



Electronic and Computer Engineering Department

Diploma Thesis with title:

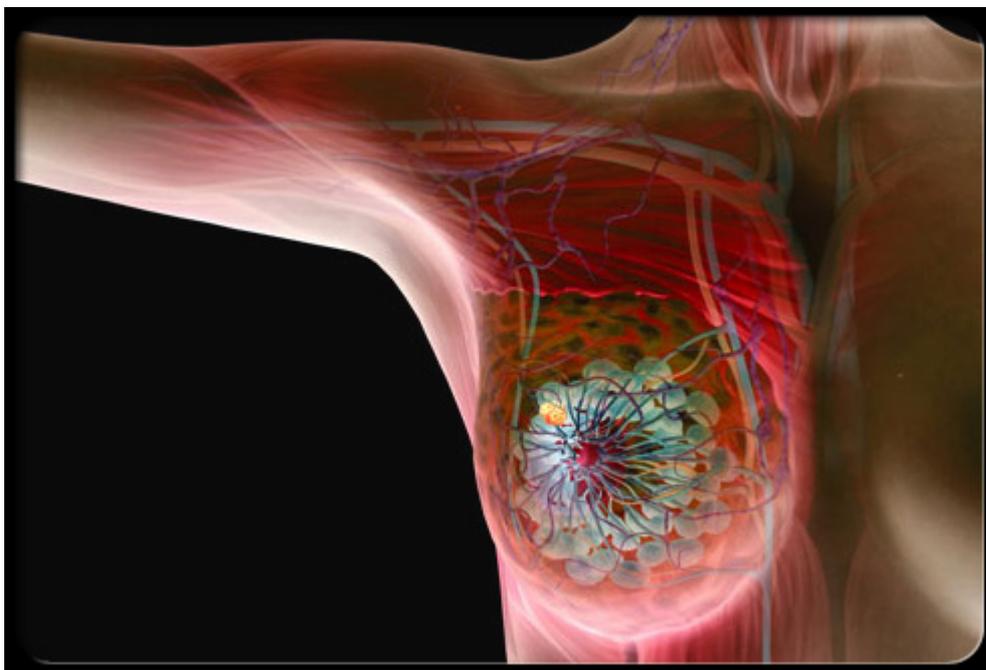
"Development of breast cancer surgery magnetic navigation system"

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Abstract

Precision in biopsy surgery procedures is of utmost importance. A sample has to be withdrawn from the suspicious area of the patient's body without damaging the nearby healthy tissues. Until now, in breast cancer biopsy, it was up to the doctor to decide whether he had reached the suspicious area or not. There are technologies for doing this in several surgical procedures however there is none specifically designed for breast cancer surgery. In current thesis a new system is proposed for helping the doctor to monitor precisely the movements of the scalpel through a magnet attached on it. Magnetic sensors detect the magnetic field and estimate the position of the scalpel. A wire is also inserted into the suspicious area through a magnetized needle. The needle shows the position of the suspicious area. The needle is then withdrawn and the wire is attached through a hook at its edge to the area of concern. In that way the surgeon can monitor the movement of the scalpel in reference to the position of the tumor and the sensors detecting the magnetic field. The device is constructed with ultra small dimensions, making it flexible and discreet to use. Unlike to previous works regarding magnetic surgery navigation, the system offers high position accuracy estimation with less than 1mm error.

Chapter 1: Breast Cancer Description and Biopsy Techniques ([1] - [6])

1.1 Breast Cancer: Symptoms

Breast Cancer may have or may not have symptoms. Many women can detect the symptoms themselves, whereas others may discover it by performing diagnostic tests, such as screening exams. Abnormalities detected , which can be a sign of breast cancer are :

- a. Lumps or masses, which can cause no pain.
- b. Skin changes.
- c. Swelling.
- d. Changes in the size or the feel of the breast tissue.

Self examination should be a part of every woman's routine once every month . In case that an abnormality is found, visiting a doctor is crucial.



1.2 Breast Cancer: General Description of Biopsy Procedures

Breast biopsy's purpose is to remove a portion or the whole breast lump for examination. The sample is then examined to determine if the lump is non-cancerous or cancerous tissue.

So, the basic purpose of the breast cancer biopsy is to determine if a suspicious lump is cancerous. In case it is a cancerous one, what type is it.

Breast cancer biopsy procedures are:

- i. fine needle aspiration biopsy(FNAB).
- ii. core needle biopsy(CNB).
- iii. excision biopsy(surgery).
- iv. incision biopsy(surgery).
- v. vacuum-assisted breast biopsy.

1.3 How is every breast biopsy procedure performed?

1.3.1 Fine Needle Aspiration Biopsy (FNAM).

A FNAM can be done in several ways :

- o Fine needle aspiration biopsy (FNAB) for palpable growths: A palpable growth is one that can be felt. The patient sits up and the doctor injects a small hollow needle with a syringe to withdraw fluid and cells from the suspicious growth for examination. To guide the needle to the right place(the growth) doctor palpates the suspicious area. When the needle reaches the mass, the doctor withdraws a sample with the syringe. This procedure is repeated for several times. If the growth is a cyst, the withdrawn samples consist mostly of fluid, whereas, in the case that the growth is solid , the sample consists mainly of tissue cells.

If the sample consists of fluid , the doctor may conclude that the growth was just a cyst and discard the samples. In any other case , the samples are placed in slides and are sent for laboratory examination.



- o Guided FNAB for Non-Palpable Growths: In the case that the growth is too small or too deep to be palpated(felt) , it has to be located by one of several imaging techniques [7]. First, the patient lies face down on a table with the breasts suspended through an opening. With stereotactic mammography, mammograms of the suspicious breast site are taken from different angles to form a virtual three-dimensional (stereotactic) image that precisely pinpoints the location of the suspicious area. The

computer then uses a motor to guide a small hollow needle to the site to remove the samples. The withdrawn samples are then analyzed for the presence of cancer. Ultrasound and MRI are other imaging techniques that may be used to guide breast biopsies.



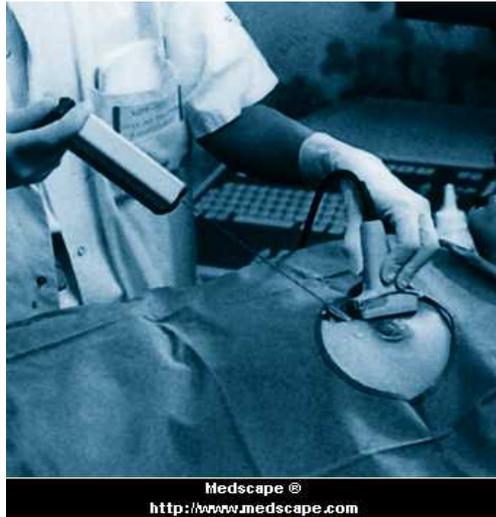
1.3.2 Core Needle Biopsy(CNB).

CNB can be performed in several ways as well :

- CNB for palpable growths: This procedure is similar to FNAB for palpable growths except that that the needle used has a wider diameter and is equipped with a cutter that removes cores of tissue up to a half-inch long. A key advantage of this procedure is that the samples are larger than in FNAB and thus enhance the possibility of making an accurate laboratory analysis.



- Guided CNB for Non-Palpable Growths: As with the guided FNAB, this procedure also uses a wide needle with a cutter that removes cores of tissue large enough to enhance the accuracy of laboratory analysis. However, because the growth is deep in the breast or otherwise not palpable, stereotactic imaging, ultrasound, or MRI is used to locate the growth.



1.3.3 Excision Biopsy(surgery).

Excision biopsy, the most involved form of biopsy, is surgery to remove the entire area of suspicious tissue from the breast. In addition to removing the suspected cancer, the surgeon generally will remove a small rim of normal tissue around it as well, called a margin.

If the surgeon cannot feel the lump or suspicious area, he or she may need to use mammography or ultrasound to find the right spot. Surgeon also may use needle wire localization to mark the right area for biopsy.

Excision biopsy is the surest way to establish a definite diagnosis without getting a false negative result. Also, having the entire lump removed may provide you with some peace of mind. However, excision biopsy is more like regular surgery, and it will leave a scar and require more time to recover. Excision biopsy is performed with local anesthesia.



1.3.4 Incision Biopsy(surgery).

Incision biopsy is more like regular surgery. After using local anesthesia to numb the breast and giving you an injection to make you drowsy, the surgeon uses a scalpel to cut through the skin to remove a piece of the tissue for examination.

As with needle biopsy, if the surgeon cannot feel the lump or suspicious area, he or she may need to use mammography or ultrasound to find the right spot. Your

surgeon also may use a procedure called needle wire localization. Guided by either mammography or ultrasound, the surgeon inserts a small hollow needle through the breast skin into the abnormal area. A small wire is placed through the needle and into the area of concern. Then the needle is removed. The doctor can use the wire as a guide in finding the right spot for biopsy.

Your doctor may recommend incision biopsy if a needle biopsy is inconclusive — that is, the results are unclear or not definite — or if the suspicious area is too large to sample easily with a needle. As with needle biopsy, there is some possibility that incision biopsy can return a false negative result. However, you do get the results fairly quickly. Given that it is a surgical procedure, incision biopsy is more invasive than needle biopsy, it leaves a scar, and it may require more time to recover.



1.3.5 Vacuum-Assisted Breast Biopsy.

Vacuum-assisted breast biopsy uses a special instrument and imaging guidance to remove samples of breast tissue through a single, small skin incision. This technique allows the surgeon to remove more tissue through a single incision than is possible with a traditional core biopsy and is a much less invasive procedure than an open surgical biopsy.

The vacuum-assisted biopsy involves the placement of a biopsy probe using radiology imaging studies for guidance. Stereotactic mammography, ultrasound, and MRI have all been successfully used to identify the abnormal areas to be sampled by vacuum-assisted breast biopsy. Once the biopsy probe has been positioned, a vacuum pulls the breast tissue through an opening in the probe into the sampling chamber of the device. Then a rotating cutting device in the instrument removes the tissue sample, which is carried through the biopsy probe to a tissue collection receptacle.

The surgeon or radiologist then turns a control knob on the biopsy probe that moves the sampling chamber to a new position. This procedure is repeated until all desired areas have been sampled. In this way, samples can be taken all around a suspicious area through a single insertion of the biopsy probe. With a traditional core biopsy,

sampling of multiple areas would involve repeated insertions of the biopsy instrument.

The vacuum-assisted biopsy technique is performed under local anesthesia and leaves a small incision that does not require stitches for closure. It takes less than an hour to perform, and patients can usually return to normal activities soon after the procedure.



1.3.6 What are the advantages and disadvantages of non-surgical procedures versus surgical breast biopsies?

Generally, non-surgical biopsies are less stressful, do not disfigure the skin, leave no internal scar to interfere with the accuracy of future mammograms, and minimize the risk of complications.

However, non-surgical biopsies are not always as reliable as surgical biopsies in producing a conclusive diagnosis. For this reason, some patients who undergo a non-surgical biopsy must also undergo a follow-up surgical biopsy.

1.3.7 What specialties of physicians and practitioners do breast biopsies?

Many physicians and healthcare practitioners can be involved in evaluating a woman for a breast biopsy.

- For example, breast abnormalities during a physical examination might be noticed by a family physician, internist, gynecologist, or nurse practitioner. Women themselves are frequently the first to detect abnormalities in their breasts.
- Radiologists are specialists in interpreting x-rays such as mammograms, as well as other imaging studies. Radiologists or surgeons often perform the procedure to obtain the breast tissue sample.
- Anesthesiologists (specialists in administering anesthesia and monitoring a patient's vital signs) are sometimes necessary during surgical procedures.
- Pathologists are physician specialists who examine and identify under a microscope the type of cells in the samples and determine whether or not cancer is present.

1.4 Other Diagnostic Tests for Breast Conditions

1.4.1 Diagnostic Mammogram

If a woman has noticed breast changes or symptoms, or if a routine screening mammogram has found a suspicious-looking area, she may need to get a diagnostic mammogram. During a diagnostic mammogram, more x-rays are taken of the breast than during a screening mammogram. Extra pictures are focused on the area of concern.

Mammograms are usually a black-and-white picture of the breast tissue on a large sheet of film that is read, or interpreted, by a *radiologist* (a doctor specially trained to read these kinds of tests). For a mammogram, the breast is pressed between 2 plates to flatten and spread the tissue. This may be uncomfortable, but it's needed to get a good, clear picture. The pressure only lasts a few seconds. The entire mammogram procedure takes about 20 minutes.

A digital mammogram is done the same way, but it's another option. A digital mammogram produces computer images instead of film. These images can be read on a computer screen and saved in the system. The images can be looked at from different angles. The radiologist can enlarge the pictures and zoom in to look at any suspicious areas.

But mammograms alone cannot prove that an abnormal area is cancer. Tissue from the area must be taken out and looked at under a microscope. This is called a biopsy. Breast cancer cannot be diagnosed without a biopsy.

You should also know that a mammogram is not perfect at finding breast cancer. If you have a breast lump, you should have it checked by your doctor and talk about having a biopsy even if your mammogram is normal.

1.4.2 Breast Ultrasound

Breast ultrasound uses sound waves to make a computer picture of the inside of the breast. This test is sometimes used to target a certain area of concern that was found on the mammogram or physical exam.

Ultrasound is useful for looking at some breast changes, such as those that can be felt but not seen on a mammogram. It also helps tell the difference between fluid-filled cysts and solid masses. If a lump is really a cyst, it's benign (not cancer). If this is the case, your doctor may not have to put a needle into it to take out fluid.

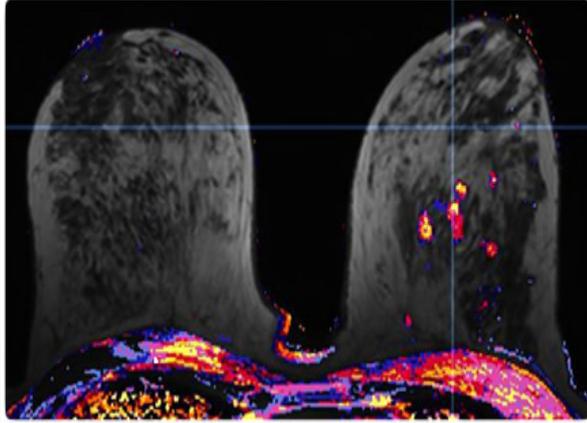
Ultrasound uses high-frequency sound waves to outline a part of the body. The sound waves are sent into the area of the body being studied and echoed back. These echoes are picked up by the ultrasound probe. A computer changes the sound waves into a picture that is shown on a screen. Radiation is not used to do this test.



1.4.3 Magnetic resonance imaging

Magnetic resonance imaging (MRI) is sometimes used to look for breast cancer in women who are known to be at high risk. It may also be used to get a closer look after breast cancer has been found. An MRI can show if your lymph nodes are enlarged, which may be a sign that they contain cancer. (Lymph nodes are small bean-shaped collections of immune system tissue that are connected by small vessels or tubes. They remove cell waste, germs, and other harmful substances from the body. Cancers sometimes spread into them or through them.)

MRI is sometimes used to look for breast tumors that did not show up on the mammograms. It's also used to help guide the biopsy needle into tumors that can't be seen on mammograms. This is known as *MRI-guided biopsy*.



1.4.4 Ductogram

Ductograms are sometimes used to find the cause of nipple discharge. A ductogram is also called a *galactogram*.

In this test, a small amount of dye is put into one of the ducts in the nipple through a tiny plastic tube. The dye can be seen on an x-ray, which can then show if there is a mass inside the duct.



In this point it is very important to refer to biopsy , because biopsy IS THE ONLY SURE WAY TO DIAGNOSE CANCER

1.4.5 Second Opinions

Even before a biopsy, a second opinion would be good. This way, another expert from another hospital or mammogram center will look at the mammogram.

It takes great skill and experience to read a mammogram, either from film or from a digital picture. It is important to make sure that the mammogram is being read by an expert.

1.5 Conclusions and Contribution of this project implementation to the biopsy techniques.

One big problem in performing the biopsy is the localization of the tumor. The location of the tumor is very important since it will save time and will not harm healthy issues during the surgery.

Current techniques for tumor localization as mentioned above (MRI, breast ultrasound, etc.) are not too reliable, since they provide an approximation of the location of the tumor. So, it is up to the doctor to locate the tumor, based on the information these techniques provide.

Finding a more accurate technique for locating the tumor is crucial for the sure success of the biopsy, because it provides the accurate location of the tumor and it is a great help for the doctor for performing the surgery faster and more accurately without causing any discomfort, plus without causing any damage to the healthy tissues of the patient's breast.

To conclude, what this project provides is an assistance to the doctor, so that he knows with a very good approximation (which goes down to mm) where the lancet is in accordance to the location of the tumor. This will help the doctor reach the tumor faster, precisely and without damaging the healthy tissues of the patient.

Chapter 2: General description of the purpose and the background of the project presented here.

2.1 Field of the invention

The purpose of this project is to build a magnetic navigation system which will give in real time conditions to the doctor, information through a monitor about where the surgical lancet is regarding the position of the tumor within the breast(which is available to the doctor through the MRI, mammography, etc.). This project offers many advantages to the surgical biopsy such as:

- Will help the doctor reach the tumor precisely (the position error calculation does not surpass the max value of 1mm in 3d space). As a result, doctor will not have to cut more breast tissue than it is needed or make a larger cut to the breast of the patient.
- Low cost comparing to other navigation systems which are available (for example: navigation through ultrasound, navigation through laser). Magnetic sensors and the magnet which will be attached to the lancet (description of the implementation will be analytically discussed) are cheap and very reliable. For example the cost for the implementation which is presented here does not surpass 90 Euros.
- Harmless for the patient. The magnetic field which is emitted through the magnet is completely harmless for the patient and the body. This make it even more suitable for many other projects , which require navigation through the body or examination of the body of the patient.
- Magnetic field is not affected from the body tissue. The magnetic permeability of the body tissue is approximately the same with the vacuum (more information regarding the magnetic permeability will be discussed later on).

2.2 Description of related art

In the field of surgery, there was always the need for guidance and one way to achieve this was through the magnetic field.

Examples of prior and similar arts are given below not necessarily for medical applications but useful for performing magnetic localization in general, with the full

content of each of the cited documents are herein incorporated by reference in their entirety:

The most similar project, was the one from Donald G. Polvani [32] . Mr. Donald G. Polvani invented a magnetic guidance system for brain surgery by adapting a probe in the edge of the scalpel. In this paper the Levenberg-Marquardt algorithm is being used (which did not work for the project being presented here), but there is no reference about calibrating the magnetometers, what other algorithms were tested and most important, what is the overall accuracy that the system being proposed had.

Another paper, which was a great help for implementing this project, was the magnetic position and orientation measurement system proposed from Per K. Hansen[33]. In this paper the inventor uses Hall-effect devices and a permanent magnet. The drawback of this invention is the size of the permanent magnet which was being used (32.2mm x 7mm) which was too big for the needs of the project being introduced here . It is important to note that a bigger magnet can result in better position localization results due to the fact that stronger magnetic field is more robust to noise thus measurements in longer distances can be acquired. The use of the small permanent magnet gave birth to the need for more sensitive magnetometers, which Hall-effect devices found at the market could not provide. Using the method proposed in this paper did not provide any reliable result , especially when the orientation of the magnet was arbitrary.

Moreover, another paper which was taken into consideration was the " Detection of Magnetic Object Movements by Flux Density Tracking Control" by Wu-Sung Yao, Mi-Ching Tsai, Jian-Zhi Lai and Fu-Yun Yang[34]. The drawback about this paper is the fact that the tracking control system proposed here can be used for detecting the movement of large magnetic object movements. Another drawback is the "useful" distance , since the system can detect the motion of the magnet (whose size is 10mm x10mm) without erroneous results within a 20mm distance.

"Tracking system with five degrees of freedom using a 2D-array of Hall sensors and a permanent magnet" proposed V. Schlageter, P.-A. Besse, R.S. Popovic , P. Kucera [35] is another project which was taken into consideration. The most interesting part regarding this project is the use of many Hall-sensors (8-16) in a array form and the distance in which the system is capable of measuring the magnetic field (up to 140mm). The main disadvantage of this method is the position error when the orientation of the magnet is being changed.

In the "Efficient Magnetic Localization and Orientation Technique for Capsule Endoscopy" developed by Chao Hu, Max Qinghu Meng, Mrinal Mandal[37] they have concluded in the fact that the Levenberg-Marquardt method is the appropriate method for the magnetic localization of the capsule, since the capsule which is small enough to be swallowed , includes a small permanent magnet. Testing the above algorithm, as it was already for mentioned, resulted in non appropriate results,

especially when the magnet was rotating, whereas the algorithm is highly dependent on the initial value which will be given in order to start the localization process.

In the "REMOTE OBJECT POSITION AND ORIENTATION LOCATOR" invented by Frederick H. Raab[38], the use of sensing coils is being introduced for detecting the position and orientation of an object. While the use of coils, can be a useful addition to magnetic localization systems, it is not suitable for this project, due to the size of the coils, and the complexity of the system in comparison to the system being designed in this project.

"METHOD AND APPARATUS FOR POSITION AND ORIENTATION MEASUREMENT USING A MAGNETIC FIELD AND RETRANSMISSION" again by Per K. Hansen[39] was a great contribution in understanding the meaning of orientation and the equations describing it. The use of coils again and the complexity of the system in relation to the advantages which the magneto-resistive sensors and the arduino used in this project provide, make the proposed system non-suitable for this application.

"MEASURING POSITION AND ORIENTATION USING MAGNETIC FIELDS" introduced by Mark Schneider[40] , "OBJECT TRACKING USING A SINGLE OR A PAIR OF SENSORS" by Pinhas Gilboa[49] , "SYSTEM FOR DETERMINING THE LOCATION AND ORIENTATION OF AN INVASIVE MEDICAL INSTRUMENT" by Shlomo Bel Haim(Haifa(IL)), Daniel Osadchy(Haifa(IL), Udi Peless(Even-Yehuda(IL)), Ilan GreenBerg(Haifa(IL))[42] again make use of orthogonal coils in order to perform motion tracking of another coil. Such technique can be really useful for motion tracking , but the size of the coils is a drawback for the low-cost and small dimension sensors and magnets needed for this project.

"THREE-AXIS COIL SENSOR" by David E. Acker[41], is a very similar project to the one being presented here. The great advantage of this invention is the fact that the coils sensing each axis can be placed anywhere around the place of the body where the surgery will be conducted . What is not suitable for this project is the size of the movable transducers in relation to the magneto-resistive sensors being used here. The plane including the magneto-resistive sensors can be placed in arbitrary positions too in order to help the doctor perform the surgery without interferences, since the position of the probe is calculated in addition to the distance from the sensors.

"Indirect Measurement of a Bar Magnet Position Using a Hall Sensor Array" by Uwe Marschner, Wolf-Joachim Fischer [43] and "ROTATIONAL POSITION SENSOR WITH A HALL EFFECT DEVICE AND SHAPED MAGNET" by W. T. Wu[44], where a real contribution in helping understanding the procedure of how the position and rotation of a magnet is being interpreted, however were not suitable for this project, since 3d movement and orientation tracking is being required.

"SURGICAL GUIDANCE METHOD AND SYSTEM FOR APPROACHING A TARGET WITHIN A BODY" by Kim H. Manwaring, Dr., Ahwatukee; Mark L. Manwaring, Dr., Pullman[45] is a system which indicates to the doctors the trajectory that a probe is following in accordance to a pre-defined trajectory from an initial point to a target within the body of the patient. The project being introduced here combines the predefined trajectory with the target meaning that if the position of the tumor is known, the doctor knows exactly every time where the scalpel is in addition to the tumor.

"EFFICIENT MAGNET SYSTEM FOR MAGNETICALLY-ASSISTED SURGERY" by Francis M. Creighton; Andrew F. Hall; Roger N., all of MO (US); Rogers C. Ritter, Charlottesville, VA(US)[46] , is another similar project designed for guiding magnetically a surgery. It has the great disadvantage of the huge size of the system , therefore huge cost too.

"A Cubic 3-Axis Magnetic Sensor Array for Wirelessly Tracking Magnet Position and Orientation" by Chao Hu, Mao Li, Shuang Song, Wan'an Yang, Rui Zhang, and Max Q. -H. Meng[48] presents an interesting and very helpful way of determining the position of the magnet. The drawbacks of this invention is the use of too many sensors, which can expand the cost of the system, the localization error is more than 1.82mm , the setup of the system is a cubic setup where the magnet is free to move inside which does not meet the demands for which these project was developed.

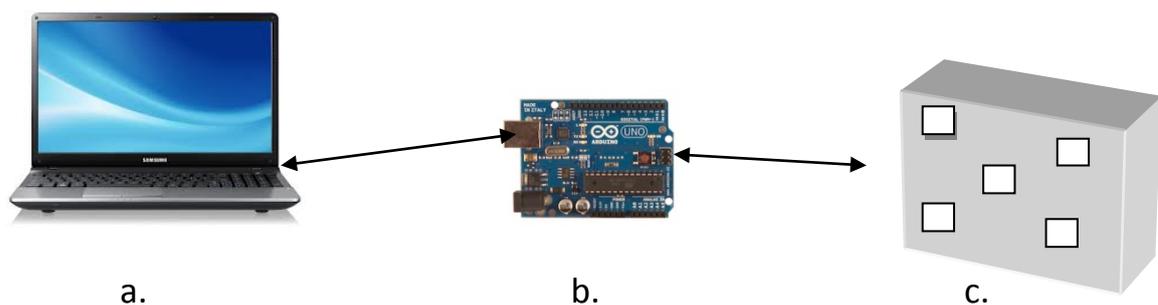
"SYSTEM AND METHOD TO DETERMINE THE LOCATION AND ORIENTATION OF AN IDWELLING MEDICAL DEVICE" by David R. Haynor, Christopher P. Somogyi and Robert N. Golden[50] is another similar project to the one presented. The inventors make use of the magnetic sensors(can be of any kind), to determine the position and orientation of a medical device, which contains a small permanent magnet" within the body of the patient. The drawback of this invention is the need for an accurate initial value of the position of the magnet. The project presented here appears to have a robustness on the initial which will be given in order to produce accurate position estimation results.

"IMPLANTABLE MEDICAL DEVICE WITH HALL SENSOR" by William J. Linder and Angela M. Muttonen[51] is another similar project being presented. The drawback of this project is the use of the Hall Sensor Device. Hall Sensors tested in the project presented here where not as much sensitive as the magneto-resistive sensors, so the use of Hall-Sensors is not a trusty solution for the implementation of the system.

2.3 General description of how the hardware of the project is implemented.

For the implementation of the project the following items were used:

- 5 magnetometers
- 1 neodymium cylinder N52 permanent magnet
- 1 plane to adjust the magnetometers on
- 1 Arduino Uno rev3 microcontroller ([8])
- 1 laptop



Picture 1.General description of the hardware

Picture 1. Shows the pc(a.) which is used for the project. A laptop uses Matlab, to perform calculations and locate the magnet in 3D space. It also displays the position of the magnet both in 2D plots and 3D animation so that the doctor has the best possible perspective of the position of the magnet.

As **Picture 1** shows, the laptop is connected through a USB cable with the arduino board (in this project an ARDUINO UNO REV3).



Finally, we use cables to connect the 5 magnetometers, which are used to measure magnetic field produced by the magnet, to the different pins of the arduino board. The 5 magnetometers are placed symmetrically in a plane with dimensions 5cmx5cm (corners and center of the plane). The locations of the magnetometers are as following:

	x(m)	y(m)	z(m)
Up left corner	-0.01560	0.01776	0
Down left corner	-0.01560	-0.01776	0
Up right corner	0.01560	0.01776	0
Down right corner	0.01560	-0.01776	0
Center	0	0	0

2.4 Why use 5 magnetometers with this setup?

When the project had started, there was only one magnetometer used. The disadvantage of using 1 magnetometer is the fact that no reliable measurements can be achieved. Measurements can be or can't be right. Using more than 1 magnetometer is a reliable way to measure the magnetic field generated by the magnet from many different sources. The reasons behind using 5 magnetometers are:

- The full space of the plane being used had to be exploited, so to fulfill the plane, the magnetometers were placed in "strategic" positions so that wherever the magnet was moved in accordance to the plane equal measurements would be acquired.

- The mathematical model being used in this project makes usage of 5 unknown parameters, 3 for position and 2 for orientation. As a result, using 5 or more magnetometers makes the measurements more reliable.

- Using 5 magnetometers does not mean that no more magnetometers can be used. In fact, the more magnetometers being used, the more reliable the measurements will be. In this project, 5 magnetometers were used due to the restriction of working in small dimensions.

As far as this setup is concerned, many different planes were tested, such as putting the magnetometers in semicircle, in different planes, in different positions in accordance with the z axis. Nothing seemed to work as good or as reliable as this setup did and as result this setup, with all magnetometers in the same plane, was preferred.

Chapter 3: Hardware Analysis:

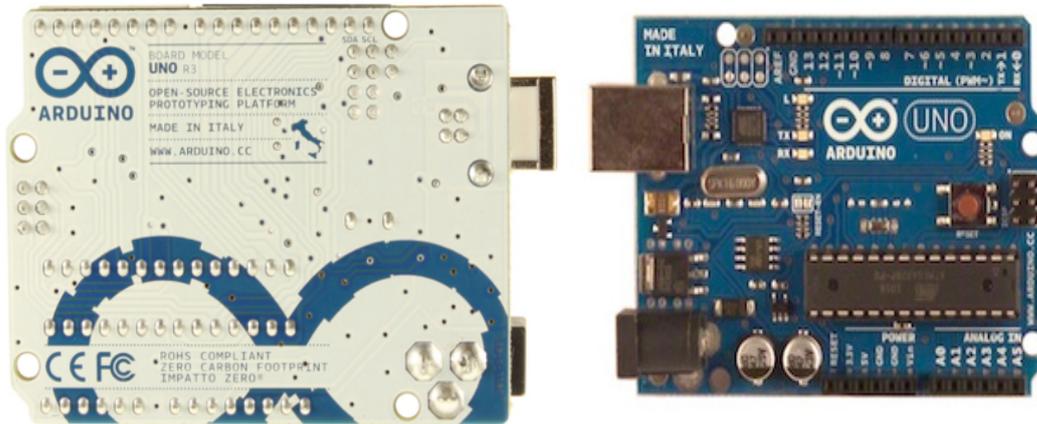
3.1 Arduino Uno Rev3 Microcontroller

One of the first problems which needed to be dealt when the implementation of the project had started was how to establish communication between the attached magnetometers of the plane and the laptop, where the software for magnet's localization was designed and executed. Arduino is an open-source physical computing platform based on a simple microcontroller board, and a development environment for writing software for the board.

Why was the use of Arduino suitable for the project? :

- The development environment is pretty simple to use and is based in C programming language.
- Low cost. The Arduino Microcontroller is pretty cheap compared to other microcontroller platforms available in the market.
- Huge Internet Information of how to use an Arduino . The Arduino Forum provides a huge amount of information of how to use Arduino under any circumstances or needs.
- It is open source. There is no need to buy any updates or extensions for the Arduino since everything is free.
- Runs on all operating systems. So if the need comes to run the project in Linux for example, nothing will have to change.

As it is mentioned above, the Arduino board which was used in the project was the Arduino Uno Rev3:



The Arduino Uno is a microcontroller board, which has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz ceramic resonator, a USB connection, a power jack, an ICSP header, and a reset button. To operate it, the only thing required is to connect it through a USB cable with the computer. The specifications of the Arduino are:

Microcontroller: ATmega328

Operating Voltage: 5V

Input Voltage (recommended): 7-12V

Input Voltage (limits): 6-20V

Digital I/O Pins: 14 (of which 6 provide PWM output)

Analog Input Pins: 6

DC Current per I/O Pin: 40 mA

DC Current for 3.3V Pin: 50 mA

SRAM: 2 KB (ATmega328)

EEPROM: 1 KB (ATmega328)

Clock Speed: 16 MHz

The power pins of the Arduino are as following (we will use 3.3V to power up the magnetometers):

- **VIN.** The input voltage to the Arduino board when it's using an external power source (as opposed to 5 volts from the USB connection or other regulated power source). You can supply voltage through this pin, or, if supplying voltage via the power jack, access it through this pin.
- **5V.** This pin outputs a regulated 5V from the regulator on the board. The board can be supplied with power either from the DC power jack (7 - 12V), the USB connector (5V), or the VIN pin of the board (7-12V). Supplying voltage via the 5V or 3.3V pins bypasses the regulator, and can damage your board.
- **3V3.** A 3.3 volt supply generated by the on-board regulator. Maximum current draw is 50 mA.
- **GND.** Ground pins.
- **IOREF.** This pin on the Arduino board provides the voltage reference with which the microcontroller operates. A properly configured shield can read the IOREF pin voltage and select the appropriate power source or enable voltage translators on the outputs for working with the 5V or 3.3V.

3.2 Magnetometers [9] - [14]

The magnetometers are the most important part of the project. We use them to measure the magnetic field produced by the magnet . More specifically, magnetometer is a measuring instrument, used to measure the strength of magnetic fields. The first magnetometer was created by Carl Friedrich Gauss, who is often called "the Prince of Mathematics," and who published a paper in 1833 describing a new device he called a "magnetometer."

Based on the principle of working, there are different kinds of magnetometers.

3.2.1 Fluxgate Magnetometers:

Fluxgate magnetometers were invented in the 1930s by Victor Vacquier at Gulf Research Laboratories. Vacquier applied them during II as an instrument for detecting submarines and after the war confirmed the theory of plate tectonics by using them to measure shifts in the magnetic patterns on the sea floor.

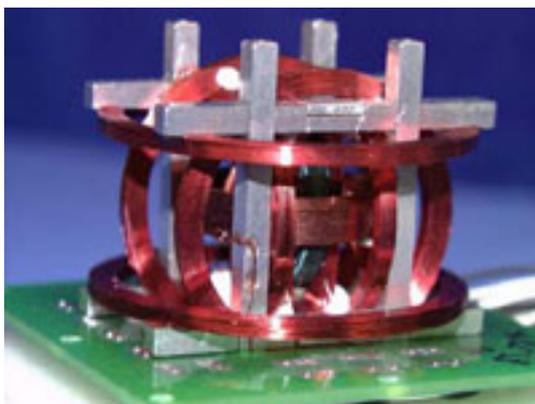
A fluxgate magnetometer consists of a small, magnetically susceptible core wrapped by two coils of wire. An alternating electrical current is passed through one coil, driving the core through an alternating cycle of magnetic saturation; i.e., magnetised, unmagnetised, inversely magnetised, unmagnetised, magnetised, and so forth. This constantly changing field induces an electrical current in the second coil, and this output current is measured by a detector. In a magnetically neutral background, the input and output currents will match. However, when the core is exposed to a background field, it will be more easily saturated in alignment with that field and less easily saturated in opposition to it. Hence the alternating magnetic field, and the induced output current, will be out of step with the input current. The extent to which this is the case will depend on the strength of the background magnetic field. Often,

the current in the output coil is integrated, yielding an output analog voltage, proportional to the magnetic field.

A wide variety of sensors is currently available and used to measure magnetic fields. Fluxgate compasses and gradiometers measure the direction and magnitude of magnetic fields. Fluxgates are affordable, rugged and compact. This, plus their typically low power consumption makes them ideal for a variety of sensing applications. Gradiometers are commonly used for archaeological prospecting and unexploded ordnance (UXO) detection such as the German military's popular *Foerster*.

The typical fluxgate magnetometer consists of a "sense" (secondary) coil surrounding an inner "drive" (primary) coil that is wound around permeable core material. Each sensor has magnetic core elements that can be viewed as two carefully matched halves. An alternating current is applied to the drive winding, which drives the core into plus and minus saturation. The instantaneous drive current in each core half is driven in opposite polarity with respect to any external magnetic field. In the absence of any external magnetic field, the flux in one core half cancels that in the other, and so the total flux seen by the sense coil is zero. If an external magnetic field is now applied, it will, at a given instance in time, aid the flux in one core half and oppose flux in the other. This causes a net flux imbalance between the halves, so that they no longer cancel one another. Current pulses are now induced in the sense coil winding on every drive current phase reversal (or at the 2nd, and all even harmonics). This results in a signal that is dependent on both the external field magnitude and polarity.

There are additional factors that affect the size of the resultant signal. These factors include the number of turns in the sense winding, magnetic permeability of the core, sensor geometry and the gated flux rate of change with respect to time. Phase synchronous detection is used to convert these harmonic signals to a DC voltage proportional to the external magnetic field.



3.2.2 Proton-Precession Magnetometers:

By far the most commonly used magnetometer in both stationary and mobile modes are proton magnetometers. In these instruments the sensor element is water (or some other liquid containing a large number of hydrogen nuclei eg kerosene or methanol) in a small bottle surrounded by a suitable coil. A strong magnetic field (polarizing field), oriented at a large angle to the earth's field direction, is applied by

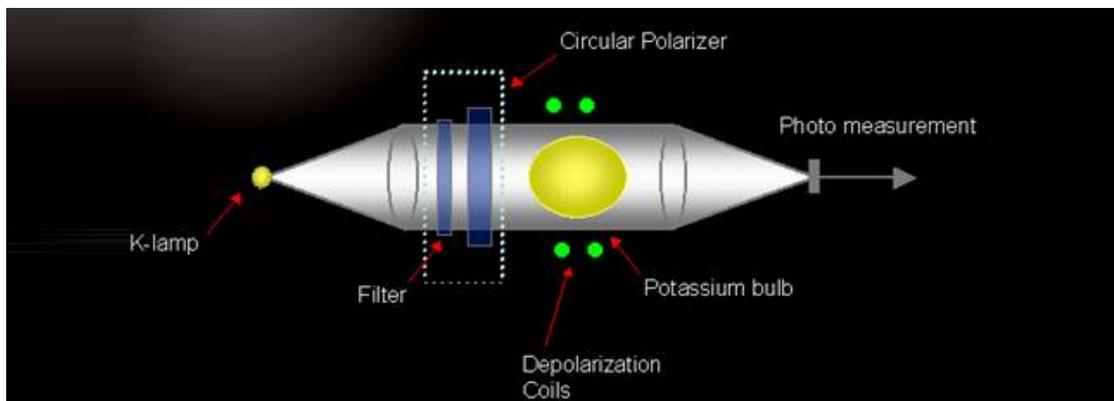
sending a direct current in the coil to displace the protons out of the earth's field. When the polarizing field is switched off, the protons, while returning to their original alignment, precess (to re-align themselves with the "normal" magnetic flux density) for a short time around the direction of the earth's ambient field. The frequency of this precession is related to the absolute earth's field through a well known constant, - the gyrometric ratio of the proton. The measured frequency divided by the gyrometric ratio gives the value of the earth's total field.

An important advantage of instruments constructed on this principle is that orientation of the sensor is not critical. The only requirement is that the polarizing field should make a sufficiently great angle with the direction of earth's field. Also, in contrast to the fluxgate magnetometers, which can measure the field continuously, the proton magnetometers give a series of discrete measurements at intervals of a few seconds because of the polarizing and relaxing time taken by the protons.



3.2.3 Alkali-Vapour (or Optically Pumped) Magnetometers:

These instruments (also called optical absorption magnetometers or optically pumped magnetometers) operate on the principle of optical pumping, a development in radiofrequency spectroscopy based on irradiating alkali metal (eg rubidium, cesium) atoms with spectral beams of appropriate frequency. Like a proton magnetometer, the alkali-vapour magnetometer measures the total ambient field, and the orientation of the instrument is not critical. The sampling rate of the instrument is much higher than that of proton magnetometers.



3.2.4 Magnetic Gradiometers:

A magnetic gradiometer can be considered to be a differential magnetometer where the spacing between two sensors of the same type is fixed and small with respect to the distance to the sources whose fields are measured. The difference in measured field intensity divided by the vertical distance between sensors is taken to be the gradient at the midpoint of sensor spacing.

Gradient measurements are free from noise coherent in time, such as the time variations of the earth's field (diurnal variations). Gradiometers are also used to suppress noise effects from regional (distant) sources to emphasize anomalies from shallow sources. This application can be considered as a distance filter. Anomalies vary inversely with distance at a rate one order higher for a gradiometer than for a magnetometer. The utility of these instruments to survey through periods of high temporal magnetic variations (especially in regions of high magnetic latitude) is considered to be their major advantage.



3.2.5 Vector magnetometers:

Vector magnetometers measure one or more components of the magnetic field electronically. Using three orthogonal magnetometers, both azimuth and dip (inclination) can be measured. By taking the square root of the sum of the squares of the components the total magnetic field strength (also called total magnetic intensity, TMI) can be calculated by Pythagoras's theorem.

Vector magnetometers are subject to temperature drift and the dimensional instability of the ferrite cores. They also require leveling to obtain component information, unlike total field (scalar) instruments. For these reasons they are no longer used for mineral exploration.

3.2.8 SQUID magnetometer:

SQUIDs, or superconducting quantum interference devices, measure extremely small magnetic fields. They are very sensitive vector magnetometers, with noise levels as low as $3 \text{ fT Hz}^{-1/2}$ in commercial instruments and $0.4 \text{ fT Hz}^{-1/2}$ in experimental devices. Many liquid-helium-cooled commercial SQUIDs achieve a flat noise spectrum from near DC (less than 1 Hz) to tens of kilohertz, making such devices ideal for time-domain biomagnetic signal measurements. SERF atomic magnetometers demonstrated in laboratories so far reach competitive noise floor but in relatively small frequency ranges.

SQUID magnetometers require cooling with liquid helium (4.2 K) or liquid nitrogen (77 K) to operate, hence the packaging requirements to use them are rather stringent both from a thermal-mechanical as well as magnetic standpoint. SQUID magnetometers are most commonly used to measure the magnetic fields produced by brain or heart activity (magnetoencephalography and magnetocardiography, respectively). Geophysical surveys use SQUIDS from time to time, but the logistics is much more complicated than coil-based magnetometers.

3.3 MAG3110 Magnetometers

The 5 magnetometers used in this project are the MAG3110 magnetometers, product of Freescale. They were bought from the Greek site : grobotronics.com . They were low cost with the best sensitivity and price combination from any other product found on the internet through the market research. The site provides them in a breakout board with all the necessary pull-up resistors and capacitors on it so there is no need for us to design the circuit for the magnetometer to work properly.

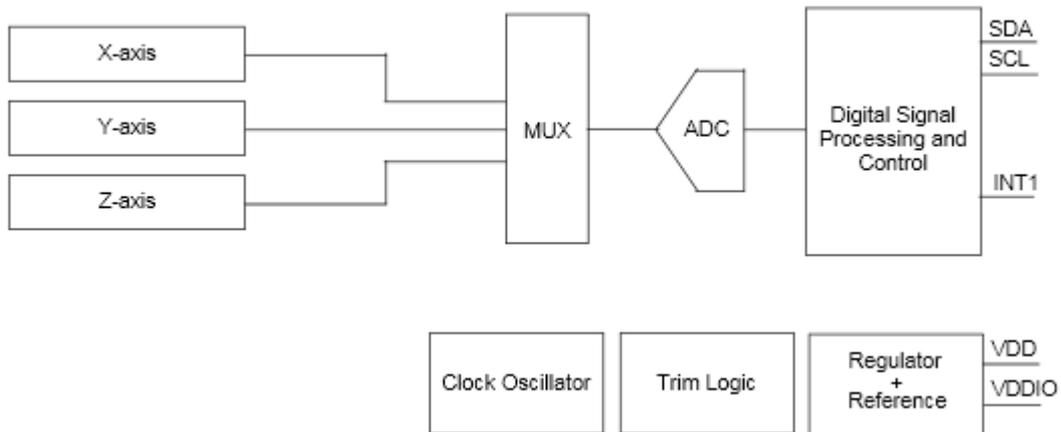
One more important asset this product has and made it suitable for the project, is the size of the magnetometer(with the breakout board), 13.3 x 14.5 mm, cause small size is very important for the project.

MAG3110 is a small, low power, digital 3-axis magnetometer, composed of 3 1-axis magneto resistive magnetic sensors.

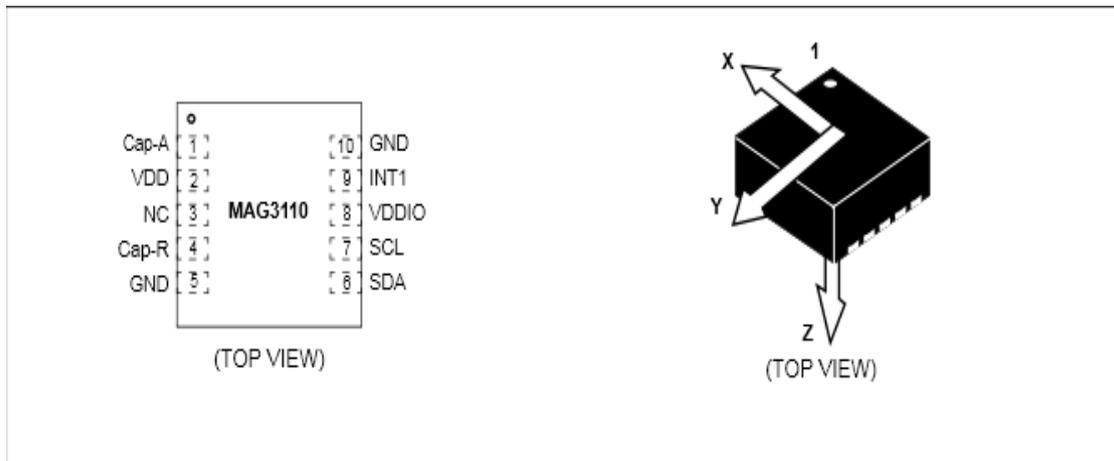
The MAG3110 features :

- 1.95V to 3.6V Supply Voltage (VDD)
- 1.62V to VDD IO Voltage (VDDIO)
- Ultra Small 2 mm x 2 mm x 0.85 mm, 0.4 mm Pitch, 10 Pin Package
- Full Scale Range $\pm 1000 \mu\text{T}$
- Sensitivity of $0.10 \mu\text{T}$
- Noise down to $0.25 \mu\text{T rms}$
- Output Data Rates (ODR) up to 80 Hz
- I2C digital output interface (operates up to 400 kHz Fast Mode)
- 7-bit I2C address = 0x0E
- Sampled Low Power Mode
- RoHS compliant

Block diagram of MAG3110:



Pin Description of MAG3110:



Pin	Name	Function
1	Cap-A	Bypass Cap for Internal Regulator
2	VDD	Power Supply, 1.95V – 3.6V
3	NC	Do not connect.
4	Cap-R	Cap for Reset Pulse
5	GND	GND
6	SDA	I ² C Serial Data (Write = 0x1C; Read = 0x1D)
7	SCL	I ² C Serial Clock
8	VDDIO	Power for I/O Buffers, 1.65V - VDD
9	INT1	Interrupt - Active High Output
10	GND	GND

MAG3110 communicates with the Arduino through the I2C bus that the magnetometer and the Arduino support. How this is possible for more than one magnetometer will be explained later on. The MAG3110 also has an interrupt signal indicating that new magnetic data readings are available. Interrupt driven sampling allows operation without performing it manually through the software. The Digital Interface of the magnetometer, as it is also used in the project, consists of the following pins:

VCC : IO voltage

GND : ground

SCL : I2C serial clock

SDA : I2C serial data

INT : data ready interrupt pin

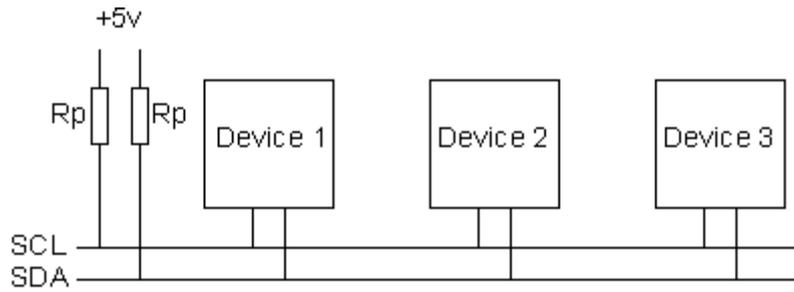
The last one is not used in the implementation, as continuous measurements are required.

3.3.1 How does I2C bus work? ^[15]

In the project, as mentioned above, the magnets communicate with the Arduino through the I2C bus. A simple explanation about how does the I2C bus work follows:

3.3.1.1 The physical I2C bus

there are just two wires, called SCL and SDA. SCL is the clock line. It is used to synchronize all data transfers over the I2C bus. SDA is the data line. The SCL & SDA lines are connected to all magnetometers on the I2C bus. There needs to be a third wire which is just the ground or 0 volts. There may also be a 5V wire is power is being distributed to the magnetometers. Both SCL and SDA lines are "open drain" drivers. What this means is that the chip can drive its output low, but it cannot drive it high. For the line to be able to go high pull-up resistors must be provided to the 5V supply (our breakout board provides them).

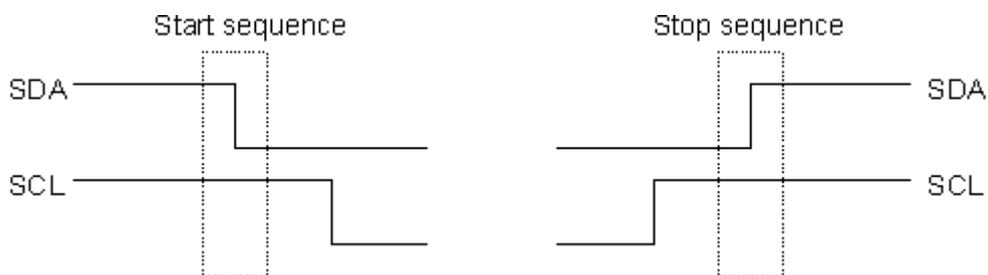


3.3.1.2 Masters and Slaves

The devices on the I2C bus are either masters or slaves. The master is always the device that drives the SCL clock line. The slaves are the devices that respond to the master. A slave cannot initiate a transfer over the I2C bus, only a master can do that. There can be, and usually are, multiple slaves on the I2C bus, however there is normally only one master. It is possible to have multiple masters too. On this project, Arduino is the Master and the Magnetometers are the slaves. Slaves will never initiate a transfer. Both master and slave can transfer data over the I2C bus, but that transfer is always controlled by the master.

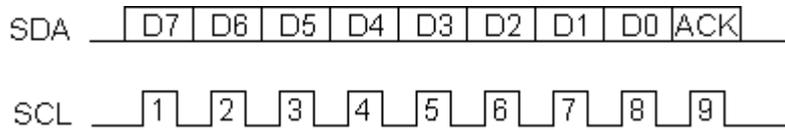
3.3.1.3 The I2C Physical Protocol

When the master (Arduino) wishes to talk to a slave (MAG3110) it begins by issuing a start sequence on the I2C bus. A start sequence is one of two special sequences defined for the I2C bus, the other being the stop sequence. The start sequence and stop sequence are special in that these are the only places where the SDA (data line) is allowed to change while the SCL (clock line) is high. When data is being transferred, SDA must remain stable and not change while SCL is high. The start and stop sequences mark the beginning and end of a transaction with the slave device.



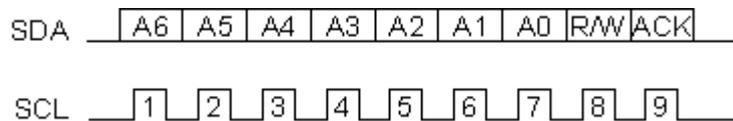
Data is transferred in sequences of 8 bits. The bits are placed on the SDA line starting with the MSB (Most Significant Bit). The SCL line is then pulsed high, then low. Remember that the chip cannot really drive the line high, it simply "lets go" of it and the resistor actually pulls it high. For every 8 bits transferred, the device receiving the data sends back an acknowledge bit, so there are actually 9 SCL clock pulses to transfer each 8 bit byte of data. If the receiving device sends back a low ACK bit, then it has received the data and is ready to accept another byte. If it sends

back a high then it is indicating it cannot accept any further data and the master should terminate the transfer by sending a stop sequence.



3.3.1.4 I2C Device Addressing

All I2C addresses are either 7 bits or 10 bits. The use of 10 bit addresses is rare though. All of our modules and the common chips used have 7 bit addresses. This means that someone can have up to 128 devices on the I2C bus, since a 7bit number can be from 0 to 127. When sending out the 7 bit address, 8 bits are always sent. The extra bit is used to inform the slave if the master is writing to it or reading from it. If the bit is zero the master is writing to the slave. If the bit is 1 the master is reading from the slave. The 7 bit address is placed in the upper 7 bits of the byte and the Read/Write (R/W) bit is in the LSB (Least Significant Bit).



The placement of the 7 bit address in the upper 7 bits of the byte is a source of confusion. It means that to write to address 21, you must actually send out 42 which is 21 moved over by 1 bit. It is probably easier to think of the I2C bus addresses as 8 bit addresses, with even addresses as write only, and the odd addresses as the read address for the same device. To take MAG3110 for example, this is at address 0x0E.

3.3.1.5 The I2C Software Protocol

The first thing that will happen is that the master will send out a start sequence. This will alert all the slave devices on the bus that a transaction is starting and they should listen in incase it is for them. Next the master will send out the device address. The slave that matches this address will continue with the transaction, any others will ignore the rest of this transaction and wait for the next. Having addressed the slave device the master must now send out the internal location or register number inside the slave that it wishes to write to or read from. This number is obviously dependant on what the slave actually is and how many internal registers it has. Some very simple devices do not have any, but most do. Having sent the I2C address and the

internal register address the master can now send the data byte (or bytes, it doesn't have to be just one). The master can continue to send data bytes to the slave and these will normally be placed in the following registers because the slave will automatically increment the internal register address after each byte. When the master has finished writing all data to the slave, it sends a stop sequence which completes the transaction. So to write to a slave device:

1. Send a start sequence
2. Send the I2C address of the slave with the R/W bit low (even address)
3. Send the internal register number you want to write to
4. Send the data byte
5. [Optionally, send any further data bytes]
6. Send the stop sequence.

In the Arduino source code that is implemented in the project , it goes like this :

```
Wire.beginTransmission(MAG_ADDR); // transmit to device 0x0E

Wire.write(0x11);           // cntrl register2

Wire.write(0x80);           // write 0x80, enable auto resets

Wire.endTransmission();    // stop transmitting
```

3.3.1.6 Reading from the Slave

Before reading data from the slave device, one must tell it which of its internal addresses wants to read. So a read of the slave actually starts off by writing to it. This is the same as when wanting to write to it: send the start sequence, the I2C address of the slave with the R/W bit low (even address) and the internal register number to write to. Now send another start sequence (sometimes called a restart) and the I2C address again - this time with the read bit set. You then read as many data bytes as you wish and terminate the transaction with a stop sequence. So to read the compass bearing as a byte from the CMPS03 module:

1. Send a start sequence
2. Send 0x0E (I2C address of the MAG3110)
3. Send 0x01 (Internal address of the bearing register)
4. Stop sequence.
4. Send a start sequence again (repeated start)
5. Send 0x0E (I2C address of the MAG3110)
6. Read data byte from MAG3110
7. Send the stop sequence.

In our source code this is implemented like this :

```
Wire.beginTransmission(MAG_ADDR); // transmit to device 0x0E

Wire.write(0x01);           // x MSB reg

Wire.endTransmission();    // stop transmitting

delayMicroseconds(100); //needs at least 1.3us free time between start and stop

Wire.requestFrom(MAG_ADDR, 1); // request 1 byte

while(Wire.available()) // slave may write less than requested
{
    xh = Wire.read(); // read the byte
}
```

3.4 Magnets

In order to conduct the experiments and to test the system, cylinder neodymium magnets were used. The dimensions of the magnets are :

Diameter: 6mm,

Height: 3mm.

Here is a picture of how the magnets look like:



Note: For the project only 1 magnet is needed.

3.4.1 Why use so small magnets?

Discreetness is needed. The magnets are going to be attached on a scalpel, so they have to be as small as possible, in order not to prevent the doctor from performing the surgery without obstacles or not fast enough.

The magnets were bought from [eBay](#), from the company under the name [Spider Magnets](#).

3.4.2 Why use neodymium magnets??

- Neodymium magnets (NdFeB or Neo) consist of a sintered alloy of the rare-earth element neodymium with iron and boron. The alloy has very high

coercivity, magnetic remanence and energy and is stronger than any other permanent magnet material. Neodymium magnets are manufactured in a large number of grades. The material grade determines the energy and thermal characteristics of the magnet.

3.4.3 Why use N52 neodymium magnets? What does N52 stand for? [16]

N52 neodymium magnets are the strongest magnets and produce a stronger magnetic field than any other grade of neodymium magnet with the same size as them.

The Neodymium magnets have a simple nomenclature. They all start with "N" which simply stands for "Neo" (industry simplification of Neodymium) and is followed by a two digit number.

This number represents the maximum energy product in Mega-Gauss Oersteds (MGOe) where 1MGOe (cgs units) equals 7958kJ/m³ (SI units). The range available used to be N24 up to N52. The lower grades are no longer made and the range now starts at around N30 or N33. N52 is the highest readily available grade. Although the maximum possible energy product is calculated in to be N64, it is unlikely such high strengths of Neodymium will be achievable in the near future (when the newest grades are commercially available they are often available only for direct sale into military applications).

A suffix letter (or two letters) may then follow the number. The letters actually indicate the Intrinsic Coercivity (Hci) of the material. The higher the Hci, the higher the temperature the Neodymium magnet material can be exposed to before the magnet will start to show permanent losses in output. It is this fact that is used to link the last letter(s) to a temperature rating.

The current range of Neodymium Iron Boron magnets is as follows:-

N27, N30, N33, N35, N38, N40, N42, N45, N48, N50, N52, N30M, N33M, N35M, N38M, N40M, N42M, N45M, N48M, N50M, N30H, N33H, N35H, N38H, N40H, N42H, N45H, N48H, N30SH, N33SH, N35SH, N38SH, N40SH, N42SH, N45SH, N28UH, N30UH, N33UH, N35UH, N38UH, N40UH, N28EH, N30EH, N33EH, N35EH, N38EH, N33VH/AH.

However, the temperature rating for Neodymium is merely a guide value. It is the physical size and shape of the NdFeB magnet and the total magnetic circuit that actually determines how well a magnet will perform at raised temperature. For example a NdFeB magnet in free space will demagnetize at a lower temperature than the same sized NdFeB magnet connected to a piece of mild steel. It will also demagnetize at a lower temperature than a NdFeB magnet of twice the length in the direction of magnetization. The Intrinsic curve shape also plays a part in the temperature performance of NdFeB.

For the magnets used in this project the specifications are :

N52	Remenance[Br] Gauss (mT)	14300-14800 (1430-1480)
	Coercivity[bHc] Oersted (kA/m)	>10000 (>796)
	Energy Product[BHmax] MGOe (kJ/m³)	50-53 (398-422)
	Intrinsic Coercivity[jHc] Oersted (kA/m)	>11000 (>876)
	Max Operating Temp °C (°F)	60 (140)
	Surface Flux Density Gauss (mT)	5230 (523)
	Calculated Pull* (g)	1425

In the implementation of the project the magnet was moved in any position and in any orientation within the 3d area (imagine it as a cube), that the plane, where the magnets are attached, defines **(Picture 1)**.

In the final implementation of the project, the magnet will be attached on the scalpel.

If this is the scalpel:



The magnet is attached like this:



The distance between the surface of the magnet and the edge of the scalpel will be known, so when the position of the magnet is calculated, the known distance between the magnet and the edge will be known, so the position of the scalpel will be easily detected.

Chapter 4: Steps towards the implementation of the project:

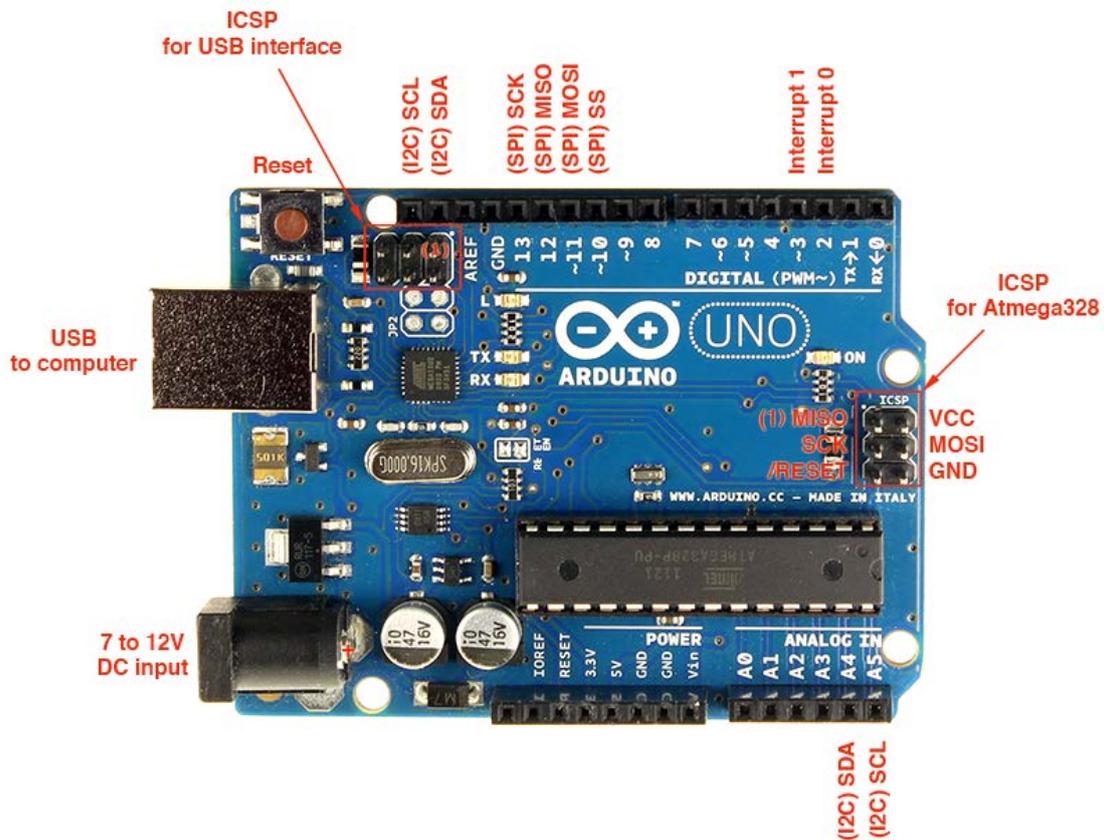
4.1 Connecting multiple I2C devices to the Arduino I2C.

One of the problems that had to be dealt in order for the implementation to work properly was how to connect multiple I2C devices, **with the same address**, with the Arduino I2C pins.

If the 5 MAG3110 had different addresses with each other, then the connection would be pretty simple. A simple board would be used to connect all the Devices to the I2C pins, which the Arduino Uno Rev3 provides and every device would be easy to access just by giving the address of the device.

Unfortunately, all 5 MAG3110 have the same address, so some kind of multiplexer should be constructed in order to connect simultaneously all 5 Magnetometers to the Arduino.

The Arduino Uno Rev3, which is used in this project provides 2 I2C pins (2 SDA and 2 SCL pins) as it can be seen in the image below:



Since there are 5 magnetometers, 10 I2C pins are needed (5 SDA and 5 SCL pins).

There were 2 solutions to this problem:

- 1) Buy an I2C multiplexer or,
- 2) Use some other pins of the Arduino as I2C pins.

The first solution seems easier to implement, since it is simpler. All that is needed is to connect each pin of the I2C multiplexer to the corresponding pins of the Magnetometers. The drawbacks are, that this implementation costs money to buy the multiplexer, plus time, considering the fact that the multiplexer must be ordered first, so it will take a couple of days to be delivered. Moreover, the multiplexer is very small, so it will need time to design the circuit, in which the pins of the magnetometer will be connected in order to be controlled by the multiplexer.

So the second solution was preferred. The difficult part was that this idea, to use other pins of the Arduino as I2C pins, was not an easy task, considering the fact that there was no library provided by the Arduino site. Searching the Internet, resulted in finding a library called "[SoftI2Cmaster.h](http://todbot.com/blog/)" provided from [Tod E. Kurt](http://todbot.com/blog/), <http://todbot.com/blog/>.

SoftI2CMaster is an Arduino library that implements a simple "bit-bang" software-only I2C (aka "TWI") Master.

This allows using any two Arduino pins to be the SDA & SCL pins needed to communicate with I2C devices like BlinkMs.

So, after this, the code to use this library had to be designed in order to establish I2C communication between the Arduino and the 5 Magnetometers.

Below is a brief Explanation of some parts of the Code Designed for this task:

```
#include "SoftI2CMaster.h" //Here we include the library
```

Definition of the Digital pins which will be used as clocks(the numbers refer to the digital pins of the arduino

```
#define SCL_PIN1 5  
#define SCL_PIN2 7  
#define SCL_PIN3 9  
#define SCL_PIN4 11  
#define SCL_PIN5 13
```

Definition of the Digital Pins which will be used as SDAs

```
#define SDA_PIN1 4  
#define SDA_PIN2 6  
#define SDA_PIN3 8  
#define SDA_PIN4 10
```

```
#define SDA_PIN5 12
```

After the definition is completed, the pins which will be used are provided to the library in order to perform the necessary changes, so that these pins will be able to perform I2C communication. It is reminded, that since 5 Magnetometers are used , 10 pins are needed, 5 for SDA and 5 for SCL. It is advised that the SDA and the SCL pin, which will be connected to the same magnetometer, to be next to each other , so that confusions will be avoided and the proper connections will be established. The instances are being created (i2c1,i2c2,etc..) which will allow to use the functions required in order to receive and send data with each magnetometer.

```
SoftI2CMaster i2c1 = SoftI2CMaster (SDA_PIN1, SCL_PIN1);  
SoftI2CMaster i2c2 = SoftI2CMaster (SDA_PIN2, SCL_PIN2);  
SoftI2CMaster i2c3 = SoftI2CMaster (SDA_PIN3, SCL_PIN3);  
SoftI2CMaster i2c4 = SoftI2CMaster (SDA_PIN4, SCL_PIN4);  
SoftI2CMaster i2c5 = SoftI2CMaster (SDA_PIN5, SCL_PIN5);
```

Here we configure consecutively each magnetometer

```
void setup(void)  
{  
  Serial.begin(9600);  
  
  i2c_config (1);  
  i2c_config (2);  
  i2c_config (3);  
  i2c_config (4);  
  i2c_config (5);  
}
```

Here we use this loop in order to continuously read each magnetometer consecutively.

```
void loop(void)  
{
```

```

if (Serial.read() == 'a' )
{
    i2c_transaction (1);
    // delay (1000);
    i2c_transaction (2);
    // delay (1000);
    i2c_transaction (3);
    // delay (1000);
    i2c_transaction (4);
    // delay (1000);
    i2c_transaction (5);
    // delay (1000);
}
}

```

Note: The magnetometers are read consecutively, since the master (the Arduino) can communicate with only one Device (MAG3110) at a time. This process takes only a few ms to be performed.

4.2 Calibration of the magnetometers. [17] - [24]

4.2.1 What is calibration?

- Calibration refers to the process of determining the relation between the output (or response) of a measuring instrument and the value of the input quantity or attribute, a measurement standard. In non-specialized use, calibration is often regarded as including the process of adjusting the output or indication on a measurement instrument to agree with value of the applied standard, within a specified accuracy.

For example, a thermometer could be calibrated so the error of indication or the correction is determined, and adjusted (e.g. via calibration constants) so that it shows the true temperature in Celsius at specific points on the scale.

- In biomedical technology and other fields, calibration is the setting or correcting of a measuring device or base level, usually by adjusting it to match or conform to a dependably known and unvarying measure.

4.2.2 Why do the magnetometers need to be calibrated?

- Magnetometers, as explained above, measure the magnetic field which they detect depending on their sensitivity. For various reasons, which will be explained below, the magnetic fields can vary within the range of the magnetometers' measurement capability. So, in the case where only one magnetic field needs to be detected (in this project the magnetic field produced by the magnet), the presence of the other magnetic fields can also be detected by the magnetometers. These results, in measurements, which do not reflect the correct measurement of the magnet's magnetic field. In other words, noise is being added in the measurements, which needs to be reduced to the lowest level possible, so that the measurements are reliable and therefore the position of the magnet can be detected with the least error position, making the system reliable and suitable for use.

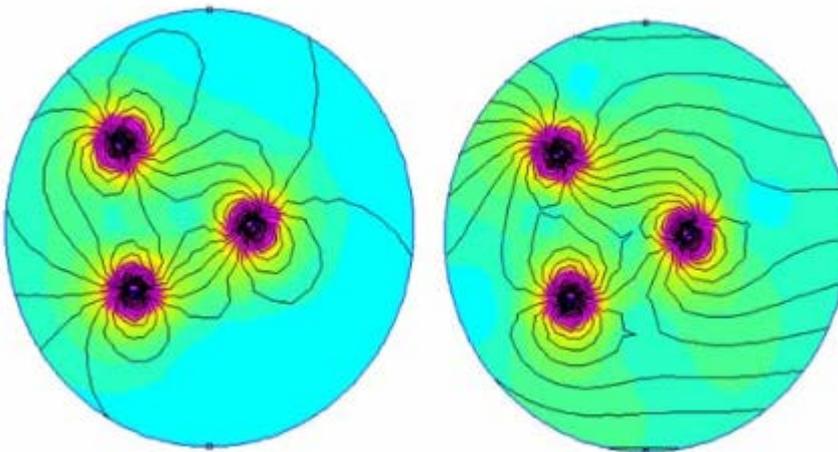
4.2.3 What kind of interferences does the calibration method reduce?

- As mentioned above, purpose of the calibration is to take the raw measurements of the magnetometers (raw measurements are the measurements taken from the magnetometers and need to be processed), extract the noise and then send the processed measurements to be used for the calculation of the position of the magnet.

What are the interferences which the calibration has to deal with?

- Bias or offset, refer to the indications provided by the magnetometers, when no magnetic field is present. This constant offset produced by the sensor is in some cases as large as about 25% of the full signal range measured during normal operation. The amount of bias varies from sensor to sensor, but is very repeatable from test to test for an individual sensor. Bias' presence in the magnetic field can result to errors in the estimation of the magnet's position.

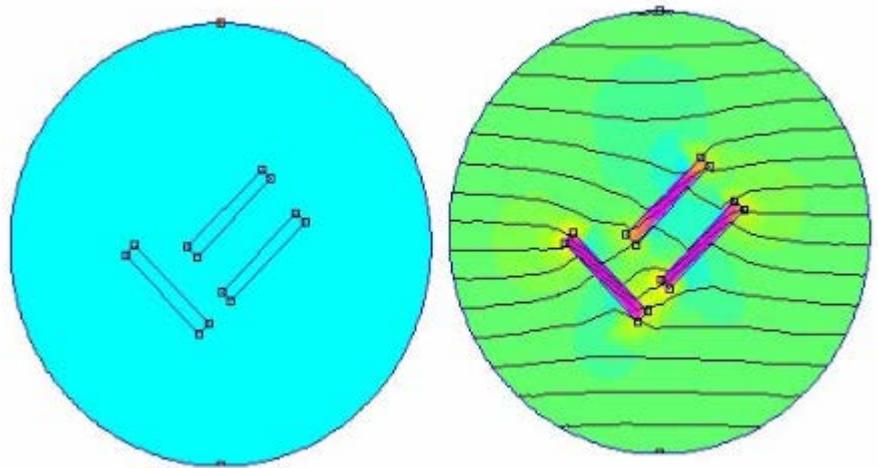
- Hard iron effects, refer to interferences which are generated by permanently magnetized ferromagnetic components (for example, ferromagnetic components are the audio speakers). Permanently magnetized components also create permanent induced magnetic fields in normally unmagnetized ferromagnetic materials in their vicinity and these are also included as 'hard iron' fields. Since the magnetometers on the plane (**Picture 1.**) are in fixed positions with respect to each other, the hard iron interference manifests as an additive magnetic field vector when measured in the magnetometer reference frame. It makes little sense for manufacturers to supply carefully calibrated magnetometers with no zero field offset into the market since the magnetometer will be exposed to an unknown additive hard iron field. So it is crucial to calibrate the magnetometers every time they are set to work.



Picture 2. Hard iron interference in a uniform magnetic field

In **Picture 2**, there is an example of a hard iron interference in a uniform magnetic field. On the left is the magnetic field created by three permanent magnets in the absence of external magnetic fields, whereas on the right is the total magnetic field resulted from the three permanent magnets and the external magnetic field. A magnetometer without the presence of a calibration method, which can detect the magnetic field of the magnets, will measure the sum of the magnetic field of the magnets plus the external magnet field, resulting in a wrong measurement and therefore in a wrong position estimation. Even in the presence of a calibration method, it is strongly advised to place the magnetometers away from strongly magnetized ferromagnetic materials.

- Soft-iron effect , unlike to hard-iron effect where the magnetic field is additive to the earth's field, 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. Soft iron effects are more complex to model than hard iron since the induced soft iron magnetic field depends on the relative orientation of the magnetometer to the earth's geomagnetic field.



Picture 3. Soft iron interference of a uniform magnetic field

In picture 3, an example of soft iron interference is illustrated. The three unmagnetized ferromagnetic bars are set in different orientations. On the left there is no external magnetic field, therefore there is no magnetic field at all. On the right, the sum of the induced magnetic field in the bar and the external magnetic field is being shown. The bars are magnetized by the external magnetic field and direct it along their axes.

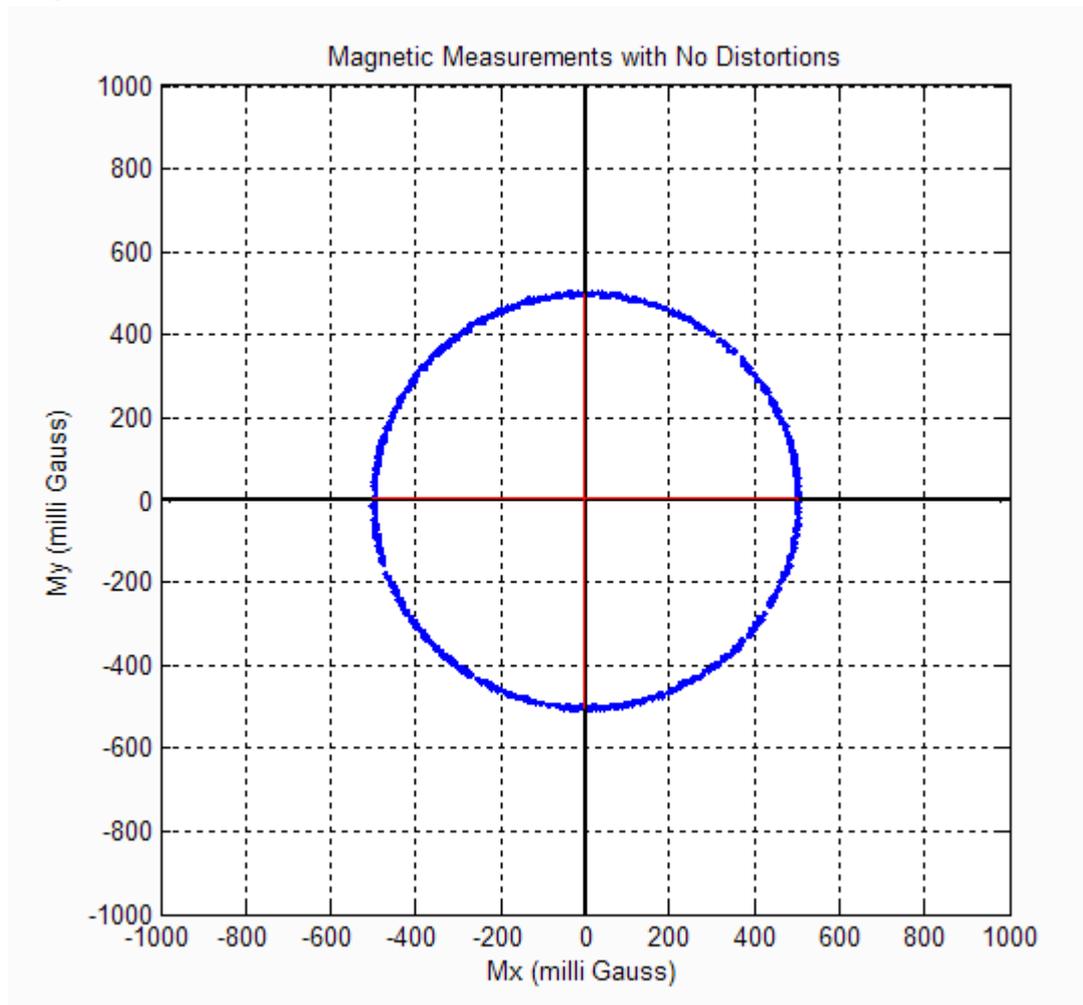
- Scale factors .For example in a 3-axis magnetometer, like the ones used in the project, there is one sensor for each axis(x,y,z). Each sensor of the 3 has a different sensitivity compared to the other 2. So, if the sensitivity on the sensor measuring the Z axis is bigger than the sensitivity the other 2

sensors have, these sensors need to be scaled with each other in order to acquire a correct measurement.

4.2.4 How are hard-iron and soft-iron effects visualized?

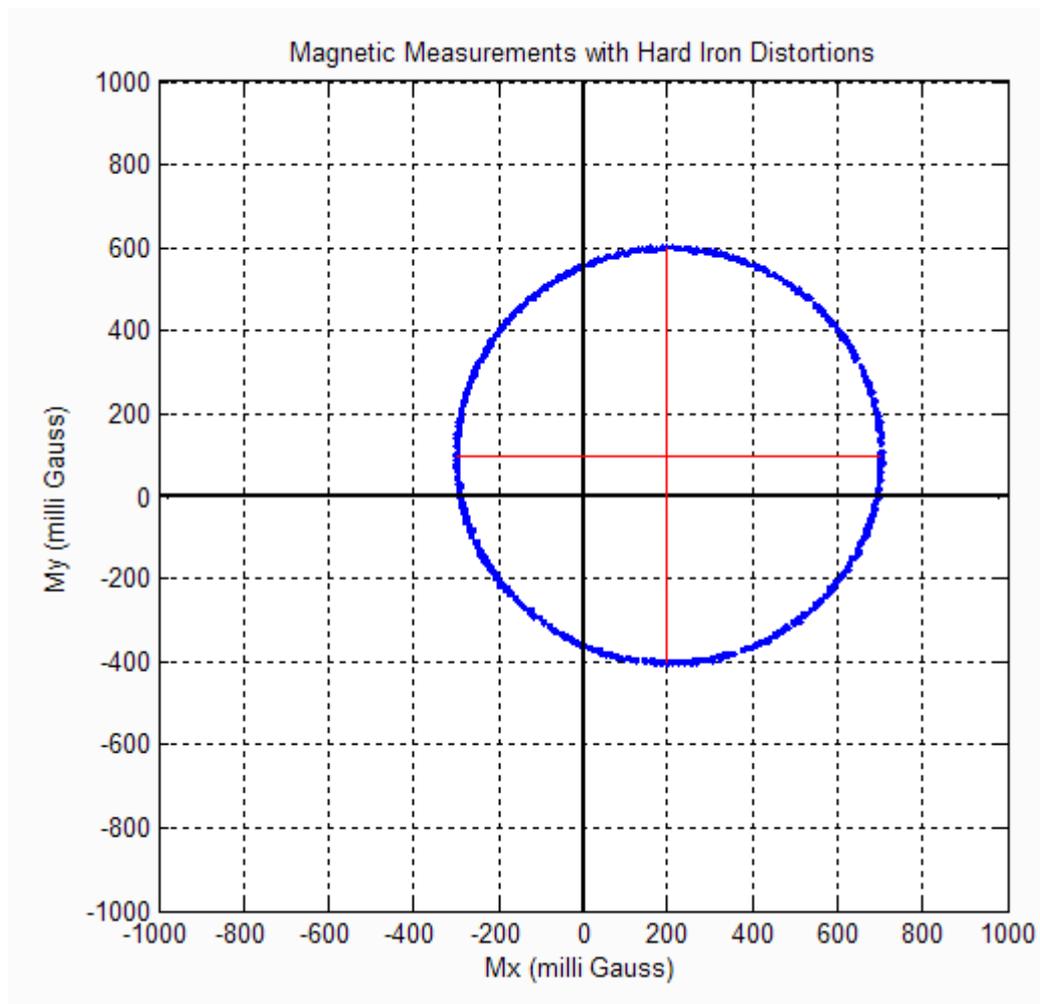
Using plots from the internet referring to a magnetometer, here is a presentation of the visualization of the effects using 2D graphs.

Graph 1 - No Interferences



In the event that there are no hard or soft iron distortions present, the measurements should form a circle centered at $X=0$, $Y=0$. The radius of the circle equals the magnitude of the magnetic field. Hard iron distortions will cause a permanent bias to be present in the outputs. The effect of hard iron distortions on the plot will be to shift the center of the circle.

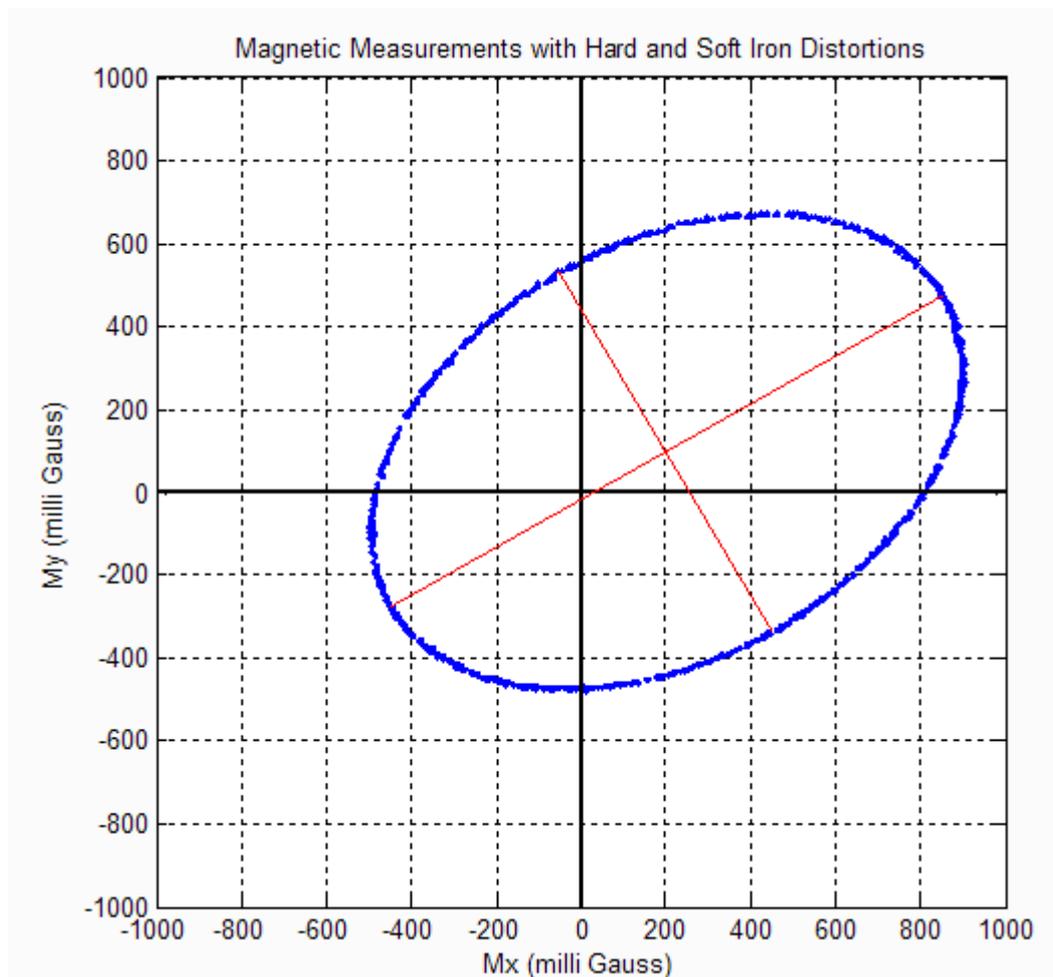
Graph 2 - Hard-Iron Interferences



As it can be seen the center of the circle with hard iron distortions is now at X=200, Y=100. Therefore, there is 200 mGauss hard iron bias in the X-axis and 100 mGauss hard iron bias in the Y-axis. Hard iron distortions will only

shift the center of the circle away from the origin. Hard iron distortions will not distort the shape of the circle. Soft iron distortions on the other hand distort and warp the existing magnetic fields. When you plot the magnetic output soft iron distortions are easy to recognize since they will distort the circular output. Soft Iron effects warp the circle into an elliptical shape.

Graph 3 - Hard-Iron and Soft-Iron Interferences



As shown in the above magnetometer output, there is an ellipse instead of a circle. The center of the ellipse is still located at $X=200$ mGauss and $Y=100$ mGauss since the hard iron distortions are the same as before. Every ellipse has a major and minor axis which corresponds to the long and short

dimensions respectfully. As shown in the above plot the ellipse has its major axis aligned 30 degrees up from the body frame X direction.

4.2.5 How are all these effects eliminated?

From the above information becomes clear that in order to eliminate these effects we have to find the ellipsoid which best fits the raw measurements of the magnetometer. In other words, we have to perform an ellipsoid fitting algorithm using the raw measurements acquired from the magnetometers. Searching in the Internet, a Matlab implementation of ellipsoid fitting algorithm was found, Ellipsoid fitting by Q Li. The code implements a special case of the ellipsoid fitting technique proposed in the paper "Least Squares Ellipsoid Specific Fitting", corresponding to case $k=4$.

Chapter 5: Implementation of the calibration algorithm.

Important Note: Each magnetometer has to be calibrated separately because every magnetometer's measurements, as it was noticed, differ from the other magnetometers' measurements, so the calibration factors are going to be different as well. There were 2 methods tested. It is important to point out that the second method is by far more reliable and safe to use.

The first method is based on the fact that the magnetometers are being steady. So by removing near the magnetometers any possible object which can produce magnetic field and interfere with the sensors the offsets for each axis of every sensor are being measured. Then when the measurements are acquired when we move the magnet near the magnetometers we subtract the offset from each measurement like this:

SensorOutput1 - offset1

SensorOutput2 - offset2

SensorOutput3 - offset3

SensorOutput4 - offset4

SensorOutput5 - offset5

Where SensorOutput1- SensorOutput5 and offset1 - offset5 consist of three parameters , one for each axis. This method worked pretty well for this project.

Second method: for each magnetometer a large number of measurements n is acquired by holding steady the position of the magnetometer and changing its orientation in all possible ways.

After the rotation is completed, the measurement values x_1, y_1, z_1 to x_n, y_n, z_n which were saved in a .txt file are imported into the Matlab code in order to build the matrix D:

$$D = \begin{bmatrix} x_1^2 & x_2^2 & x_3^2 & \dots & x_n^2 \\ y_1^2 & y_2^2 & y_3^2 & \dots & y_n^2 \\ z_1^2 & z_2^2 & z_3^2 & \dots & z_n^2 \\ 2y_1z_1 & 2y_2z_2 & 2y_3z_3 & \dots & 2y_nz_n \\ 2x_1z_1 & 2x_2z_2 & 2x_3z_3 & \dots & 2x_nz_n \\ 2x_1y_1 & 2x_2y_2 & 2x_3y_3 & \dots & 2x_ny_n \\ 2x_1 & 2x_2 & 2x_3 & \dots & 2x_n \\ 2y_1 & 2y_2 & 2y_3 & \dots & 2y_n \\ 2z_1 & 2z_2 & 2z_3 & \dots & 2z_n \\ 1 & 1 & 1 & \dots & 1 \end{bmatrix}$$

(Matrix D has 10 rows x n columns.)

Now create the 10x10 symmetric matrix S by multiplying D by its own transpose D^T :

$$D \cdot D^T = S \quad \text{In Matlab code : } S=D \cdot D';$$

Now split the 10x10 S matrix in 4 smaller matrices as follows:

$$S = \begin{bmatrix} S_{11}(6 \times 6) & S_{12}(6 \times 4) \\ S_{12}^T(4 \times 6) & S_{22}(4 \times 4) \end{bmatrix}$$

Because S is a symmetric matrix, S_{12}^T is the transpose of S_{12} .

Calculate S_{22}^{-1} , the Moore-Penrose pseudo-inverse of the square matrix S22.

Note: the pseudo-inverse of a square matrix is identical to its inverse, except if the matrix is singular, which should not occur unless you have a really bad or incomplete sample of measurements.

$$\text{Calculate } SS = S_{11} - S_{12} * S_{22}^{-1} * S_{12}^T .$$

$$\text{First calculate } S_{22a} = S_{22}^{-1} * S_{12}^T .$$

$$\text{Then calculate } S_{22b} = S_{12} * S_{22a} .$$

$$\text{Finally calculate } SS = S_{11} - S_{22b} .$$

Setup the constraint matrix C:

$$C(6,6)=0;$$

```
C(1,1)=-1; C(2,2)=-1; C(3,3)=-1;
```

```
C(4,4)=-4; C(5,5)=-4; C(6,6)=-4;
```

```
C(1,2)=1; C(2,1)=1;
```

```
C(1,3)=1; C(3,1)=1;
```

```
C(2,3)=1; C(3,2)=1;
```

Invert matrix C in place.

Calculate $E = C * SS$.

Calculate eigenvalues wr(6x1) and eigenvectors vr(6x6) of matrix E . In Matlab this is implemented as : `[gevec, geval]=eig(E);`

Find the zero-based position of the only positive eigenvalue. The associated eigenvector will be in the corresponding column of matrix vr(6x6). Matlab code:

```
In=1;
maxVal=geval(1,1);
for i=2:6
    if (geval(i,i)>maxVal)
        maxVal=geval(i,i);
        In=i;
    end;
end;
```

Find the fitting:

```
v1=gevec(:, In);
v2=-pinv(S22)*S12*v1;
v=[v1; v2];
```

The algorithm described above is the algorithm which was implemented by Q Li. The rest of the code had to be implemented on Matlab, cause of the fact that there was not a so fast calibration code for magnetometer using ellipsoid fitting technique available. So the steps described below are the steps which were followed too in order to design the rest of the Matlab code.

Continuing from the previous page, the vector v was calculated .
At this point the general equation of the fitted ellipsoid was found :

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

where :

$$\begin{aligned} A &= v[0] && \text{- term in } x^2 \\ B &= v[1] && \text{- term in } y^2 \\ C &= v[2] && \text{- term in } z^2 \end{aligned}$$

- D = v[5] - term in xy
- E = v[4] - term in xz
- F = v[3] - term in yz
- G = v[6] - term in x
- H = v[7] - term in y
- I = v[8] - term in z
- J = v[9] - constant term .

Note the different order of terms in xy, xz and yz between this general equation and the matrix D above, which explains why we find the order v[5], v[4], v[3] instead of v[3], v[4], v[5].

Quadric Surfaces in Matrix Form

The equation of a general quadric can also be put into matrix form:

$$\mathbf{x} = \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \quad \mathbf{x}^T = [x, y, z, 1] \quad \mathbf{Q} = \begin{bmatrix} A & D & E & G \\ D & B & F & H \\ E & F & C & I \\ G & H & I & J \end{bmatrix}$$

where (x, y, z) is the coordinates of a point. This form translates the general second polynomial of a quadric to the following matrix form:

$$\mathbf{x}^T \mathbf{Q} \mathbf{x} = 0$$

Defining:

$$\mathbf{Q} = \begin{bmatrix} A & D & E \\ D & B & F \\ E & F & C \end{bmatrix} \quad \mathbf{U} = \begin{bmatrix} G \\ H \\ I \end{bmatrix}$$

Then the center of the ellipsoid can be calculated as the vector
 $\mathbf{B} = -\mathbf{Q}^{-1} * \mathbf{U}$.

The center of the ellipsoid as it is mentioned above represents the combined bias.

Setup symmetric matrix Q (3x3).

Setup vector U.

Calculate matrix \mathbf{Q}^{-1} , the inverse of matrix Q.

Calculate $\mathbf{B} = \mathbf{Q}^{-1} * \mathbf{U}$

Calculate combined bias $\mathbf{B} = \mathbf{B} * (-1)$;

It can be shown that :

$$A^{-1} = \frac{H_M}{\sqrt{B^T Q B - J}} Q^{1/2}$$

Where H_M is the norm of the field provided by the user.

Calculate $btqb = B^T * Q * B$.

First calculate $QB = Q * B$.

Calculate $btqb = B^T * QB$.

Calculate $hmb = \text{sqrt}(btqb - J)$.

Calculate SQ, the square root of matrix Q

$hm = 45\mu\text{T}$; This value represents the Earth's magnetic field in the area where the system is being designed. Below it will be explained how the Earth's magnetic field for the different areas is being calculated.

Calculate A^{-1} .

Now all that is needed in order to calibrate the measurements is available. For example for the measurements $[x, y, z]$ the calibrated measurements are :

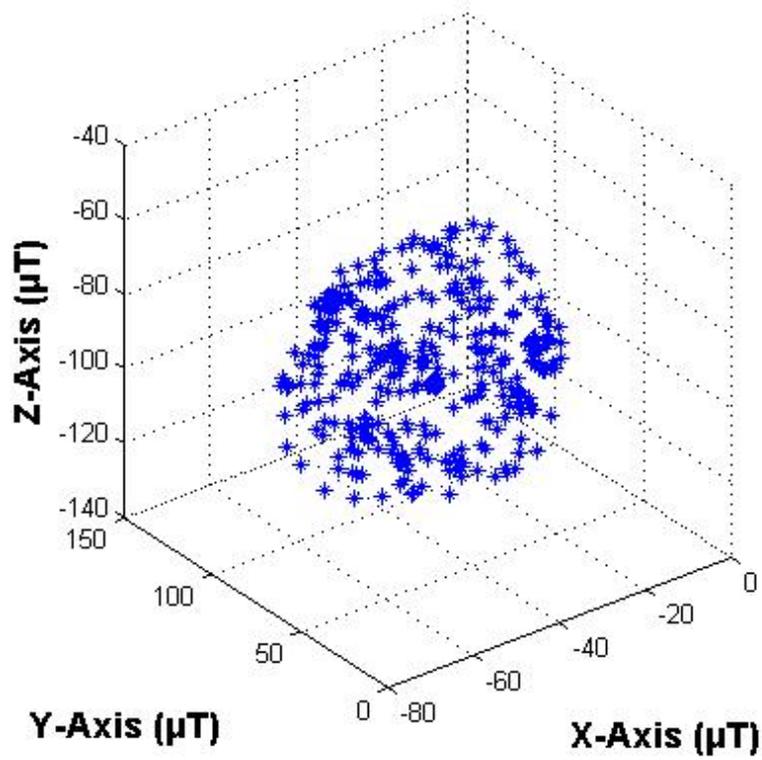
$$[x_{\text{Calibrated}}, y_{\text{Calibrated}}, z_{\text{Calibrated}}] = A^{-1} * ([x, y, z] - B)$$

Here are the values that the magnetometers have recorded before and after calibration:

Magnetometer number 1:

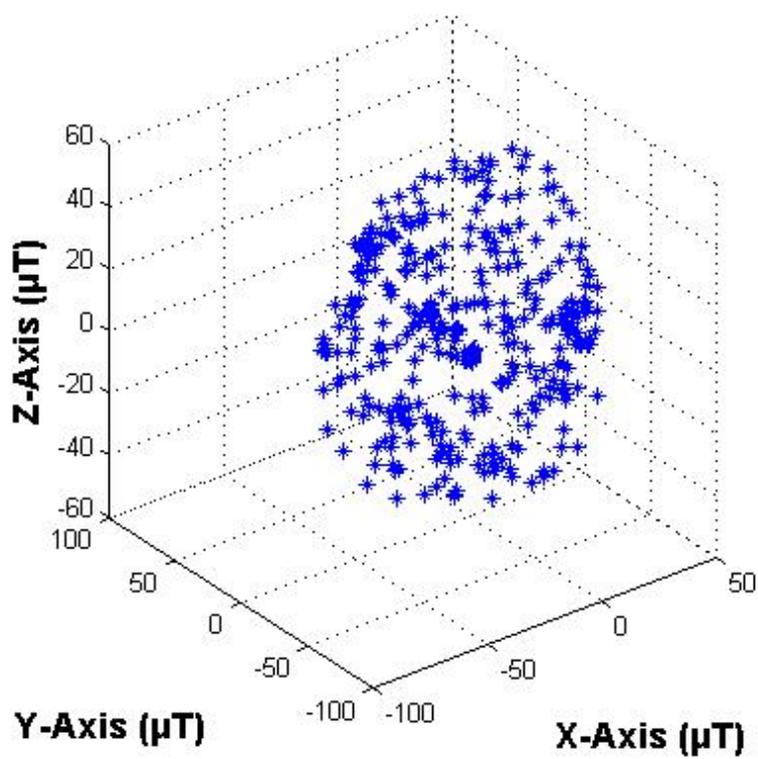
Before:

UnCalibrated Values



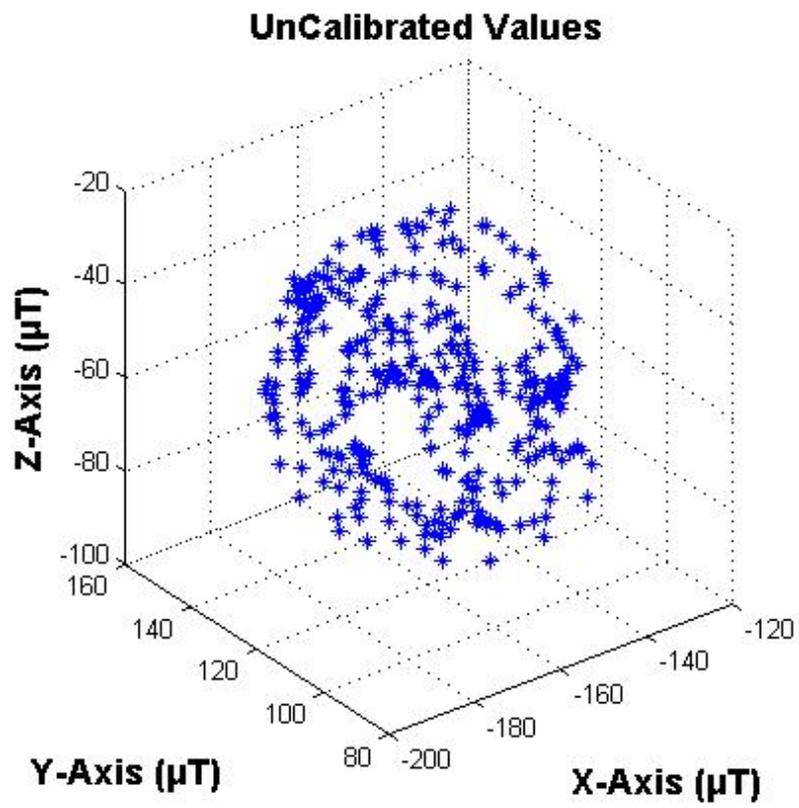
After :

Calibrated Values

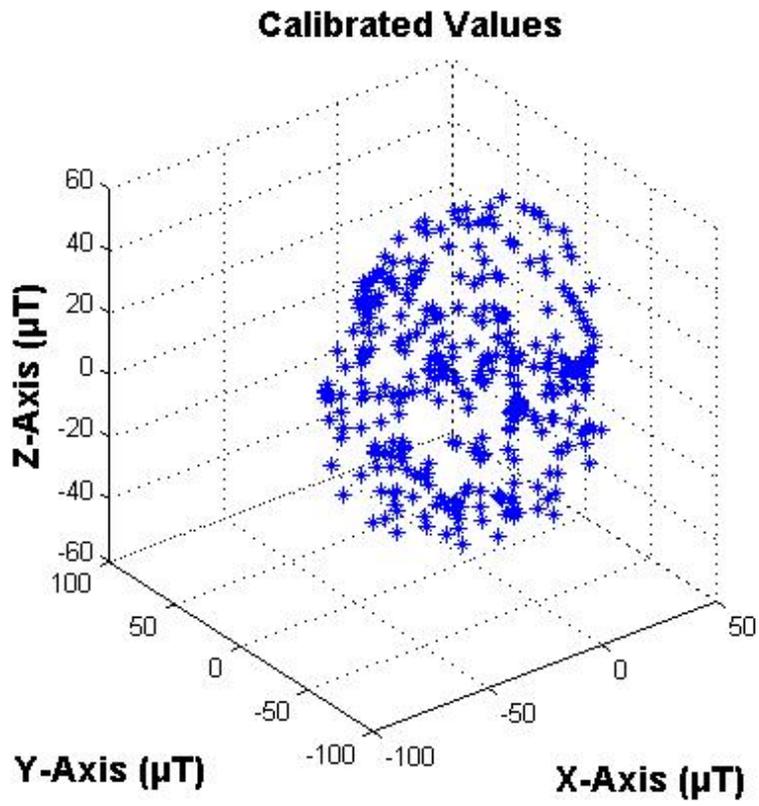


Magnetometer number 2:

Before:



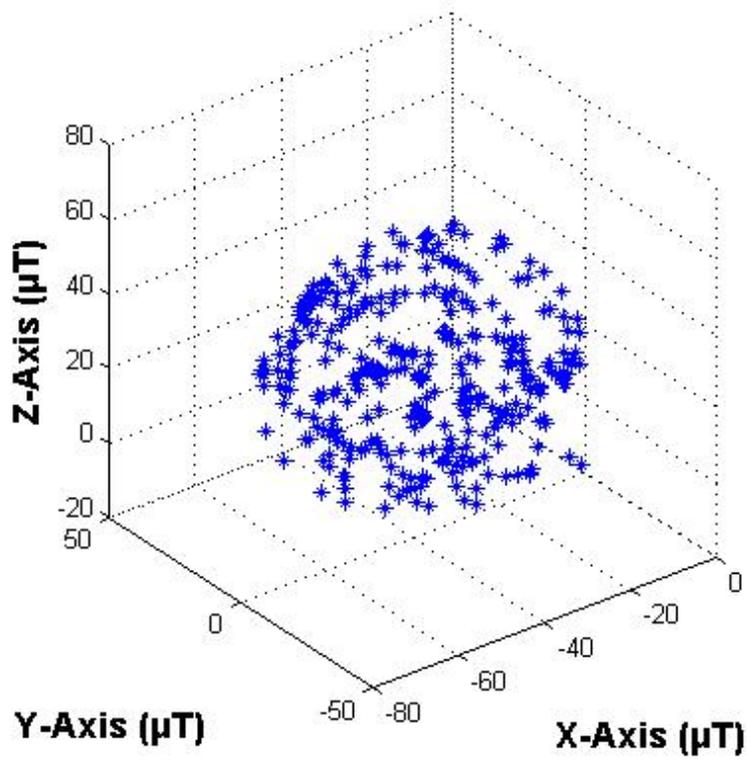
After:



Magnetometer number 3:

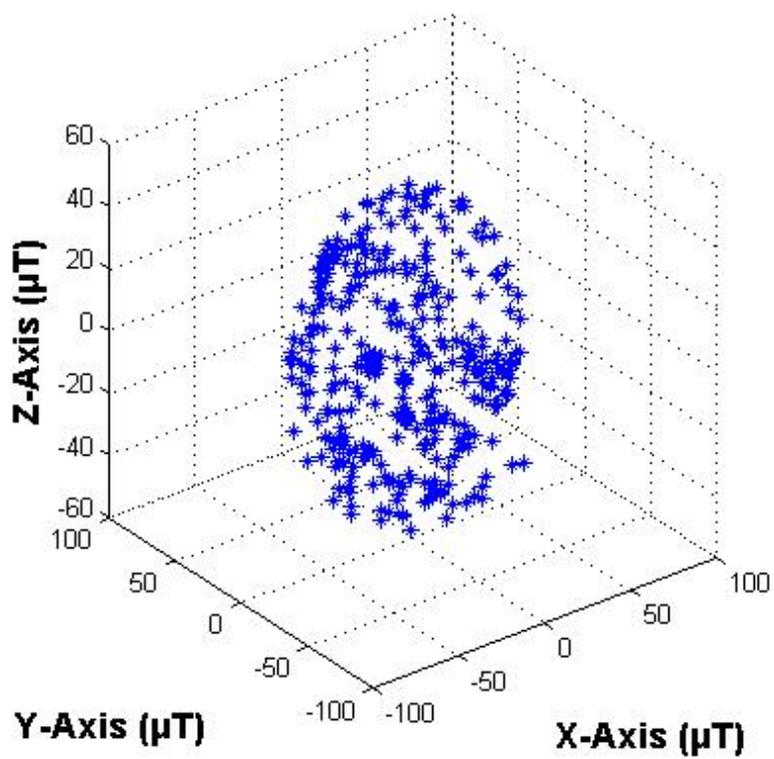
Before:

UnCalibrated Values



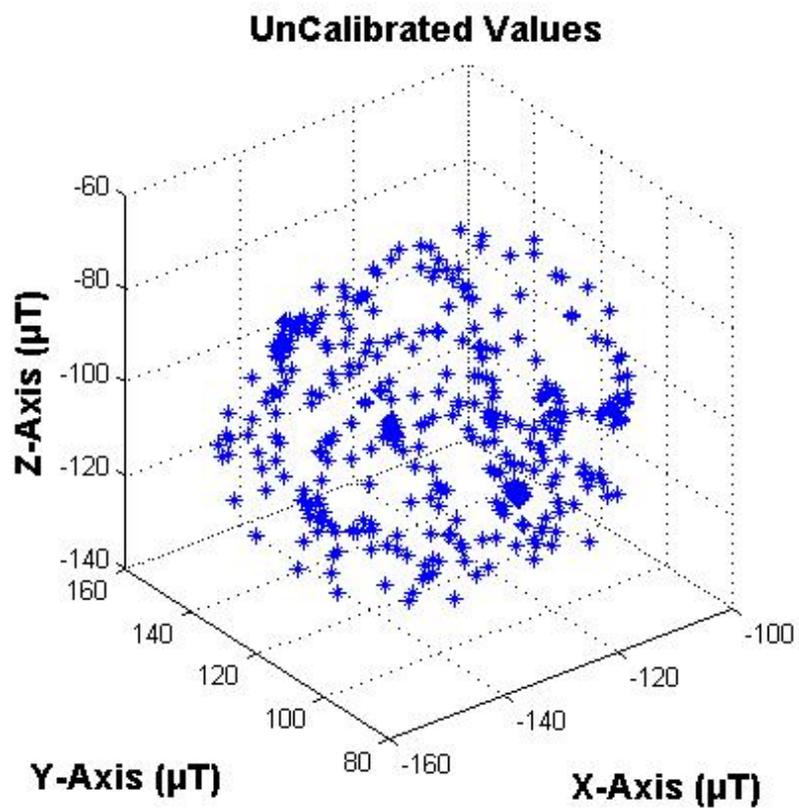
After:

Calibrated Values



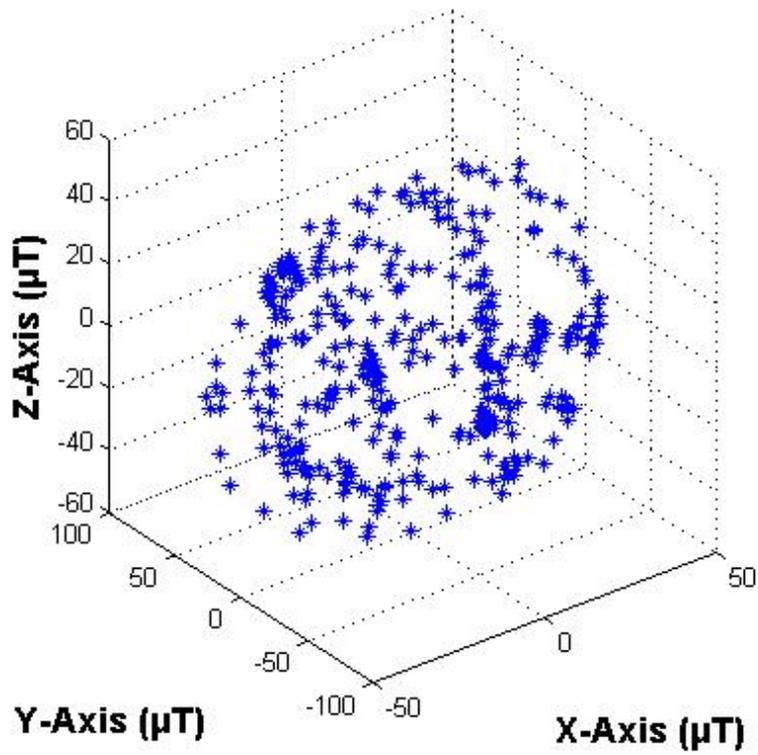
Magnetometer number 4:

Before:



After:

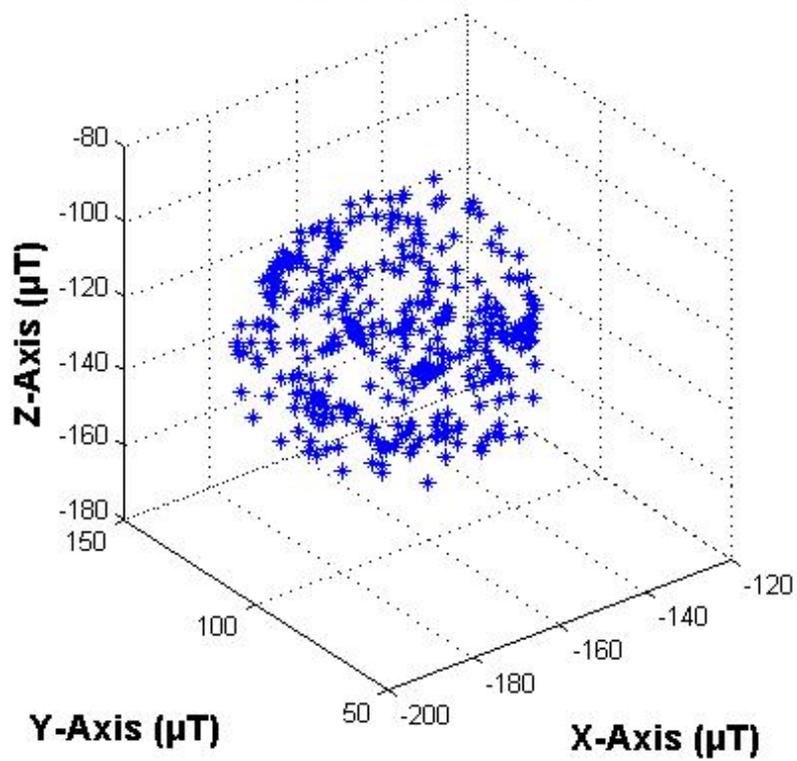
Calibrated Values



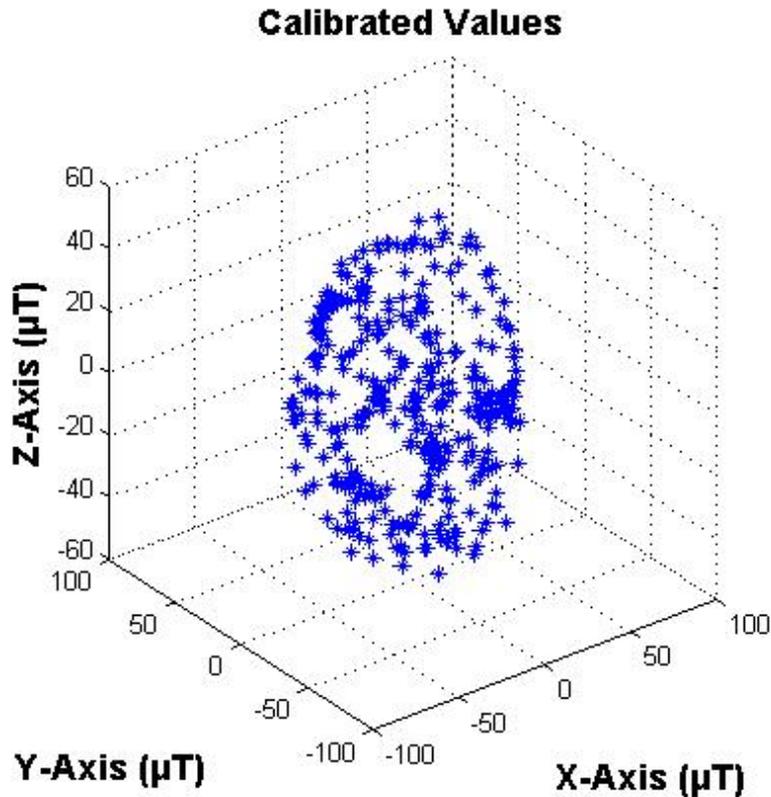
Magnetometer number 5:

Before:

UnCalibrated Values



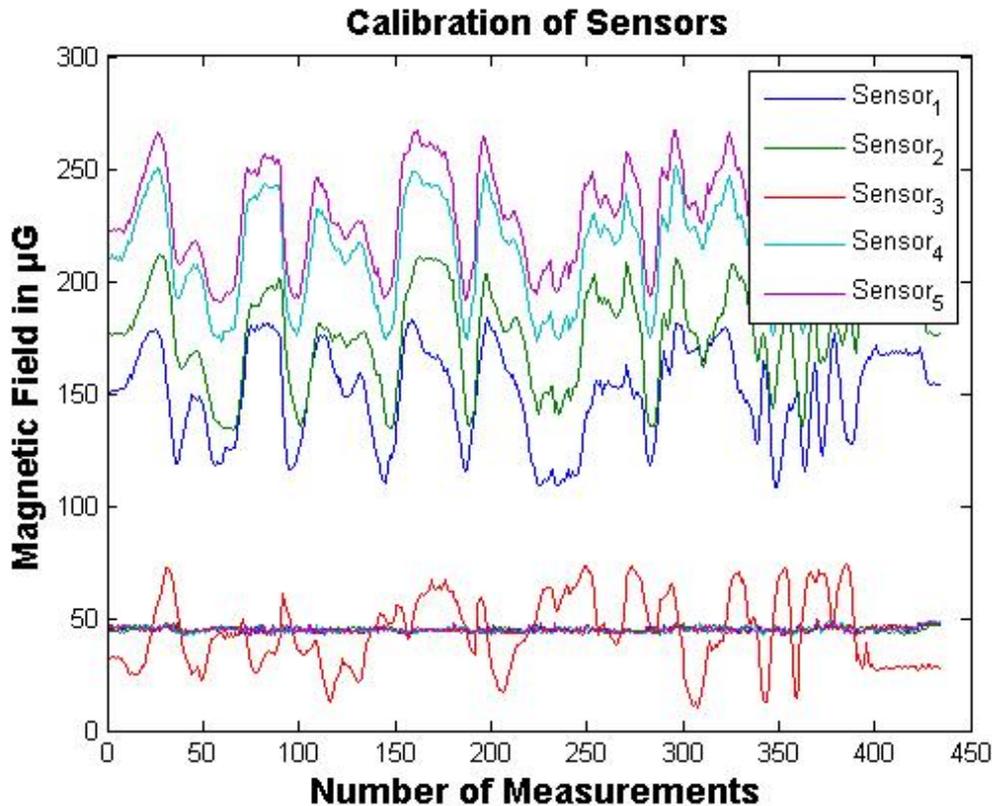
After:



What these figures show is what was mentioned before. The figures with the title "Before" represent the RAW values which the magnetometers measure in the x, y, z axis. The shape which these values create depends highly on the different rotations which the user performs when trying to calibrate the magnetometers. So it is very important for a good calibration that many different rotations will be performed in order for the values to shape an ellipsoid/sphere when trying to plot the raw measurements. Summing up, for a good calibration to be performed, the user must rotate the magnetometers to all possible orientations.

The "After" figures show the result of the calibration, meaning that the calibrated values now shape an ellipsoid which is centered to 0, 0, 0 for each axis respectively. The fact that the calibrated values are centered to 0, 0, 0 means that the hard iron effects are corrected, whereas the ellipsoid shape shows that there was calibration for the soft iron effects too.

Summing up all the calibrations for the 5 sensors:



➤ How is the Earth's magnetic field in each area calculated?

To calculate the earth magnetic field at an area the following procedure was followed:

- 1) Find the latitude, longitude and elevation of the area where the project is being implemented from this site: <http://veloroutes.org/elevation/>. Here is: Chania.
- 2) Enter the information acquired above to calculate the earth's magnetic field in any area with the help of the following online calculator: <http://www.ngdc.noaa.gov/geomag-web/#igrfwmm> .

What is the Earth's magnetic field?

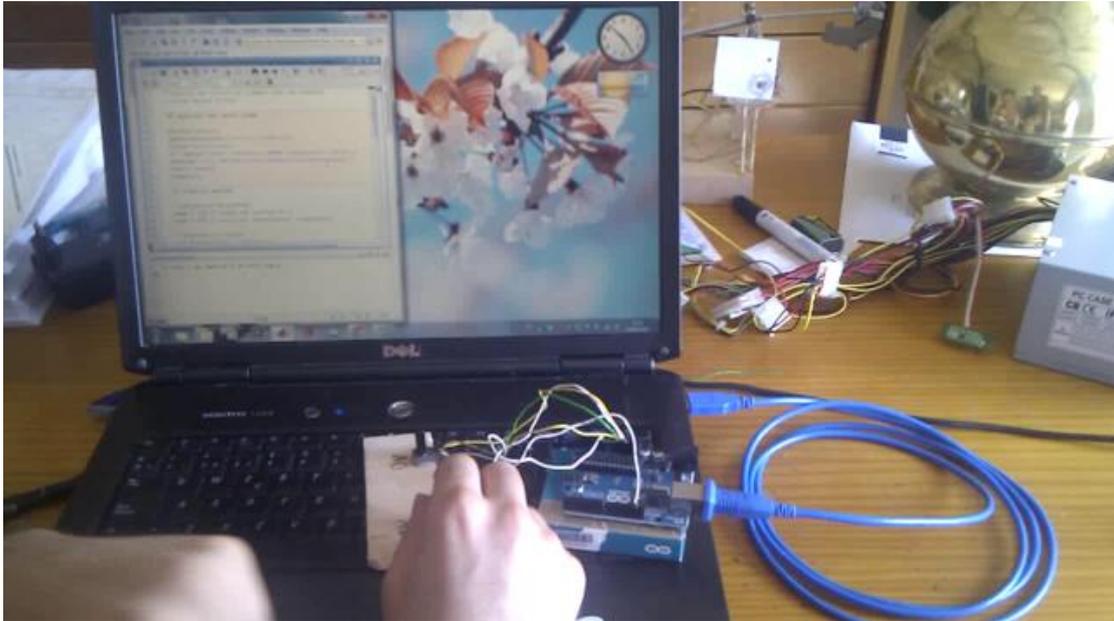
Earth has a magnetic field. Earth is like a gigantic bar magnet. Earth's magnetic field is slightly tilted with respect to the planet's spin axis; there is currently a difference of about 11° between the two. Because of this difference, the Geographic North Pole and the North Magnetic Pole are not actually in the same place; likewise for the South Poles.

Earth's magnetic field extends thousands of kilometers (miles) outward into space. The field forms a gigantic magnetic "bubble" in space around Earth. This magnetic bubble is called the magnetosphere. Earth's magnetosphere shields our planet from

most particle radiation that flows our way from the Sun and other radiation sources in space. The magnetosphere is not actually a sphere; it is shaped more like a teardrop, with a long "tail" extending away from the Sun. Although Earth's magnetic field is roughly a dipole (like the field of a bar magnet) to a first approximation, it has a much more complex shape than a simple dipole field. The uneven flows and distributions of the molten metals that generate Earth's field, the pressure of the solar wind, the stream of charged particles flowing outward from the Sun distort the shape of the magnetic field surrounding Earth.

The names given to the Magnetic North and South Poles are potentially quite confusing. It's a fact that opposite poles of magnets attract, while like poles repel each other. If two bar magnets are placed with their North Poles near each other, they will push themselves apart, likewise for two South Poles. If the North Pole is placed near the South Pole, they will pull themselves together. The needle of a compass is a small bar magnet, with a North and a South Pole. The North Pole of the compass needle points North. But the North Pole of a magnet is attracted to a South Pole of another magnet. So Earth's North Magnetic Pole is actually a South Pole of a magnet!

Chapter 6: Connecting Arduino to Matlab



The last step in order to start the localization process is to connect Arduino to Matlab in order to implement the real time localization of the magnet. The Arduino collects the information gathered from the calibrated magnetometers regarding the magnet's magnetic field and then sends this information to the Matlab through the code implemented both in Arduino and Matlab. This information is then processed by the Matlab code and the result is the approximated position of the magnet.

To establish communication between the Matlab and the Arduino program in real time conditions the function `serial` is being used.

`Serial` constructs a serial port object associated with port, PORT, and with the specified property values. If an invalid property name or property value is specified the object will not be created.

In order to communicate with the device, the object must be connected to the serial port with the FOPEN function. When the serial port object is constructed, the object's Status property is closed. Once the object is connected to the serial port with the FOPEN function, the Status property is configured to open. Only one serial port object may be connected to a serial port at a time.

The `serial` function is implemented like this in the project:

```
s = serial ('COM5', 'BaudRate', 9600);
```

Where :

- 'COM5' is the USB port where the arduino is connected too.
- The baud rate is the rate at which information is transferred in a communication channel.
- 9600 is the number specifying the speed of the BaudRate for the communication between the Arduino and Matlab. In the serial port context, "9600 baud" means that the serial port is capable of transferring a maximum of 9600 bits per second.

9600 is the maximum speed in which we can establish communication between the Arduino and Matlab with safety and without losing information. Increasing the speed above 9600 may result in the Arduino sending garbage to the Matlab program, meaning totally wrong localization results.

Chapter 7: Matlab Algorithms implementing the localization technique for the magnet.

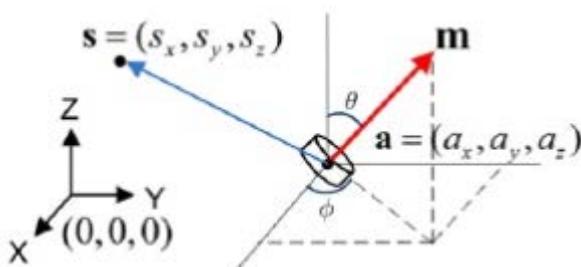
The final step in order to start the project working is the Matlab algorithm which will calculate the position of the magnet in real time, based on the information provided by the calibrated magnetometers and the Arduino.

The idea behind detecting the position of the magnet, is the fact that the precision of the localization method is not depending only on the optimization method which will be used, but also on the magnetometers, meaning how good they are calibrated, in the accurate measurements of the magnetic field of the magnet (meaning that magnetometers have to stay steady, away from interferences etc.) and of course on the earth's magnetic field in the area.

Above the calibration method was described, which takes in consideration the earth's magnetic field as well. Here the optimization method which gives the result of the position of the magnet will be described.

In order to reach to the optimization method which is the final step for the implementation of the localization, some other actions had to be taken first in order for this project to work.

Permanent Magnet Dipole:



In the above picture we can see our cylindrical magnet with height $l=3\text{mm}$ and diameter $d=6\text{mm}$, $B_r = 14300\text{-}14800\text{Gauss}$, which is at location \mathbf{a} .

$\underline{\mathbf{s}}$ is the position where our sensor is located. So here $\mathbf{s} = [s_1 \ s_2 \ s_3 \ s_4 \ s_5]$ since we have 5 magnetometers.

\underline{m} is the magnetic moment of the magnet. The orientation of the magnetic moment is depending on the 2 angles θ and φ provided in the picture above. The magnetic moment (or magnetic dipole moment) of an object is a measure of the object's tendency to align with a magnetic field. It is a vector quantity, with the positive direction defined by the way the object responds to a magnetic field: The object will tend to align itself so that its magnetic moment vector is parallel to the magnetic field lines. There are two sources for a magnetic moment: the motion of electric charge and spin angular momentum. For example, a loop of wire with a current running through it will have a magnetic moment proportional to the current and area of the loop, pointing in the direction of your right thumb if your fingers are curling in the direction of the current. Alternatively, an electron, has an intrinsic magnetic moment proportional to its spin.

The magnetometers at locations s1-s5 measure the static flux density B generated by the magnet at distances which are much greater than the size of the magnet. This is the reason why the magnet can be modeled as a magnetic dipole. This also explains why when the magnet gets to a very close distance near the magnetometers which is approximated through the experiments as <2cm the results start to be wrong. Furthermore, the sensitivity of the magnetometers, the size of the magnet and the modeling of it as a magnetic dipole is the reason that the magnetic field cannot be measured for more than 5cms away approximately.

Saying these, the mathematical model which is being optimized is the following :

$$B(s, a, m) = \frac{\mu_0}{4\pi} \frac{3((s-a) \cdot m)(s-a) - ||s-a||^2 m}{||s-a||^5} \quad (1)$$

Where $m = [m \cdot \sin(\theta) \cos(\varphi), m \cdot \sin(\theta) \sin(\varphi), m \cdot \cos(\theta)]$ is the magnetic moment vector [25] of the dipole and $m = \pi R^2 d / (4\mu_0)$ is the magnitude of m.

In order to perform the localization of the magnet, we need to solve this 5th grade equation, which is composed from 5 variables, 3 for position (a_x, a_y, a_z) and 2 for orientation (θ and φ). The way to solve this, is by calculating the mean square error between B_{sensor} which includes the measured magnetic field by the magnetometers and the estimated B from equation (1):

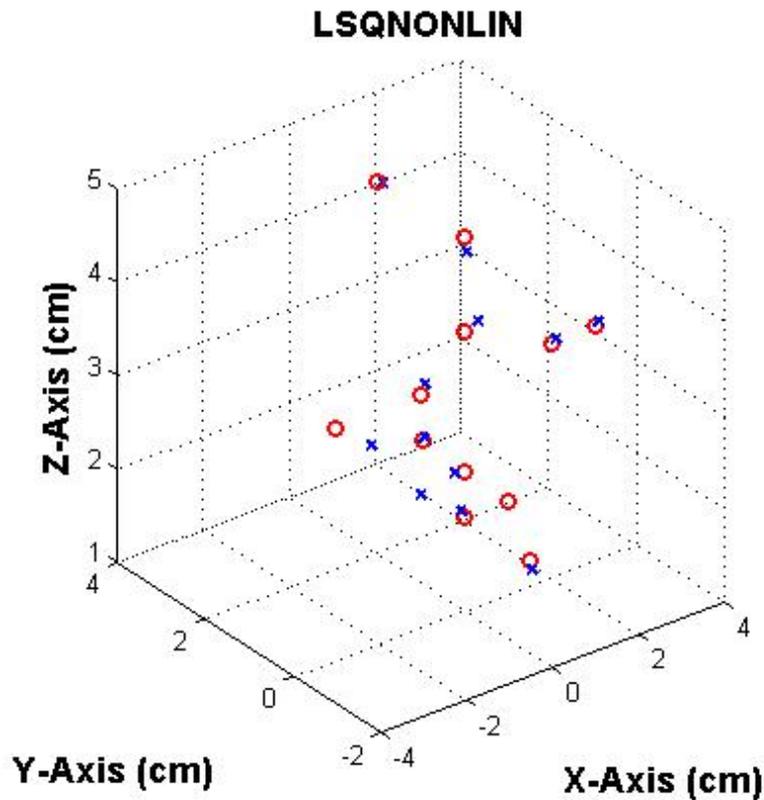
$$F(a, \theta, \varphi) = \sum_{\text{sensors}} ||B_{\text{sensor}} - B(s, a, m)||^2 \quad (2)$$

Precision is now defined as the size of F. **This means that the smaller the F is, the more precise the localization of the magnet will be.**

Optimization Algorithms:

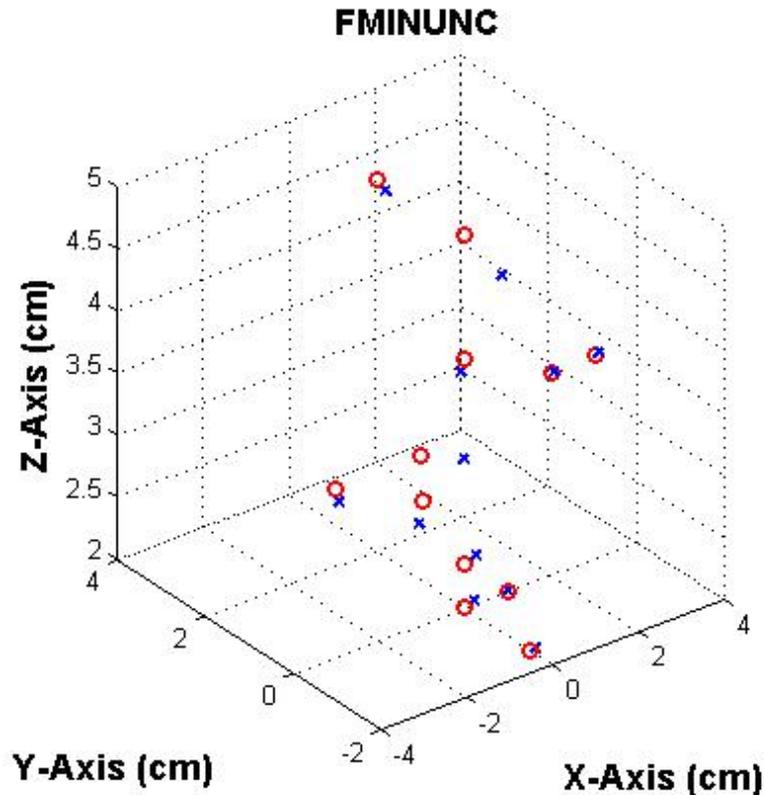
The Optimization Algorithms have now to find the smallest F possible in order for the localization to be as precise as possible. In other words, Optimization Algorithms have to minimize the F , so minimization Algorithms are going to be needed. From equation (1) is easy for someone to see that the equation which is used in the least square function is a non-linear equation. This results in using non-linear minimization Algorithms. Many minimization Algorithms where tested such as:

- **Lsqnonlin [26]**: `lsqnonlin` solves non-linear least squares problems. `lsqnonlin` is a constrained algorithm, since we can set upper and lower bounds for the results of our algorithm. When tested, it seemed to calculate precise enough the position of the magnet for a steady orientation. Changing the pole facing the magnetometers resulted in erroneous results. Another drawback of this algorithm provided from Matlab is the fact that is very much depended from the initial value it is given. Initial value is crucial for calculating precisely the position of the magnet, but `lsqnonlin` seems to be highly dependent on it in compare to other minimization algorithms. `lsqnonlin` is based on the Levenberg-Marquardt (LMA) algorithm. LMA provides a numerical solution to the problem of minimizing a function, generally nonlinear, over a space of parameters of the function. These minimization problems arise especially in least squares curve fitting and nonlinear programming. This algorithm did not work well for the project, since it is highly depending on the initial value which will be given and the position of the magnet when the measurements start should be very close to the initial value. Also, changing the orientation resulted in erroneous results.



- **LMFsolve [27], [28]:** LMFsolve is a Levenberg-Marquardt - Fletcher algorithm for nonlinear least squares problems written by Miroslav Balda and provided by the site MathWorks. LMFsolve.m finds least-squares solution of an over determined system of nonlinear equations. Testing this algorithm resulted in positions which were not accurate enough. The error was more than 1-2mm with steady orientation and when orientation changed, the position results were totally misleading.
- **fminunc :** Fminunc finds the minimum of a problem specified by

$$\min_x f(x)$$
 where $f(x)$ is a function that returns a scalar. Fminunc attempts to find a minimum of a scalar function of several variables, starting at an initial estimate. This is generally referred to as *unconstrained nonlinear optimization*. Testing this algorithm seemed to work pretty well but when the orientation changed many times the algorithm started to give erroneous results.



- **fminsearch** : Fminsearch uses the Nelder-Mead simplex algorithm. This algorithm uses a simplex of $n + 1$ points for n -dimensional vectors x . This algorithm worked pretty fine, but if the system is held open for a long duration of time, then fminsearch started to diverge from the correct position estimation.
- **fmincon** : Fmincon has the same results with fminsearch with the difference that it uses constraints. At start works pretty well but the continuous changes on magnet's orientation and position result in erroneous localization results. Fmincon attempts to find a constrained minimum of a scalar function of several variables starting at an initial estimate. This is generally referred to as *constrained nonlinear optimization* or *nonlinear programming*.
- **Direct [29], [30]**: Direct algorithm is based on the center-sampling algorithm. It was created in order to solve difficult global optimization problems with bound constraints and a real-valued objective function. DIRECT is a sampling algorithm. That is, it requires no knowledge of the objective function gradient. Instead, the algorithm samples points in the domain, and uses the information it has obtained to decide where to search next. A global search algorithm like DIRECT can be very useful when the objective function is a "black box" function or simulation. The DIRECT algorithm will globally converge to the

minimal value of the objective function .Unfortunately; this global convergence may come at the expense of a large and exhaustive search over the domain. The name DIRECT comes from the shortening of the phrase "Dividing RECTangles", which describes the way the algorithm moves towards the optimum. His slow speed is a drawback for this real-time running project. Furthermore, the algorithm is not suitable for the search we want to perform here in order to find the position of the magnet. This results in position estimations which diverge from the real ones.

- **Powell:** Powell algorithm is an optimization method, which does not require any derivative of the cost function being minimized. In this method, for minimizing a function with N parameters, a user should provide an initial parameter guess as well as N search vectors. The method transforms the multi-dimensional minimization problem into a sequence of one-dimensional minimization problem. It is also an iterative procedure. Through every iteration, a new parameter guess is determined by a sequence of line searches, starting from the previous parameter guess. The new parameter guess therefore can be written as a linear combination of all search vectors. Afterwards, the search direction which gives the largest impact is replaced by a new search direction. The iteration is performed until convergence. The problem with this method and the code tested at this project, as well as other Powell algorithms found on the internet is the fact that it reaches max iterations way too soon so no further localization can be performed. For the time that the algorithm is providing results, the results are very good and very accurate. So trying to implement the Powell method to fit the needs of this project is part of the future work.
- **Nelder-Mead Algorithm [31]:** Nelder-Mead is an unconstrained simplex algorithm as well. The version of Nelder-Mead used in this project is the nsmx, which implements the Nelder-Mead direct search method. The initial guess for this algorithm are the values [0.001, 0.001, 0.02, 0,-1] for x, y, z, θ , φ respectively. The algorithm is working pretty well with any initial guess except from [0, 0, 0, 0, 0]. This has to do with the location of the sensors in space as it is mentioned in the additional chapter above. The localization error using this algorithm is less than 1mm when placing the magnet up to 5cm away from the sensors and up to 2-5 mm when placing the magnet 6 to 7 cm away from the sensors. This is reason why this method is being preferred for the project. The only drawback is due to the algorithm's unconstrained properties and it has to do with the orientation parameter θ and φ calculation which seems sometimes to be calculated over 360° and 180° respectively. To deal with this problem control parameters were designed within the code to keep the parameters within proper bounds.

Chapter 8: Gui Interface for the project.

After completing all the preceding steps necessary for the functionality of the project, last but not least was the design of a Graphical User Interface so that the project will be easy to use for a user outside the lab. For the Gui two things were implemented which help the user understand better what does the screen show. The most difficult part was the perspective of the depth which had to be given to the Gui. Unfortunately, Matlab 3D graphics are not so helpful when it comes to perspective of depth.

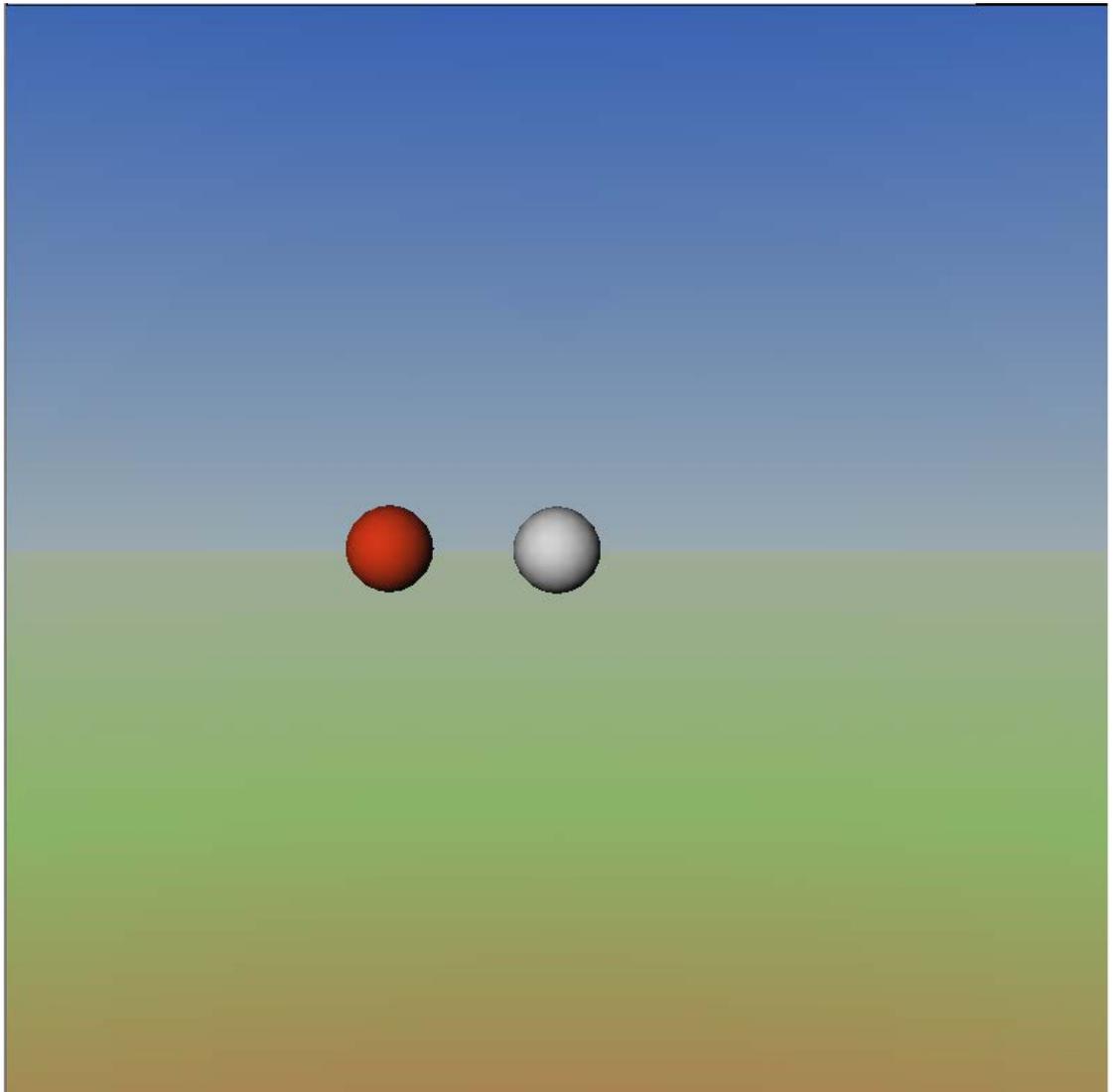
The Gui was designed with the inbuilt program provided by Matlab, V-realm builder 2.0.

This is the interface popping up when someone runs the Gui.

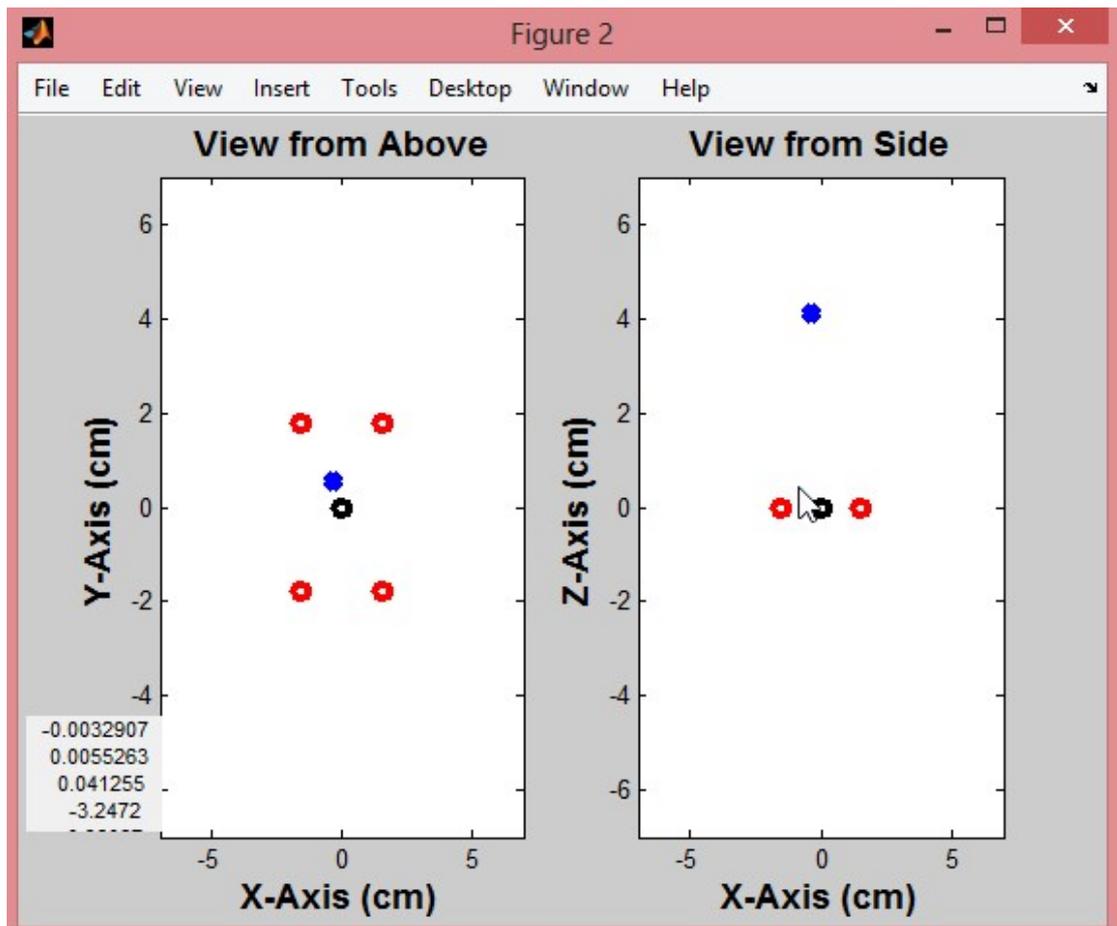


The Gui consists of 2 buttons: Calibration and Navigation. As it may be noticed the navigation button is not available, because calibration has to be performed first.

When calibration is completed, a simple message pops up notifying that the calibration was performed successfully. After that the navigation button becomes available. When the user presses the navigation button these 2 windows pop up:



And:



The first shows the position of the tumor (red sphere) whereas the grey sphere shows the position of the magnet. It is important to point out that when the user presses the navigation button a new window is asking from the user to enter the position of the tumor in 3D space. The grey sphere moves accordingly to the magnet's movements. The perspective of the depth is being achieved with the following way :

When the user moves the magnet along the z axis away from the tumor and towards the user, the grey sphere becomes larger , whereas when the user moves the magnet along the z axis and away from the tumor "inside" the screen the grey sphere becomes smaller than the tumor (red sphere).

The second picture shows the 2D plot of the magnets movement with respect to the sensors' locations. This is more like a helping tool for the user so that he knows exactly where he is without causing confusion to him. The plot consists of 2 subplots. The first one shows the movement of the magnet with respect to the sensors along the x and y axis whereas the second one shows the movement of the magnet with respect to the sensors along the x and z axis.

Chapter 9: Precision of the system

In this section the precision of the system will be discussed. The system in general is pretty accurate but the precision is highly depended on many factors which must be taken into consideration when measuring the accurateness of the calculations being implemented.

One important factor is the calibration method. It is important to point out that no calibration method works perfectly for the magnetometers. The magnetometers are very sensitive to any kind of magnetic noise and if the fact that the earth is a huge magnet, is taken into consideration, calibration will only help the estimated measurements to get more precise but not completely accurate .

Another important factor which plays a vital role in the precision of the system is the algorithm being used. No algorithm can calculate precisely the position due to the fact that these algorithms are **estimating** the location of the magnet based on the measurements of the magnetometers. Even if, theoretically speaking, the measurements were flawless, still the algorithm will not be able to perform an accurate calculation of the position of the magnet.

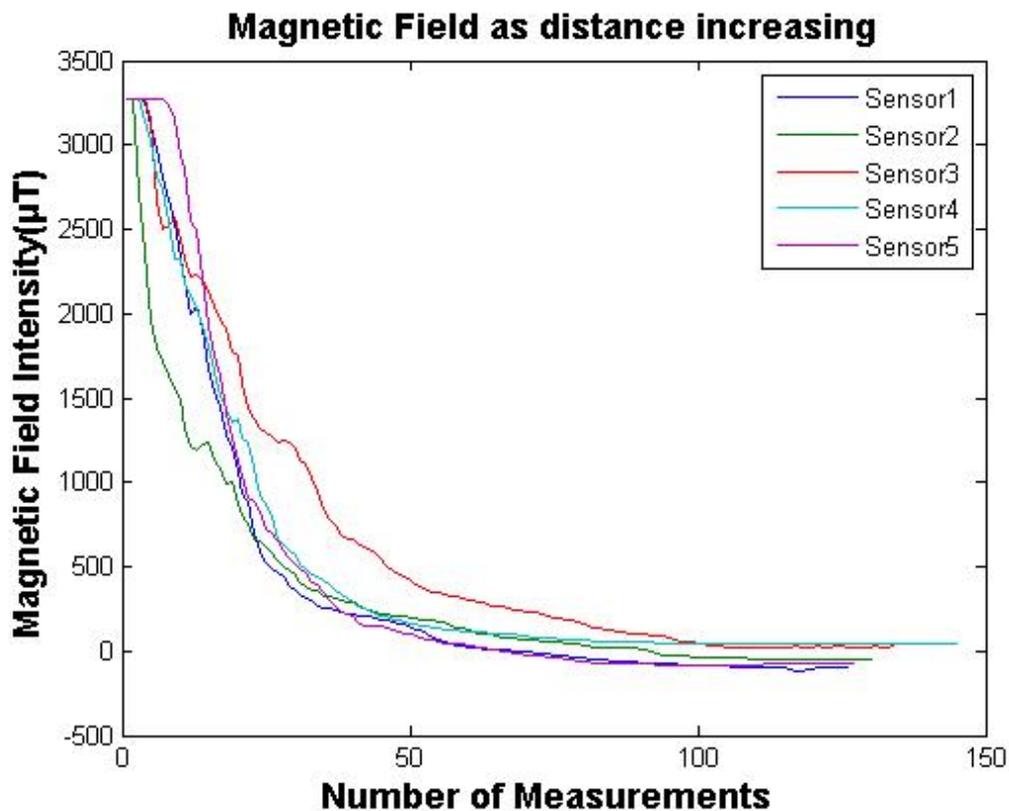
Another factor is the calculation of the position of the magnetometers since the magnetometers are the reference point of the system. The position of the magnetometers was measured using highly precision equipment, but even then the position cannot precisely calculated.

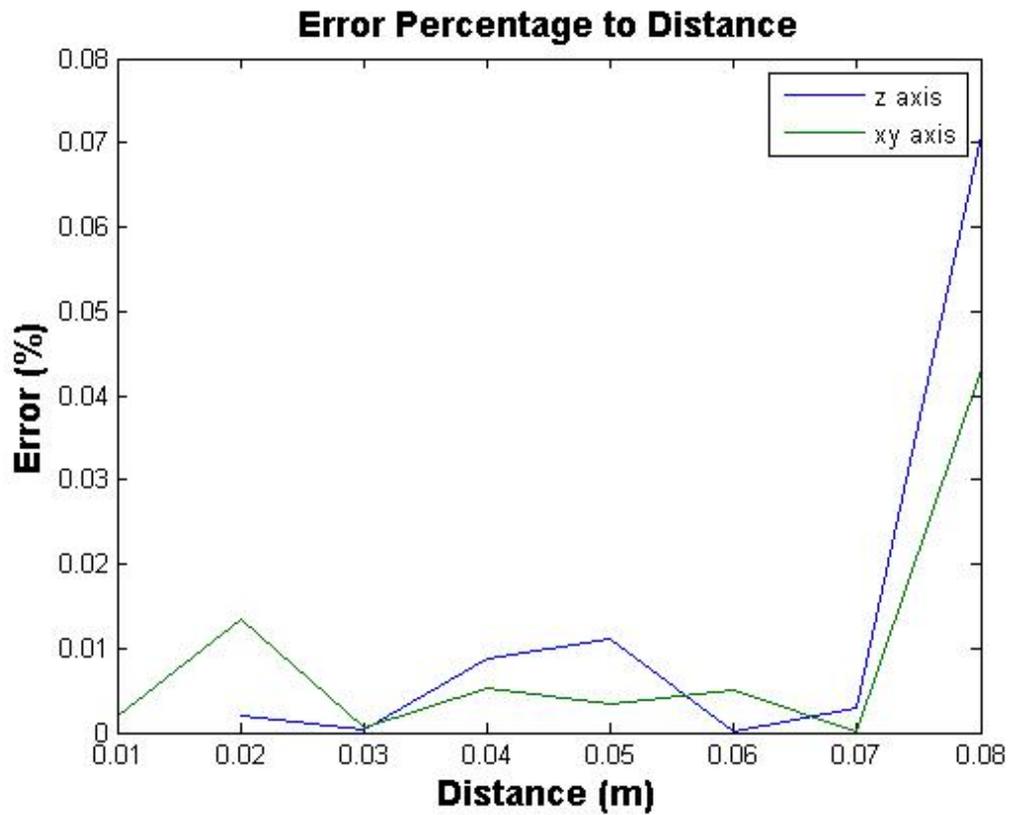
Moreover, one of the most important factors regarding the robustness and precision of the system is the initial value which will be used as a starting point for the system. Unfortunately, all minimization algorithms require an initial point from which the algorithm will start looking for the best solution (in this case for the most precise measurement). The drawback of the initial value is that there is no optimal starting point, so in this case the most "robust" initial value was the one for mentioned: $[0.001, 0.001, 0.02, 0, -1]$ for x, y, z, φ and θ respectively.

Magnet's Orientation is a very important factor which should be taken into consideration when trying to localize a magnet, since experiments have shown that changing the orientation of the magnet can interfere with the final results of the position of the magnet. None of the algorithms tested above seems to be robust to the orientation changes, but Nelder-Meads algorithm has shown the best robustness of all the other algorithms tested.

Shape and size of the magnet is another factor which should be taken under caution when trying to localize a magnet. Experimental measurements have shown that the position of the magnet which is estimated is different for different shapes of magnets. More specifically, the distance between the magnet and the sensors has a great connection with the magnet lines which pass through the sensors, so it is just a common sense to believe that the distance between the magnet and the sensor is the distance between the sensor and the magnet's surface located in the center of the magnet. In fact, the distance which is being measured is the distance between the sensor and the magnet's surface as an overall.

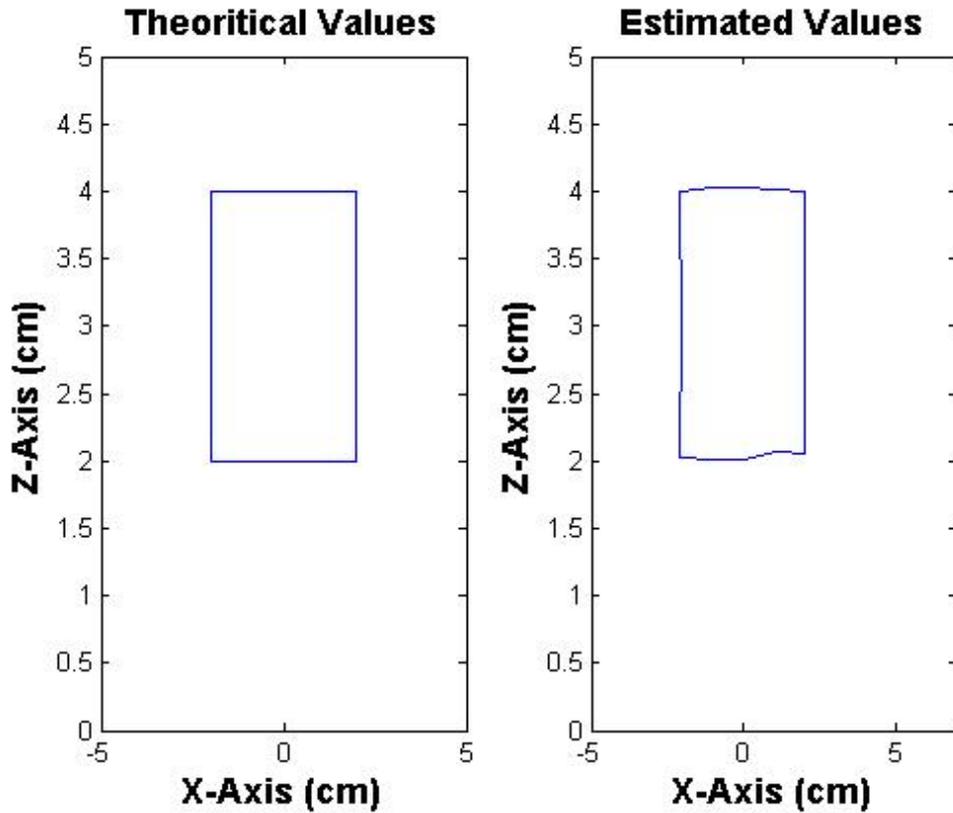
Last but not least, distance is the most important factor which should be taken into consideration when designing a magnetic localization system. Specifically, the sensed magnetic field generated by a magnet from a magnetometer is highly depending on the distance. Running back in equation (1) in Chapter 7 it is easy for someone to notice that the intensity of the magnetic field generated by a magnet weakens very fast in accordance to the distance as it can be seen and by the figure where the magnetic field which the magnetometers detected weakens significantly when moving the magnet slowly away from the magnetometer. Summing up, distance in which a magnetic field will be measured is a very important factor when designing a magnetic localization system.





Next, some measurements will be presented, the real and the estimated ones. Before moving on it is important to point out that these measurements were taken using the second calibration method. However, the reader must take into consideration and the user's error when trying to estimate the precision presented here.

Holding the y axis steady and moving the magnet along the x and z axis:

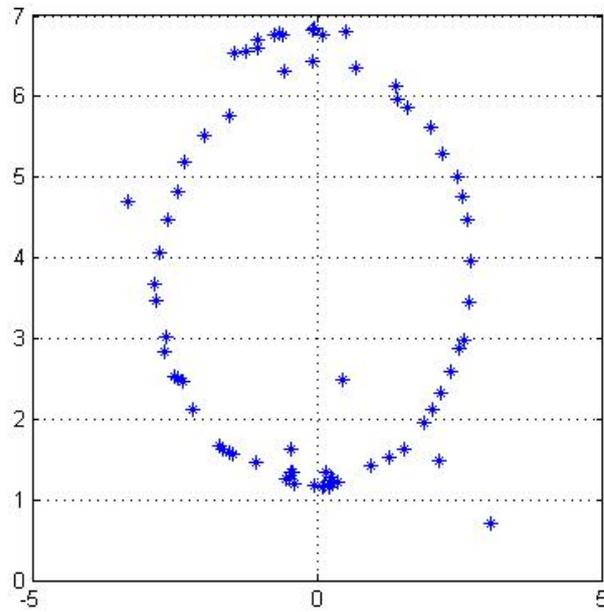


Similar results were estimated for moving the magnet when holding the z axis steady and the x axis steady respectively.

The next level testing is about the ability of the system to create shapes by moving the magnet exactly on the perimeter of the shapes and test how the system can recreate them:

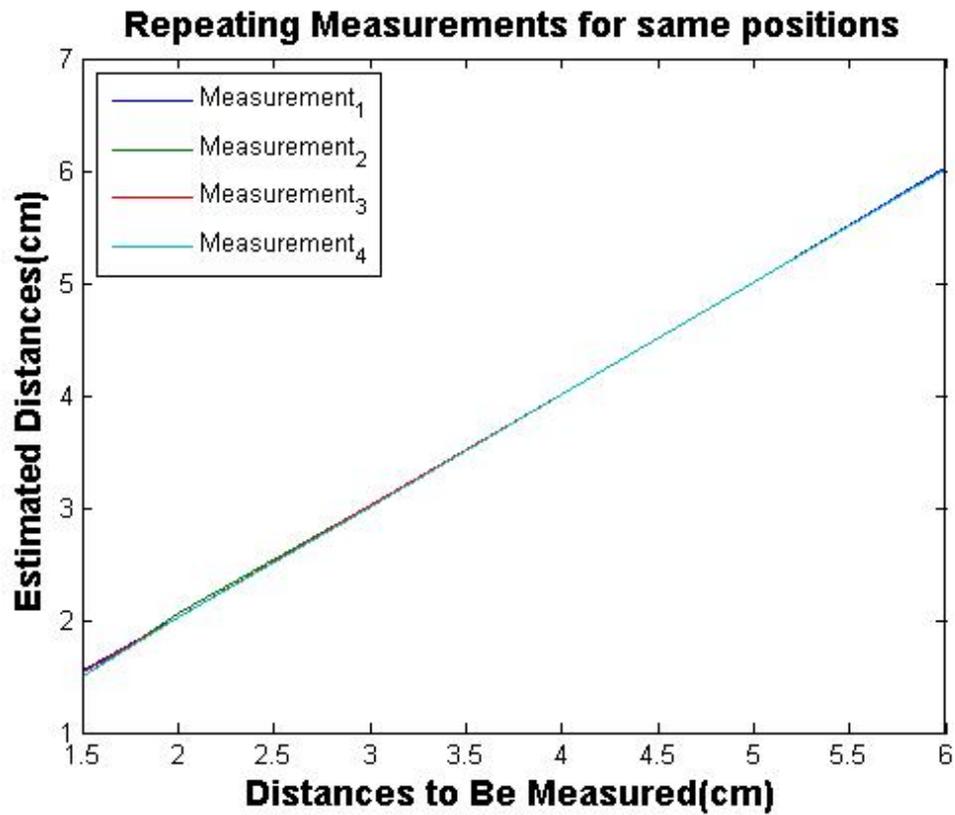
A test was performed by holding steady y and moving the magnet around the perimeter of a circle with 6.5 cm diameter:





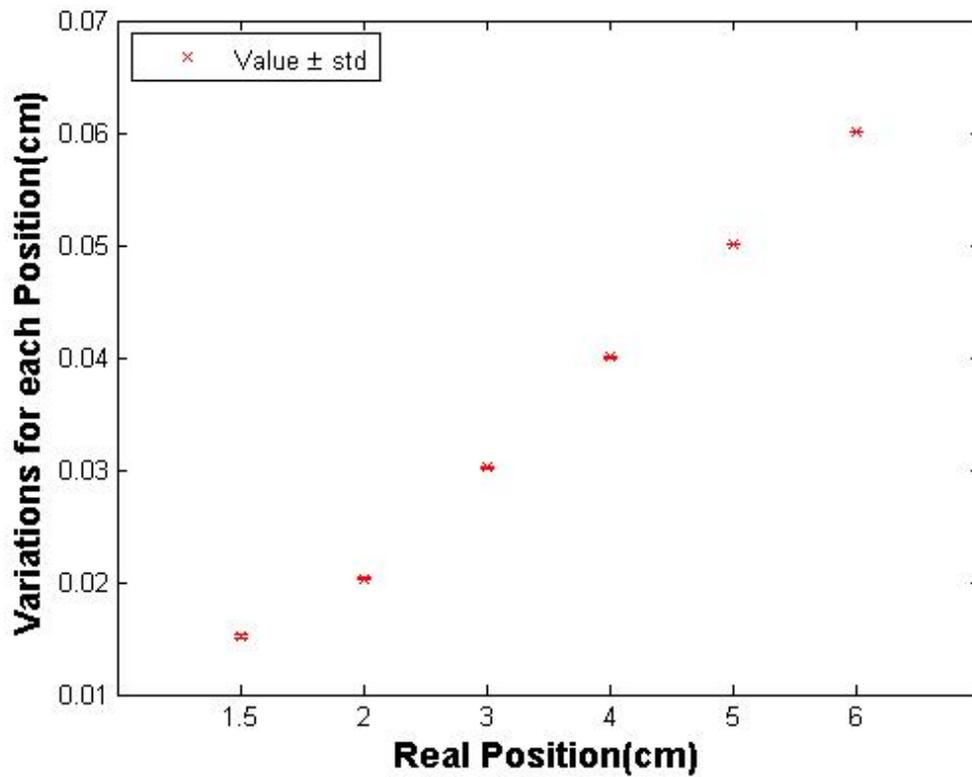
In the above picture it looks like an ellipsoid but this is due to the limits of the axis in order for the shape to look bigger. This means that the system followed precisely the trajectory of the magnet to the target. Values above 6 and approximately close to seven as well as some random spots in the graphic are due to the out of range measurements (above 6 cm) and due to the non steadiness of the magnet respectively.

Another test for the precision had to do with the ability of the system to estimate many times the same value for the same position. For example, putting the magnet in 2cm away from the sensor array it is important to test whether the system will repeatedly estimate the 2cm distance, so it is important to test the variation of the estimations of the system.



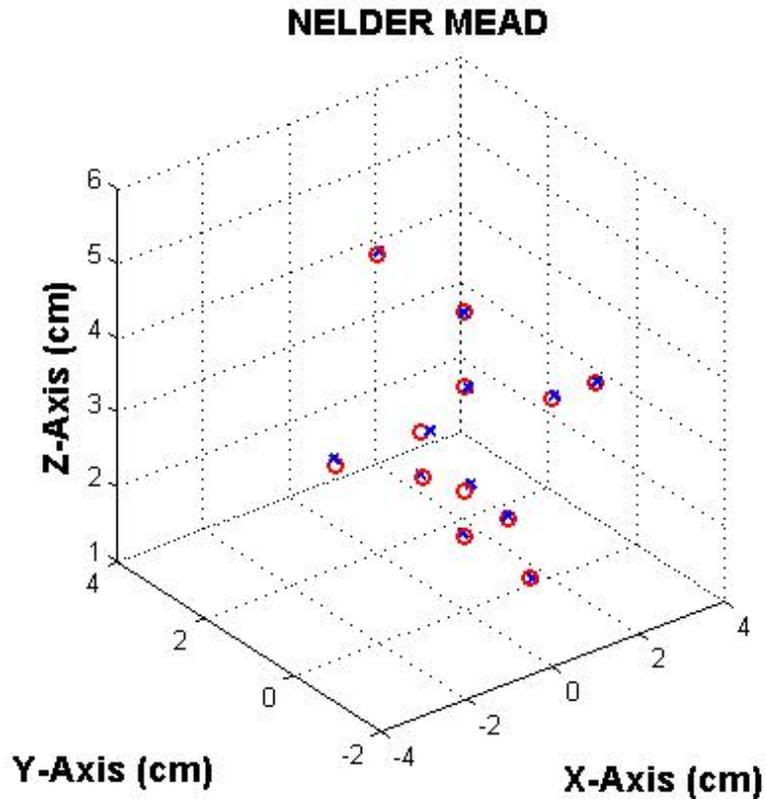
As it can be seen by the plot the measurements are almost the same for the same positions, which justifies the ability of the system to repeatedly make approximately the same estimations for the same position.

To be clearer, the standard deviation and the mean for each position (1.5, 2, 3, 4, 5,6cm) along the z axis and for many measurements will be shown:



It can be seen by the errorbar that the variations are too small to be distinguished. For example for 1.5cm the variation is 0.000383m.

Last, the system was tested for detecting the position of the magnet in pre-specified points in 3d space and as it can be seen the localization is pretty accurate:



Many measurements were taken in consideration when performing the precision test of the system, the above was just a sample of the measurements taken. Summing up it can be said that the precision regarding the movement along x and y axis is very accurate whereas the precision along the z axis depends highly on the distance with the distance up to 5-5.5cm being very accurate (less than 1mm estimation error) with a good calibration.

Finally, it can be said that the bigger the distance along the z axis, the less precise the system will be along all axis. The system is pretty accurate and fast enough for real time localization and for this reason can be used as a guidance helping tool for many applications.

Chapter 10: Summing up, Conclusions

Summing up, what is being introduced in this project is an innovation. Specifically there was the need for a medical helping-guiding tool which can be very useful for the doctor, who is performing a breast biopsy surgery, in order to have a very good approximation of where the scalpel is in accordance to the position of the tumor. As it was mentioned in the beginning of the text, this setup due to its small size and its high accuracy has great advantages in relation to similar arts being proposed or presented in the past, not only for medical applications. This project, the calibration procedure and the system as a whole, can be used in other applications as well, including motion tracking of objects, magneto-assistive applications for disabled persons, computer-based applications and many more.

Chapter 11: Future Work

Finding new more accurate and faster approximation non-linear and even linear algorithms is one of the immediate plans regarding this project. These algorithms will improve the accuracy and the speed of the system even more.

Using more magnetometers in an appropriate format (size and shape) will improve the reliability and the accuracy of the system even more.

Finding new calibration methods and better fitting algorithms can be crucial for the further improvement of the system as well.

Rewriting the code of the system in C++ can be a huge advantage regarding the speed of the system (faster calculations, less memory usage, etc).

Testing in animals and then in humans is one of the purposes of this system.

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