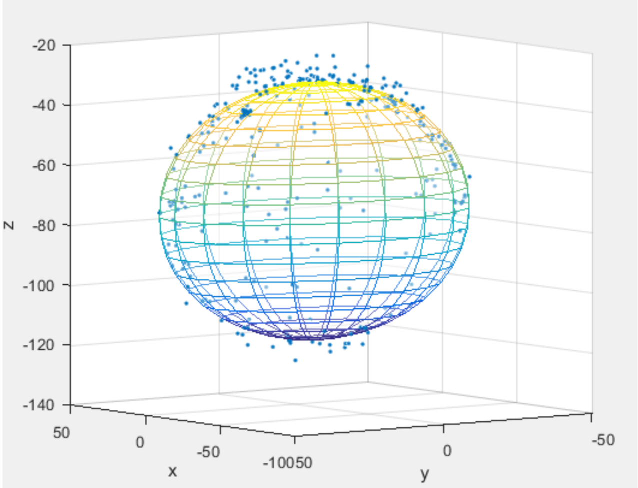


Figure 5.2: The scatter of the magnetic environment along the approximated ellipsoid

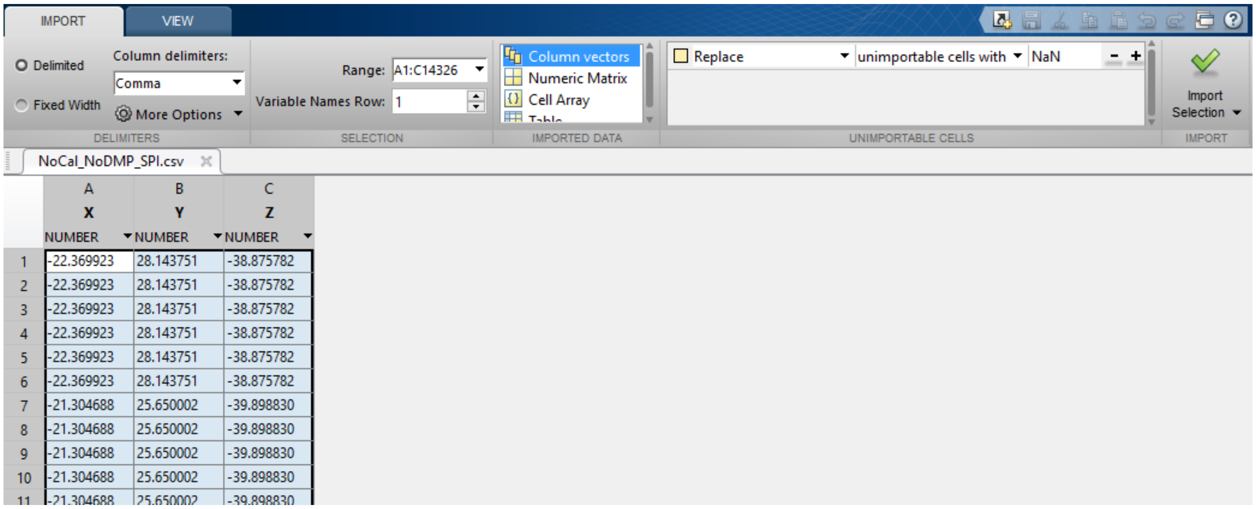
5.6 Conclusion

In this chapter, the calibration tools and procedure were discussed. A numerical example of the aforementioned process is shown in the next chapter.

Chapter 6

Numerical example

Opening the data.csv file on Matlab:



● Delimited

Column delimiters: Comma

Range: A1:C14326

Variable Names Row: 1

Column vectors

Replace unimportable cells with NaN

NoCal_NoDMP_SPI.csv

	A X NUMBER	B Y NUMBER	C Z NUMBER
1	-22.369923	28.143751	-38.875782
2	-22.369923	28.143751	-38.875782
3	-22.369923	28.143751	-38.875782
4	-22.369923	28.143751	-38.875782
5	-22.369923	28.143751	-38.875782
6	-22.369923	28.143751	-38.875782
7	-21.304688	25.650002	-39.898830
8	-21.304688	25.650002	-39.898830
9	-21.304688	25.650002	-39.898830
10	-21.304688	25.650002	-39.898830
11	-21.304688	25.650002	-39.898830

Figure 6.1: Opening a CSV file on MATLAB

The 3D magnetic data are loaded on the workspace:

Name	Value
X	14326x1 double
Y	14326x1 double
Z	14326x1 double

Figure 6.2: 3D magnetic data on the workspace

The data is passed to the *plotApprox* function.

```
[c,r]=plotApprox(X,Y,Z)
```

Offset values The execution of the functions gives the value of the offset on each axis: The ellipsoid center coordinates.

$$x_c = -14.2737$$
$$y_c = 0.3695$$
$$z_c = -74.5737$$

Scale factors To compensate for the soft-iron effect, magnetic data are rescaled in relation to the ellipsoid radii:

$$a = 47.8603$$
$$b = 47.0252$$
$$c = 42.8517$$

R being the radius on the major axis:

$$R = a = 47.8603$$

The scaling factors are then:

$$\sigma_x = 1$$
$$\sigma_y = 1.01775$$
$$\sigma_z = 1.1168$$

Chapter 7

Conclusion

In this work, a simple MATLAB based method of calibrating magnetometers was proposed. This calibration method addresses the problem hard-iron and soft-iron distortions that are locally present in the magnetic environment. This is however not a complete calibration suite as magnetometers are subject to different other systematic error such as magnetic coupling between sensors axes...

Magnetometers in Attitude and Heading References Systems are instrumental if 9 degrees of freedom data fusion algorithms are used. This can be apparent when comparing between the orientation outputs of an AHRS with a well calibrated magnetometer and an AHRS with an uncalibrated magnetometer as the latter suffers from significant orientation estimation errors.

For the future outlook of this work, several improvement can be expected:

- Real time data acquisition on MATLAB via USB
- Dealing with a skewed and rotated magnetic environment
- Adapting the ellipsoid fitting function to run directly on the microcontroller, thus eliminating the need for a PC to perform the calibration

For AHRS applications, accelerometers and gyroscopes must also be calibrated to allow maximum precision in orientation estimation.

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