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Magnetic Reference for Accurate Indoor Tracking

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MSc DISSERTATION

Master in Electrical and Computers Engineering

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Abstract

Even though GPS is a highly valuable technology its limitations when it comes to indoor positioning make it unviable in this particular context. The scattering and attenuation that the signal suffers on the roof and the building structure itself lead to positioning errors that make this system inadequate for this purpose.

There is an ongoing race to find the most suitable system that can fill this gap, hopefully a solution that can blend with GPS to achieve an ubiquitous positioning system, working both indoors and outdoors. Using smartphones as inertial measuring units due to its already widespread use is an attractive idea. However additional technology might be needed to improve its performance that suffers from cumulative errors.

The scope of this works is to explore the possibility of using magnetic references to aid in heading estimation on a smartphone-based system and also to study the most relevant approaches regarding indoor positioning.

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Acronyms

IPS	Indoor Positioning System(s)
RSSI	Received Signal Strength Indicator
AOA	Angle of Arrival
TOA	Time of Arrival
TOF	Time of Flight
POA	Phase of Arrival
TDOA	Time Difference of Arrival
RTOF	Round-trip Time of Flight
WLAN	Wireless Local Area Network
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
RFID	Radio Frequency Identification
UWB	Ultra Wide Band
IMU	Inertial Measuring Unit
AWG	American Wire Gauge

Chapter 1

Introduction

1.1 Context

Indoor localization is a field of study that gathered a lot of attention in the past few years. A system that can guide people through the corridors of a building, either a hypothetical guided tour in a museum, an emergency evacuation route of a hotel or the ability to know where people are, is very attractive and opens a whole new world for target advertisement or even assisted living [9]. Besides these, there are an immense amount of applications to be developed based on this paradigm. These scenarios led to a great number of scientists and the industry in general to research and develop a way of establishing an accurate indoor tracking system.

Figure 1.1: Idealization of an IPS application to a shopping center

As far as positioning systems are concerned the first concept that comes to mind is GPS (Global Positioning System). However, indoor environments are a more complex environment as line of sight is denied by the building structure which also attenuates, reflects and refracts the signal resulting in a position error so big that it nullifies the measurement [10]. As a result numerous solutions have been researched and developed by companies and researchers. The outcome is a wide variety of systems that use different positioning principles.

Dead reckoning has risen in popularity in this particular field as smartphones can work as inertial measuring units given the incorporation of a wide variety of sensors, and as they are already in use it becomes easier and more comfortable to implement. Nowadays it is possible to find smartphones equipped with accelerometer, magnetometer, gyroscope, proximity and barometer sensors and the tendency with technology, as always, is to reach even further. This makes this approach very promising. Furthermore there is a wide variety of wireless technologies like Bluetooth, magnetic field based or Wi-Fi that can be integrated with dead reckoning to aim for a better performance.

1.2 Motivation

Despite all the numerous alternatives explored, a single universal solution that is consensual is yet to be found. The aim of this MSc is to explore the possibility of improving indoor positioning, focusing specifically on the improvement of heading estimation, using an artificially generated magnetic field to aid a smartphone-based tracking system.

A dead reckoning smartphone-based tracking system due to its inherent way of functioning accumulates error over time which results in cumulative errors that lead to wrong positioning. In the particular case of heading the main source of information is the gyroscope that works relatively well in short periods of time but the measurement drifts with time. The indoor environment being rich in magnetic interference makes the magnetometer very situational and unreliable. This work focus on creating an artificial magnetic field that works as a quantifiable interference. This can be seen as a reference for the magnetometer and used to calculate an angle that can help to achieve a corrected heading.

1.3 Objectives

This master thesis was proposed to study indoor positioning systems and develop an accurate solution based on magnetic references.

To reach this goal the following objectives are considered:

- Review technologies and principles of indoor positioning.
- Magnetic antenna design suitable for reference points in indoor tracking systems.
- Heading and displacement correction for indoor tracking solutions.
- Developing an Android application that can identify multiple reference points on a blueprint.

1.4 Document Structure

This document is organized as follows. In Chapter 2 the state of art is presented, with relevant information regarding indoor positioning in general. Chapter 3 will present an investigation regarding electromagnetic fields and solenoids with designs and simulations. In chapter 4 the experimental setup will be described and characterized and, finally, chapter 5 and 6 will present the results and conclusions, respectively.

Chapter 2

Indoor Positioning: An Overview

In this Chapter, general indoor positioning is studied. Distance measurement techniques and position techniques are described. An overview of different positioning systems was written, as well as an analysis on the system evaluation parameters.

2.1 Distance Measurement Techniques

This section describes methods of calculating distance typically used to estimate distance between emitter and tracking device.

2.1.1 Received Signal Strength Indicator (RSSI)

RSS based systems calculate the distance travelled between emitter and receiver by focusing on signal power. With appropriate models it is possible to calculate distance knowing the attenuation the signal suffered, which is done by computing the difference between emitted signal strength and received signal strength [11]. Propagation loss which should be a degradation factor for most methods is in this case its main source of information. This is a relatively simple method, however the complexity of indoor environment causes these systems to suffer from large errors if there are heavy interferences caused by multipath or signal blockage.

2.1.2 Time of Arrival (TOA)

Time of arrival (ToA) is a technique that estimates the distance between transmitter and receiver by using the time it takes for the signal to travel its path. It takes advantage of the fixed speed of the signal (speed of light) and so the only data needed is the time of flight of a data packet, this approach makes timestamps essential. Time of flight (ToF) is another name used to describe this kind of approach. Being so reliant on time, this method requires not only high clock precision but also synchronization between transmitter and receiver which translates into complex hardware and implementation [12].

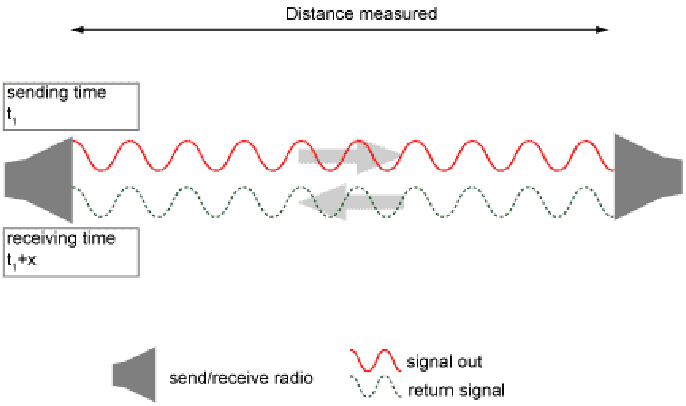


Figure 2.1: RTOF [1]

2.1.3 Round-Trip Time of Flight (RTOF)

RToF functions similarly to ToF (or ToA) the main difference being that the signal travels from emitter to receiver and back to the sender as opposed to the one way travel, as seen in image 2.1. The method is the same i.e. measuring the time it took the signal to do its route. Despite being time reliant the synchronization requirements of RToF systems are not as demanding as ToA.

2.1.4 Time Difference of Arrival (TDOA)

Time Difference of Arrival (TDoA) as the name indicates uses the difference in time between receptions on spatially separated receivers to estimate the position of the emitter. For each time difference the origin of the signal is located on a hyperboloid with a constant range difference between the two measuring units. With the addition of more receivers at different locations there are more TDoA measurements which result in more hyperboloids that intersect each other and eventually yield a point that represents the emitter position.

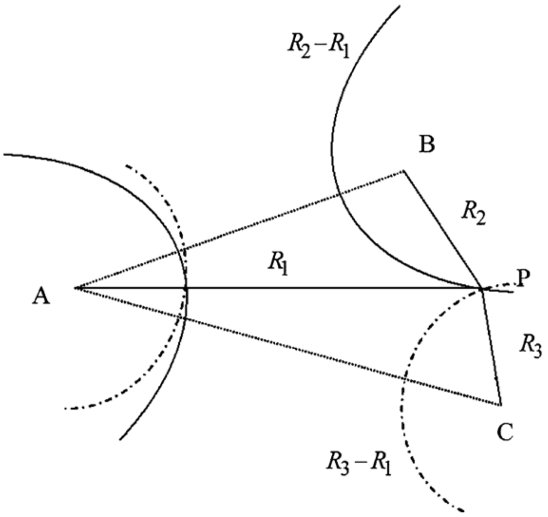


Figure 2.2: TDOA

For instance, in image 2.2, 3 receivers (A, B and C) provide two TDoA measurements (R2-R1, R3-R1) which intersect to give the 2-D location of the emitter P.

2.1.5 Phase of Arrival (POA)

The received phase method estimates distance by measuring the delay of the received signal expressed as a fraction of the wavelength. These delays or phase measurements can be computed using the same algorithms of ToA to achieve localization. TDoA algorithms can also be used given that a phase difference measurement is performed instead of a simple phase measurement. As far as hardware specifications are concerned, the transmitters are assumed to emit pure sinusoidal waves and must be specifically positioned to maximize line of sight otherwise localization errors are prone to happen.

2.1.6 Angle of arrival (AOA)

Angle of Arrival (AoA), represented in figure 2.3, also called direction of arrival (DoA) computes position by measuring the angle of incidence from ,at least, two known stations [3].

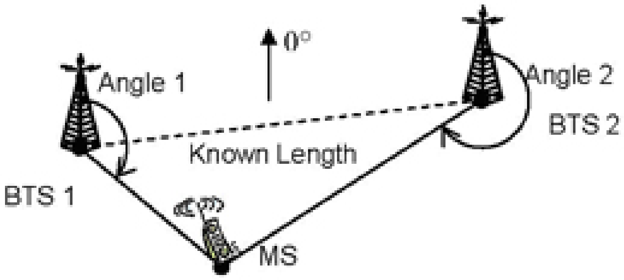


Figure 2.3: Angle of arrival [2]

The main challenge is measuring the angles which is achieved by using arrays or directional antennas. This leads to relatively large and complex hardware requirements. On the other hand, three stations are enough to achieve 3-D positioning even though the accuracy decreases considerably with the distance.

2.2 Position Estimation Techniques

The previously mentioned distance measurement principles are applied in different computing techniques used to achieve positioning. These techniques are further described below.

2.2.1 Trilateration

Trilateration works by having stations emitting a signal that can be used to compute distance by a number of different means (e.g. ToA, RSS) as previously mentioned. Even though it uses the

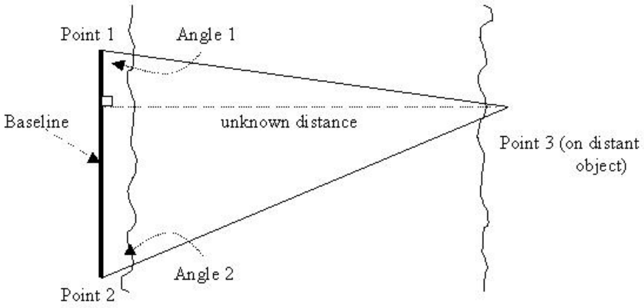


Figure 2.5: Triangulation

properties of a triangle the method is different from triangulation. In this case each distance is a radius for a group of possible locations. With at least 3 stations enough information is provided to estimate position [13].

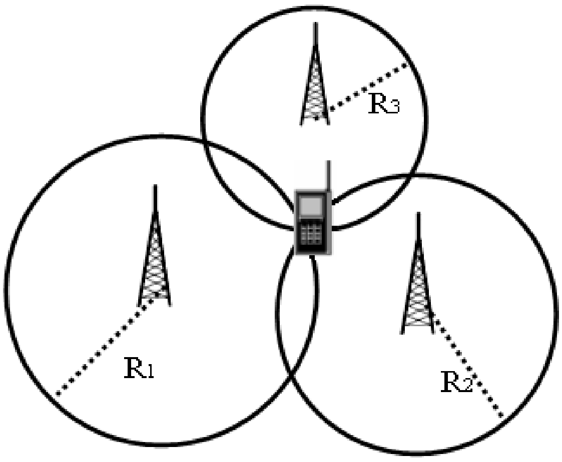


Figure 2.4: Trilateration

As seen in image 2.4, three calculated distances (R1, R2, R3) translate into 3 circumferences which intersect to give the location of the tracked target. This is the technique used by the GPS, with satellites working as stations and the GPS receiver as the target device. In reality radius measurements have always some uncertainty which translates in an area of possible locations and not just a unique point. The precision of the position will be higher the more accurate the radius measurements are, and the smallest the area of intersection is.

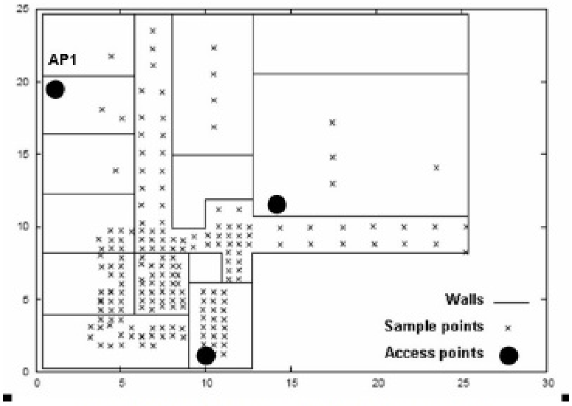
2.2.2 Triangulation

Triangulation makes use of AOA to estimate positioning of the target. As stated previously this can be done using only two known references but expensive equipment might be required.

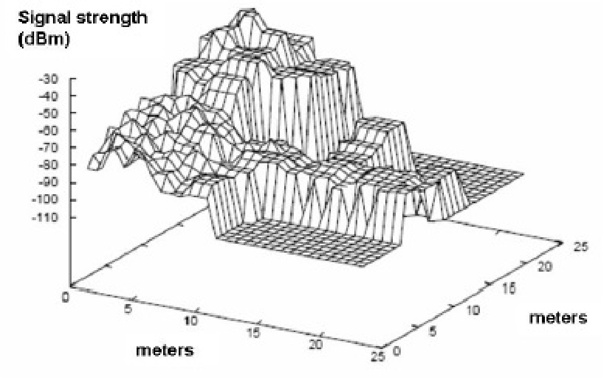
As illustrated in figure 2.5, point 3 is tracked using stations at point 1 and 2, which location is known (the baseline is also known as a result) and with the additional information of the angles of arrival a location is achievable.

2.2.3 Scene Analysis

Scene analysis or fingerprinting positioning technique is a two step method where at first there is an acquisition of data from the relevant environment and then location is achieved by comparing a real time measurement with the data previously recorded, as illustrated in figure 2.6. This method ensures a reasonable performance but requires a priori information and any significant alteration in the environment, addition of new access points or anything that changes propagation properties will call for a new mapping or training phase. For example, one approach is to measure the Wi-Fi RSSI on several points of the target environment creating a RSSI map that can be used as a cross reference for the positioning system the same procedure can also be applied to buildings' magnetic anomalies.



(a) The Experiment Environment



(b) Signal Strength for AP1

Figure 2.6: Fingerprinting(Scene analysis) example [3]

There are several algorithms used to achieve the most precise location possible among them: probabilistic methods, k-nearest-neighbour (kNN), neural networks, support vector machine (SVM), and smallest M-vertex polygon (SMP), as mentioned in [12].

2.2.4 Vision based

Vision algorithms make use of video cameras as its data obtaining method. Even though it is very comfortable for the target person as no additional equipment must be used, it implies an installation of surveillance video cameras and previous data collecting in order to compare the image and obtain the equivalent location.

The big edge of this system is not only the simplicity on the target's end but also the acquisition of valuable information regarding the person's activity and context which most of other systems are not able to retrieve. This distinctive characteristic can be an advantage but at the same time private issues may arise making it somewhat intrusive.

2.2.5 Proximity

The proximity technique is based on the creation of an area which is covered by detection sensors. When a target is detected by these same sensors it can be assumed it is located in their range like the example on figure 2.7. Therefore, a location is attributed based on the device being within the sensing area. This method in conjunction with pre generated maps is particularly useful to detect presence in a room, making it helpful in situations regarding children or seniors who may not leave certain places unattended. However, it is somewhat limited in other scenarios namely wider areas as it requires a deployment of sensors regarding a specific location and only results in a proximity value in other words a relative location.

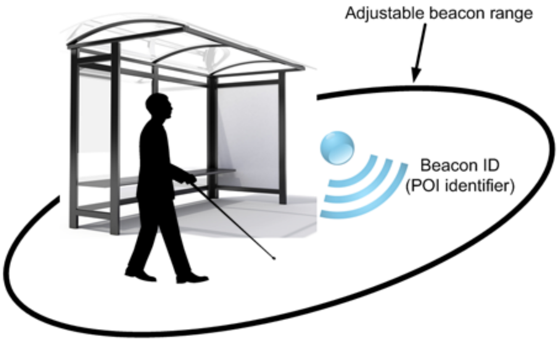


Figure 2.7: Proximity based location

2.2.6 Dead Reckoning

Inertial navigation systems use inertial sensors like accelerometer and gyroscopes to collect data regarding movement characteristics. This data is then used for Dead Reckoning, i.e., the computing of the location by incrementing an initial known position based on sensor data.

The accelerometer provides acceleration data which can be integrated twice to yield position, this is the distance travelled. In the specific case of pedestrian tracking the accelerometer is usually used as a step detector in conjunction with a stride length estimation algorithm as this approach provides better results than performing a double integration.

The gyroscope measures angular velocity (rate of rotation) which can be integrated to obtain an angle of rotation, this data represents the direction of movement or heading variation. A positioning technique like this becomes particularly interesting for indoor positioning where most other solutions are limited and even more considering the easy access to the sensors needed present on nowadays smartphones.

However inertial systems suffer from cumulative errors due to sensor noise and integration, even more considering the cheap nature of the sensors used in smartphones. In addition to the accelerometer and gyroscope smartphones have extra resources which can improve the process accuracy. For instance, the GPS can provide an initial position before entering a building or even help indoor tracking when available, magnetometer can provide additional information on heading and Wi-Fi can also be used to aid navigation.

2.3 Indoor Positioning Systems

This section describes some systems based on the technology used [14].

2.3.1 Infrared

IR based systems make use of infrared light to perform position estimation. This is usually done by having tags on the target that emit an IR signal which is received by an array of cameras that act as receiving sensors. With the acquired data, tag position is estimated by using the already mentioned distance measurement principles and positioning techniques. The opposite is also possible with a fixed number of emitters covering the tracking area and a camera on the target acting as the receiver, taking into account the emitters signal characteristics the camera device can compute its own position. The former method finds its use mostly in autonomous robot navigation while the first is more appropriate for human applications.

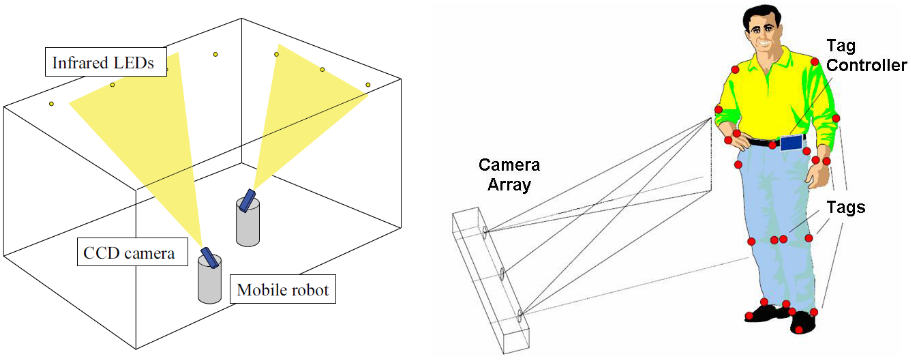


Figure 2.8: Examples of infrared tracking systems [4, 3]

IR systems can achieve high precision under very specific circumstances, which make its use very limited. It can be useful to track human motion for virtual reality applications and animations or other specific tasks under the appropriate conditions. However, the required hardware (array of cameras/tags) make it unsuitable for wide areas and performance is highly influenced by existence of line of sight and the environment light conditions, as IR systems can suffer from light interference [3].

2.3.2 Ultrasound

Ultrasound systems are very similar to IR systems as far as design or architecture are concerned. Tags and receivers are also used and the same principles apply but instead of using infrared light the calculations are done using ultrasound pulses. These systems main advantages compared to infrared are its lower cost and hardware requirements (even though the hardware has to be specifically placed), which results in better scalability, and immunity to light interference. The main downside is the susceptibility to reflections that degradate the system accuracy [16].

2.3.3 Ultra Wide Band

UWB systems make use of very short pulses (<1ns) therefore in the spectral domain it uses a UWB (>500 MHz wide). Even though it uses the traditional tag-receiver approach like IR or ultrasound , the UWB signal brings many advantages to the table. Tags are low consumption, line of sight is not required, higher penetration and less interference. UWB pulses nature make it easy to filter multipath effects and improve the system overall quality. High precision ToA/ToF measurements can be achieved moreover TDoA and AoA can be used in conjunction to decrease sensor density. Despite hardware requirements UWB systems present a set of characteristics that make it superior to its counterparts.

2.3.4 WLAN(IEEE 802.11)

Using the already deployed and widely used WLAN infrastructures to develop a positioning system has the immediate advantage of not having additional hardware requirements [19]. Furthermore the tracking target can be any WiFi device from a specific tag to a smartphone or a tablet. Due to its low cost easy access characteristics this approach gathers a lot of attention and many methods have been investigated to make it viable. The two main techniques applied are trilateration and scene analysis. Measuring the RSSI from nearby access points can be used to compute a position by trilateration. The main problem with this method is that the complexity of indoor environment requires an elaborated attenuation model in order to estimate distance accurately. Avoiding lackluster performance due to wall attenuation and multipath effects being the main concern.

Scene analysis as mentioned in the positioning techniques requires an offline phase, in this specific case the mapping of the RSSI in the zone of interest. This not only brings extra work and is in itself a heavy requirement but is also susceptible to any change that alters propagation conditions. Moreover, the AP positioning usually aims for efficiency achieved with maximum coverage for each AP which is the opposite of what would benefit positioning systems. The more measurements of RSSI for a single position the more accurate the estimation of location will be. In spite of all the drawbacks this still remains as one of the most solid methods.

2.3.5 Bluetooth (IEEE 802.15)

IPS using Bluetooth aim to benefit from low consumption, low complexity, robustness and the already distributed technology on most handheld devices. The system works by having a network of established access points on a building that work as masters to the tracked devices. These access points are interconnected and are the underlying layer of a central server that manages their operations [20].

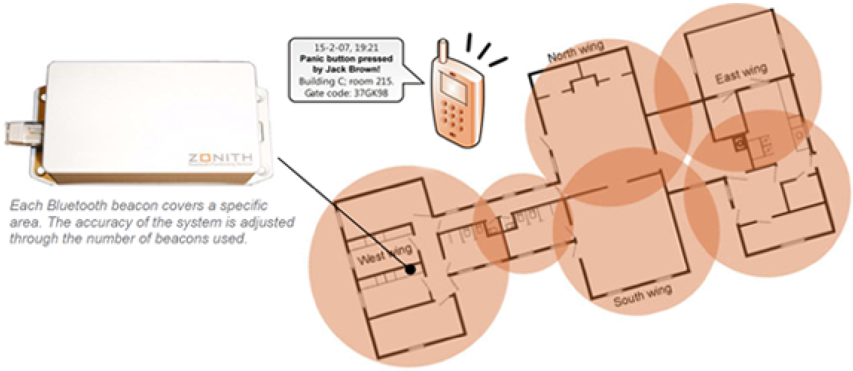


Figure 2.9: Bluetooth [5]

The handheld devices work as slaves looking for a connection, in other words they play the same role as tags in previously mentioned applications. This system incorporates wireless connection, data transfer, location and tracking in the same network and using an already established standard which makes for a cost effective solution. The main drawbacks are the same physical limitations that RF systems in general struggle to overcome indoors and also the relative low accuracy (2-3m) and delay between position calculations (10-30s) [3].

2.3.6 Radio Frequency Identification

RFID is a means of storing and retrieving data through electromagnetic transmission to an RF compatible integrated circuit and its application to the indoor positioning environment has been already proved useful by some developed systems. The main components of RFID technology are tags and receivers which communicate through a specific protocol, concept illustration can be seen in figure 2.10 [9].

There are two kinds of systems based on the two different types of existing tags. Passive tags are simpler and therefore cheaper and communicate by reflecting the signal from the reader modulating it accordingly to their ID or message. These are characterized by being very light and simple and the complexity of the system lies on the RFID reader. Passive tags have short range and

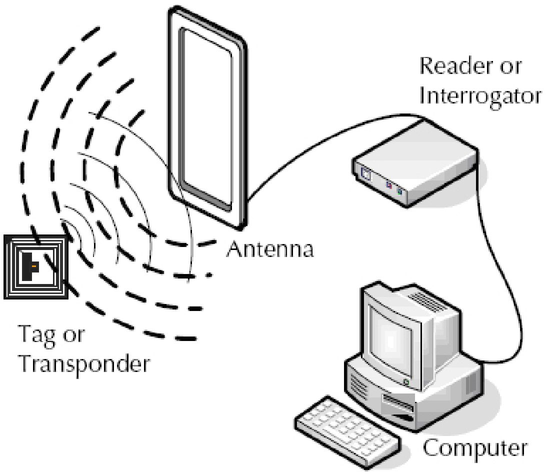


Figure 2.10: RFID [6]

are usually used to identify objects in a similar fashion to bar codes. Active tags are transceivers able to transmit their own signal, in order to achieve this the tags are self powered, more complex and expensive but also have higher communication range [21]. RFID systems are very versatile and have several uses from inventory systems to public transports, however even though systems like LANDMARC exist, positioning systems using RFID do not show high precision nor low infrastructure/hardware requirements.

2.3.7 Pseudolite

Pseudolite (pseudo-satellite) are ground-based stations that broadcast signals similar to the Global Navigation Satellite Systems (GNSS) [23]. The concept is emulating a satellite constellation on ground level with a signal strong enough that GNSS receivers can receive it as a GPS-like signal and use it for indoor navigation. There are two approaches to this concept of making GNSS signal usable for indoor purposes: setting up a constellation of pseudolites that emit their own signal (figure 2.11) or establishing repeaters outside buildings to retransmit the signal indoors (figure 2.12) with appropriate signal level.

Figure 2.11: Pseudolite example 1 [7]

Creating a system similar to what already exists and works has its own advantages but the requirements/limitations are also well known. Like regular satellites these pseudolites need precise synchronization which can be very expensive, in fact synchronization techniques in order to avoid

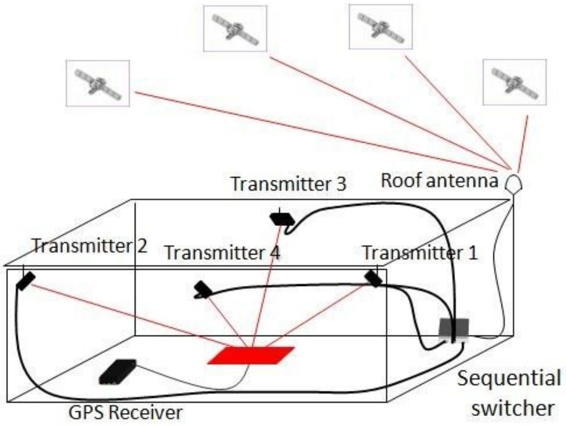


Figure 2.12: Pseudolite example 2 [8]

atomic clocks are one of the most important research points. The high attenuation associated with indoor propagation also originates near-far problems. This happens when a signal level is severely attenuated and gets indistinguishable for being much lower than another stronger signal.

2.3.8 Zigbee

Zigbee technology characteristics show potential regarding indoor positioning. Zigbee is a wireless protocol that enables low power, cost effective, flexible and low data rate networks [25]. It allows very fast neighbour recognition and it is easy to extend its network size by changing its composition into different forms (ad-hoc, star, mesh, and hybrid). Compared to other wireless technologies like Bluetooth or WLAN it has lower data rates but it is cheaper, has faster initialization, lower latency and more flexible. On the other hand it is a less known technology and working at the 2,4 GHz spectrum can suffer interference by being disturbed by other signals from the same band like Bluetooth and WLAN[26].

2.3.9 Inertial Measuring Unit based

Systems using IMU take advantage of inertial sensors and dead reckoning to compute successive position updates what is usually called a fix [27]. This old system gains renewed interest because the indoor positioning problem lacks solutions and with the evolution of hand held devices, particularly smartphones, almost every person carries a set of sensors that end up being a inertial measuring unit [28]. The main advantages are obviously the widespread technology and the easy purchase of the software through a single download. Not needing extra infrastructure/hardware is definitely a big defining factor of this technology, however as for now it is not really reliable. Even though step detecting and stride length algorithms show promising results the main problem with this approach lies on heading estimation. There are two sensors which can provide information regarding direction of movement: gyroscope and magnetometer. Gyroscope can provide angle changes between rotations whereas magnetometer can help computing orientation relative to magnetic north. The problem with gyroscope is that integration introduces cumulative error, due to the gyroscope bias, resulting in successive higher discrepancy between estimated heading and real heading, which is usually denominated as drift [29]. Unfortunately magnetometer is not really an alternative as the magnetic north it senses is not reliable due to the sea of magnetic interference caused by technology like computers, machines or even the metallic structures of buildings. Adding to these problems a portable device like a smartphone can take several stances depending on the function a person requires, so several scenarios (e.g. pocket, purse, talking, writing message) and its influences must be taken into account. Research regarding sensor fusion and filtering works towards overcoming these problems and promising approaches have been proposed.

2.3.10 Magnetic

Magnetic fields unlike RF signals do not suffer from reflections and multipath due its capability of penetrating walls. This characteristics make it appealing for indoor tracking. There are several ways magnetic fields can be useful in this scenario. First of all, the earth magnetic field can provide some useful even though unreliable information regarding orientation. The unreliability comes from the fact that electronic devices or metallic objects that populate any environment causes interference in the magnetic field [30]. However, these alterations can be put to good use. These interferences give magnetic fields special signatures so scene analysis can be applied and by mapping the magnetic field of a building it can then be used for indoor location [31]. Another approach is to generate artificial magnetic fields that can be measured by a receiver and triangulate position. Furthermore, the same magnetic field can even be modulated in order to transmit a specific message regarding location. Even though these methods have theirs advantages, the requirements for scene analysis/fingerprinting have already been stated, generating artificial magnetic fields requires extra hardware and the interferences caused by nowadays technology act as a highly degrading factor.

2.4 System Evaluation

In this section parameters of system evaluation are specified [12].

Accuracy

Accuracy is based on the difference between the estimated position and the actual target location. It is regarded as the most important factor when evaluating a system as it indicates how big the disparity between what is calculated and the real location is.

Precision

Precision evaluates the robustness of the measurement, it indicates how consistently a certain performance can be obtained.

Range

Range indicates how far the coverage of the system can reach.

Complexity

Complexity informs about how complex the hardware or software needed is. Complex hardware may result in costly installations and maintenance, whereas complicated positioning algorithms require heavy processing power making it impossible to implement on the mobile device side.

Cost

There are many costs associated with such a system these include the cost of hardware, software, energy, installation and maintenance.

Robustness

Robustness evaluates how foolproof a system is, i.e. the ability to yield a positioning result even in the event of a damaged sensor/station, an unknown value, resource limitation or any form of extraordinary situation.

Scalability

Scalability translates itself in the capability of a system retaining its characteristics even when applied to a larger scale. Positioning system's performance tend to degrade with the distance between transmitter and receiver, this parameter indicates how well the system is expected to perform in a larger scope.

2.4.1 Discussion

Despite the wide variety of technologies and measuring techniques, the principle is relatively similar between approaches. In order to be tracked, the target has a unique identifier achieved by using a tag (e.g. RFID tags, IR tags, UWB tags). This tags, which vary in complexity and size depending on the technology, are then the target of a measuring process (e.g RSS) from the reference station(s). This information is then computed and through positioning algorithms (e.g triangulation) a location is achieved. Combination of different measurements and positioning algorithms, as well as error correction models, algorithms and techniques increase the system performance [32]. Some solutions benefit from technology being already in use, for instance WLAN access points can be used as reference stations and smartphones as the tags. Other achieve high precision but require line of sight, installation of complex hardware, specific tags or previous mapping of the environment characteristics. It is a trade-off between performance and special requirements. In the end, it is about adopting the alternative whose limitations can be overcome and best suit the target environment.

Chapter 3

Project Description and Solenoid Design

This chapter explores the possibility of using a solenoid as the source of a magnetic field to be used as a magnetic reference. The main point is dimensioning the solenoid according to the system requirements. Calculations and simulations are presented.

3.1 Project Description

Systems using inertial sensors, like the ones mentioned being used by smartphones, need to be able to address the positioning error that results from the cumulative noise resulting from integration otherwise measurement eventually drifts to the point it can no longer be used [33] [34].

This happens because both magnetometer and gyroscope suffer from different limitations. Ideally the gyroscope fast and dynamic response could be used for fast rotations and the slower but steadier data of the magnetometer could help achieving precise heading values.

Magnetometer senses the magnetic field around the smartphone. This means not only the earth magnetic field of the earth that indicates magnetic north but also all the interferences generated by electronics and metallic structures that undermine the results. These interferences lead to highly unreliable magnetic data.

On the other hand gyroscope also has its own limitations. There is bias that offsets the measurement and contributes to the cumulative error. Even though this can be partially accounted for with calibration, bias can vary with factors like temperature which make it difficult to eliminate. Furthermore inherent to the process of integration there is drift resulting from the inclusion of noise. All these factors contribute to a cumulative error that increases over time and compromises the system.

In order to achieve better results, this work will focus on generating a magnetic field that can be used as a reference to help achieve more accurate heading values as well as studying some different ways of generating it.

One of the main points is studying with calculations and simulation the possibility of generating a magnetic field using a solenoid that would work as a reference. A checkpoint that provides additional information in order to improve accuracy.

The other being developing an application capable of detecting and compute an angle from the artificially generated field and finally test and characterize the application performance.

3.2 Field outside a finite solenoid: Calculations

Even though the field inside a solenoid is typically well described by $B = \mu_0(\frac{N}{L})I$, the field outside proves to be more complex. The field lines form loops and even though the field outside is much lower than the inside, due to the fact that there are the same lines but spread over a much larger volume, it is not zero and can be calculated.

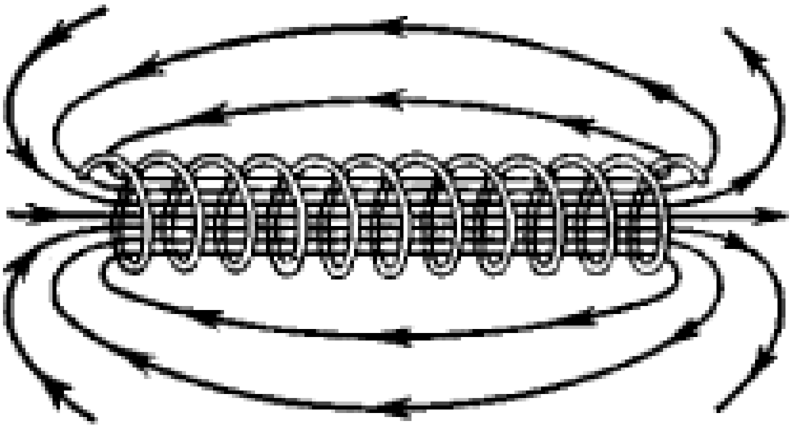


Figure 3.1: Solenoid field lines

The magnetic field outside the winding on a given point in space is given by equations [35] :

$$B_r = \frac{\mu NI}{\pi}\sqrt{\frac{a}{r}}[\frac{2-k^2}{2k}K(k) - \frac{E(k)}{k}]_{\xi_-}^{\xi_+} \tag{3.1}$$

$$B_z = \frac{\mu NI}{4}[\frac{\xi k}{\pi\sqrt{ar}}K(k) + \frac{(a-r)\xi}{|(a-r)\xi|}\lambda_0(\phi,k)]_{\xi_-}^{\xi_+} \tag{3.2}$$

where

B_r, B_z	radial and axial magnetic induction component
K	complete elliptic integral, first kind
E	complete elliptic integral, second kind
I	current in each filament
a	coil radius
L	coil length
N	number of turns per unit coil length
λ_0	Heuman lambda function
μ	permeability

$\xi_{\pm}$	$z \pm \frac{L}{2}$
ϕ	$tan^{-1}\lvert\frac{\xi}{a-r}\rvert$
k	$\sqrt{\frac{4ar}{[\xi^2+(a+r)^2]}}$

To first evaluate the magnitude of the field, a calculation was made for a solenoid with a length of 30 cm, radius of $2.5cm$ and 300 turns. The point in space chosen was 1.5 meters radially away from the center and 1 A current. At the point chosen in space the radial component should be zero and only equation Bz should provide a value. The magnetic field inside for this design would be approximately $1.26\mu T$. The resulting magnetic field obtained for the outside was $18nT$. This value confirms the much lower magnitude of the field outside the solenoid compared with the interior. However a reasonable field can still be obtained, at least big enough to be significant in comparison to the earth's magnetic field on the planet's surface, that typically ranges from $30\mu T$ to $60\mu T$. The previously presented equations assume a solenoid with an infinitely thin layer as the winding. In order to dimension a solenoid for this use a more realistic calculation method should be used. The Visual Basic routine found in Jim Hawley's unpublished note "The magnetic field in and around a finite cylindrical air-core solenoid" takes into account number of layers and the wire width, besides the already mentioned dimensions: number of turns, length, radius, coordinates of the point of interest and electric current [36]. The program works by dividing each coil in a number of arcs, 1000 in the calculations of this work, and integrating the field produced by each segment around the perimeter of each coil, along the length and height of the solenoid. The wire width in particular is calculated as the winding width over the number of layers. As a way to compare the results yielded by this method to the previous equations, a high density of coils and only one layer were considered first in order to have an approximation to the infinitely thin, one layer solenoid. The results were very similar which makes it possible to assume this is a more appropriate way of testing for a possible design given the more specific parameters. There are a series of parameter dependencies that should be taken into consideration when dimensioning the solenoid. An increase in size, turns of wire, layers of winding and current will result in a bigger field nevertheless the drawbacks and dependencies should be kept in mind. Both an increase in size and current are not desired to exceed a reasonable limit, given the indoor tracking context both power and space requirements should be watched for. For the same solenoid length it is possible to have more or less turns with thinner or wider wire. Wider wire results in a lower resistance but a more voluminous object and even though more turns equate a larger field a thinner wire results in a higher resistance which translates in the use of higher voltages for the same current. Furthermore, the increase in turns and layers eventually produces only residual increases. Aiming for an outside field close to $100\mu T$ in order to have a higher field range and also a smaller solenoid, the use of a ferromagnetic core to improve magnetic field was proposed.

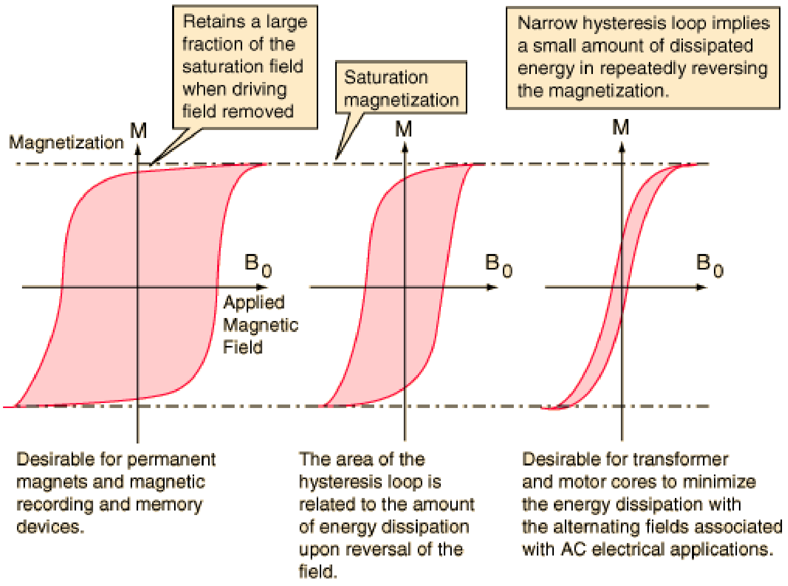


Figure 3.2: Comparison between different hysteresis loops and applications

3.3 Field outside a finite solenoid: Core material choice

In order to correctly choose a core it is important to study some defining factors and characteristics. Ferromagnetic materials can be divided in two main categories: hard magnetic materials and soft magnetic materials. Hard magnetic materials are difficult to magnetize and demagnetize, as the materials tend to keep their conditions even after the magnetization field stops existing. This property is denominated as magnetic hysteresis. When an alternating field is applied to this type of materials, its magnetization will trace an hysteresis loop. The analysis of this graph can be used to characterize and describe the material behaviour. Hard magnetic materials find its use mainly on the production of permanent magnets and memory devices applications such as magnetic tapes, hard disks and credit cards. Soft magnetic materials are the opposite of the hard ones as they are easy to magnetize and demagnetize. However hysteresis will still manifest itself, but in a much smaller scale than hard magnetic ones. This results in low hysteresis losses which makes them the materials used for core transformers. Even though the hysteresis loop is narrow it still exists so the magnetization won't exactly follow the applied field which mean that in case we have ,for instance, a sinusoid the result will be a somewhat distorted sinusoid.

The harder the material the wider the loop which represents a strong hysteresis effect whereas a narrower pulse indicates a soft magnetic material and low hysteresis effect, as illustrated by figure 3.2.

Magnetic saturation happens when all the magnetic domains in a material are aligned and as a result the further increase of the magnetization field does not increase the output field. The materials at electromagnets' and transformers' core saturate at around 2 Tesla. At this point the only possibility is an increase in size which in this particular case is not suitable.

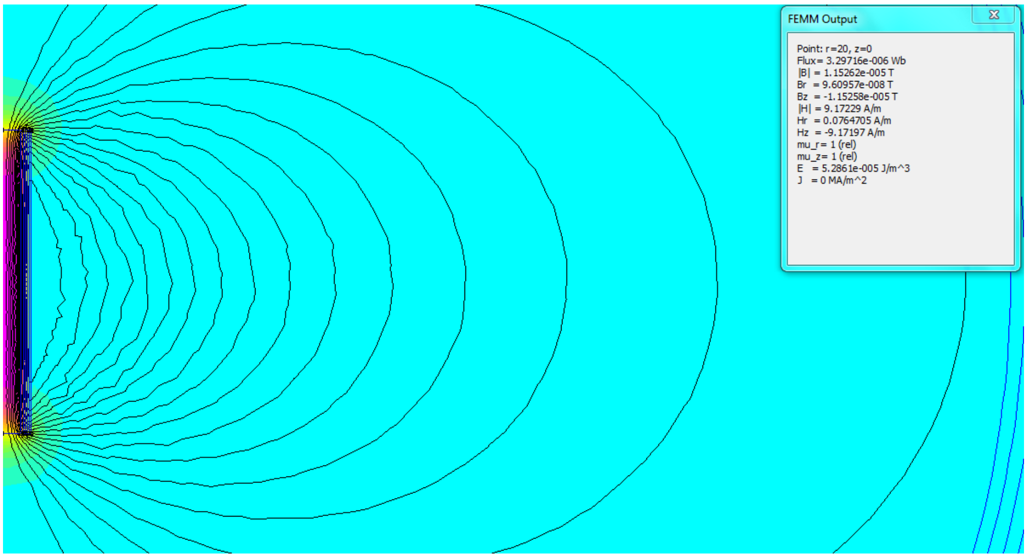
Permeability describes the degree of magnetization a material can sustain. The higher the permeability the higher will be the magnetization. Permeability for the vacuum (μ_0) is $4\pi * 10^{-7}$ $\mathrm{V \cdot s/(A \cdot m)}$. Usually permeability of materials is expressed in terms of relative permeability (μ_r) instead of absolute one, with $\mu_r = \dfrac{\mu}{\mu_0}$.

Eddy currents are loops of induced current that circulate in planes perpendicular to the magnetic field flux. This currents can produce magnetic fields that oppose the primary field resulting in flux reduction. This effect is diminished by creating the core using layers of magnetic material, or laminations.

These are the main parameters to keep in mind when choosing a core. In this particular case a soft magnetic material is required because alternated current will be used to produce the magnetic field, the permeability should be relatively high while keeping material cost reasonable and the saturation should be taken into account for efficiency purposes.

3.4 Field outside a finite solenoid: Simulations

The field can be further improved by using a ferromagnetic core instead of air. The field inside is raised by a factor of μ_0, however the same does not happen on the outside. FEMM 4.2 is a software that allows electromagnetic simulation and has a library of materials to be chosen both for wire and core. Just to explore the influence of using a magnetic material core a simulation was made for a solenoid with a length of 15 cm, a diameter of 2 cm and 5 layers of 150 turns of 18 AWG copper wire, first with an air core followed by a core of mu-metal.



```
Point: r=20, z=0
Flux= 3.29716e-006 Wb
|B| = 1.15262e-005 T
Br  = 9.60957e-008 T
Bz  = -1.15258e-005 T
|H| = 9.17229 A/m
Hr  = 0.0764705 A/m
Hz  = -9.17197 A/m
mu_r= 1 (rel)
mu_z= 1 (rel)
E   = 5.2861e-005 J/m^3
J   = 0 MA/m^2
```

Figure 3.3: Magnetic simulation core air solenoid

For the air core solenoid in 3.3 the field at a point 20 cm radially away from the center is indicated to be $11.52\mu T$.

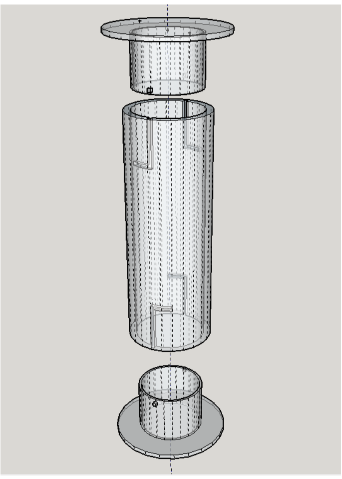
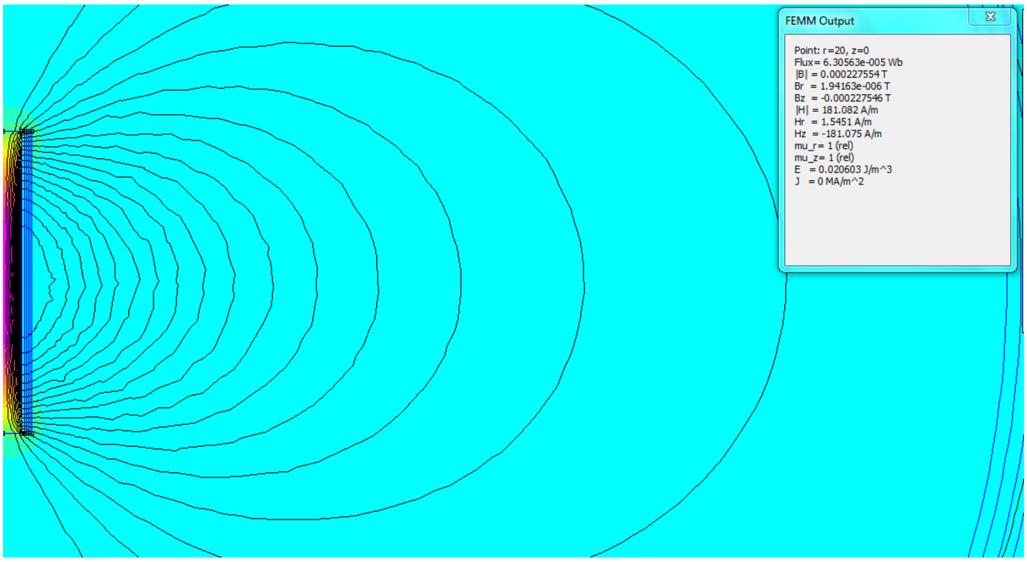


Figure 3.5: Prototype for core testing

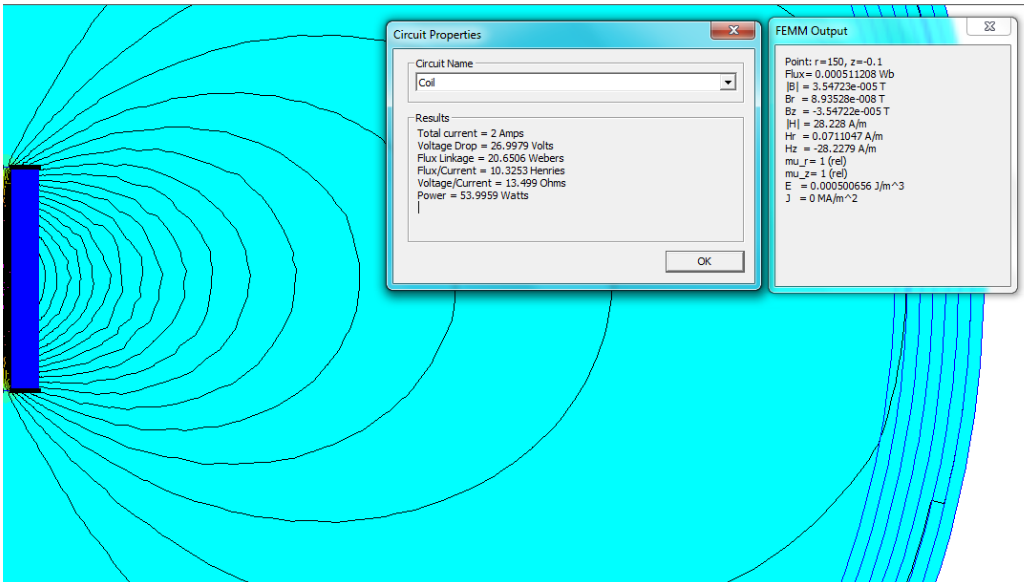


```
Point: r=20, z=0
Flux= 6.30563e-005 Wb
|B| = 0.000227554 T
Br  = 1.94163e-006 T
Bz  = -0.000227546 T
|H| = 181.082 A/m
Hr  = 1.5451 A/m
Hz  = -181.075 A/m
mu_r= 1 (rel)
mu_z= 1 (rel)
E   = 0.020603 J/m^3
J   = 0 MA/m^2
```

Figure 3.4: Magnetic simulation mu-metal core

The second simulation,figure 3.4, using the mu-metal core yields a field of $227.55\mu T$ for the same point in space. Given the fact that only the materials available on the software library can be tested, in order to explore the influence of diverse materials a structure to support a prototype solenoid with removable ends was designed for 3D printing, presented in 3.5.

This should provide a way of exploring the properties of different materials and test them in a real scenario. Materials proposed for testing are pure iron, cobalt iron, silicon iron and also low carbon steel. The characterization of the influence and performance of these materials in a practical way would bring important information that could influence the optimal choice.



Circuit Name: Coil

```
Results
Total current = 2 Amps
Voltage Drop = 26.9979 Volts
Flux Linkage = 20.6506 Webers
Flux/Current = 10.3253 Henries
Voltage/Current = 13.499 Ohms
Power = 53.9959 Watts
```

```
Point: r=150, z=-0.1
Flux= 0.000511208 Wb
|B| = 3.54723e-005 T
Br  = 8.93528e-008 T
Bz  = -3.54722e-005 T
|H| = 28.228 A/m
Hr  = 0.0711047 A/m
Hz  = -28.2279 A/m
mu_r= 1 (rel)
mu_z= 1 (rel)
E   = 0.000500656 J/m^3
J   = 0 MA/m^2
```

Figure 3.6: Magnetic simulation final design

3.5 Discussion

After some prototype simulations and evaluation of parameters a more realistic simulation for a possible solenoid was made, see figure 3.6. A solenoid able to achieve a field of $30\mu T$ at 1,5 meters could be suitable for a relatively narrow passage. For this particular case a simulation was made considering a solenoid of $50cm$ long and a total diameter of $10cm$. It consist of 25 layers of 250 turns of 12 AWG copper wire and for the core the M-27 steel, that belongs to the silicon iron group, was chosen.

Considering a current of $2A$ a power consumption of almost $54W$ is estimated for a relatively small application. It can be assumed the solenoid can be a reasonable solution for situational cases however its power consumption and material requirements are big drawbacks in a large scale application.

Chapter 4

Experimental Setup

In order to prove the concept of using a magnetic field to get heading measurements an experimental setup was prepared. The setup consists of a pair of coils facing each other, a signal generator used to apply a signal to the coils and a smartphone magnetometer used as the measuring unit.

4.1 Coils

The coils have a diameter of 13.4 cm, 320 turns, a maximum current load of 2 A and a DC resistance of 6Ω. The coils are placed in a support 23 cm apart, as seen in 4.1. Placing the coils 6.7 cm (radius of the coils) apart would constitute a Helmholtz arrangement which produces a nearly uniform field between the coils. However in order to have a more realistic view and also because it is more similar to the field outside a solenoid this specific arrangement was not performed, instead an arbitrary distance of 23 cm was used. The coils' magnetic field was modulated by a $2Hz$ square wave. In this specific case a voltage of $1V$ was used which draws a current that peaks at $70mA$ and results in a 30 μT field.

4.2 Magnetometer

The smartphone used was a Samsung Google Nexus S. The magnetometer installed in these devices is the AK8973 by Asashi Kasei Microdevices. Android methods return maximum range at $2000\mu T$, resolution at $0.0625\mu T$, power consumption at $6.8mA$ and minimum delay at $16.667ms$ which would translate in a 60 Hz frequency. However taking samples and plotting an histogram,figure 4.2, reveals that the highest frequency achievable consistently is 50 Hz, with some jitter around it.

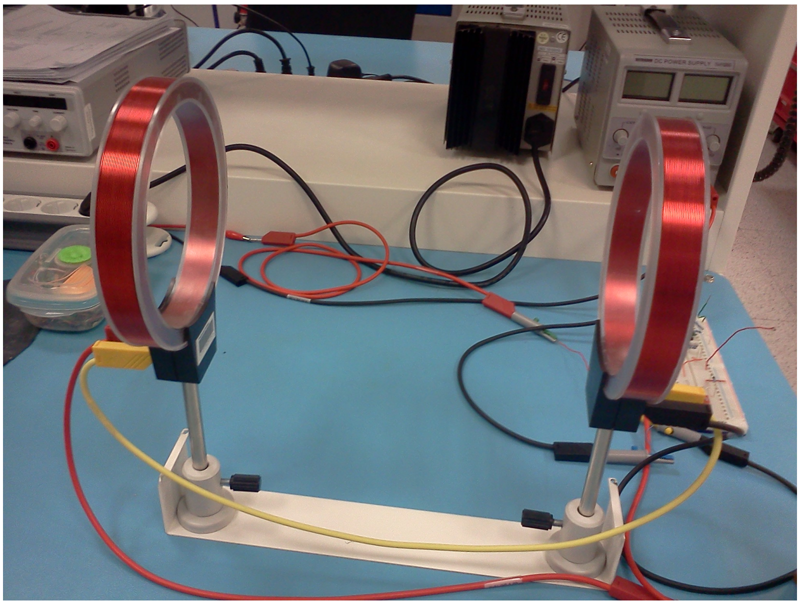


Figure 4.1: The coils

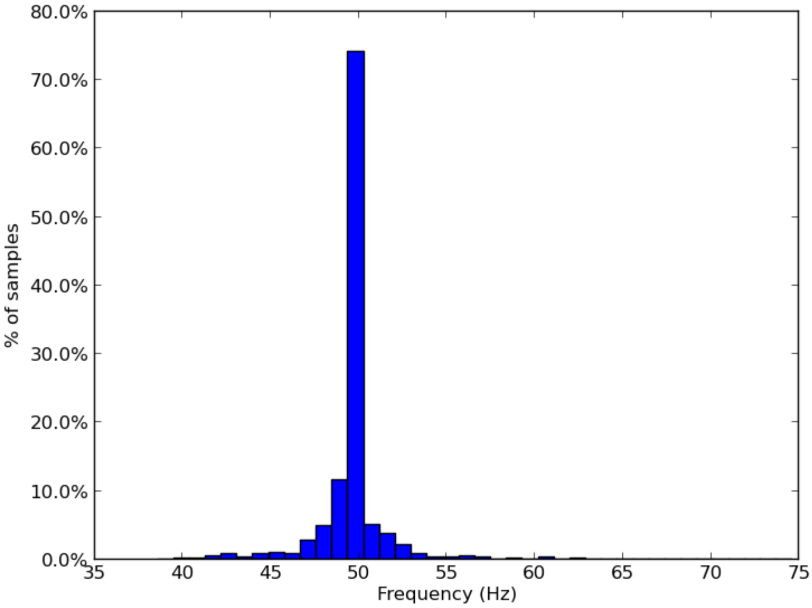


Figure 4.2: Sampling frequency (3000 samples)

Even though there are much higher and lower sampling rates than 50 Hz its relevance is residual, with most samples being taken consistently at rates between 47 and 52 Hz. Device driver modification and native methods are some strategies which were tried in an effort of improving sampling rate and the variations in time between samples, but only jitter reduction has been reported significant [37]. Given the fact that a modulation of the magnetic field will be used, a frequency characterization of the magnetometer is performed in order to evaluate its response and gather information about possible wave form and frequency use.

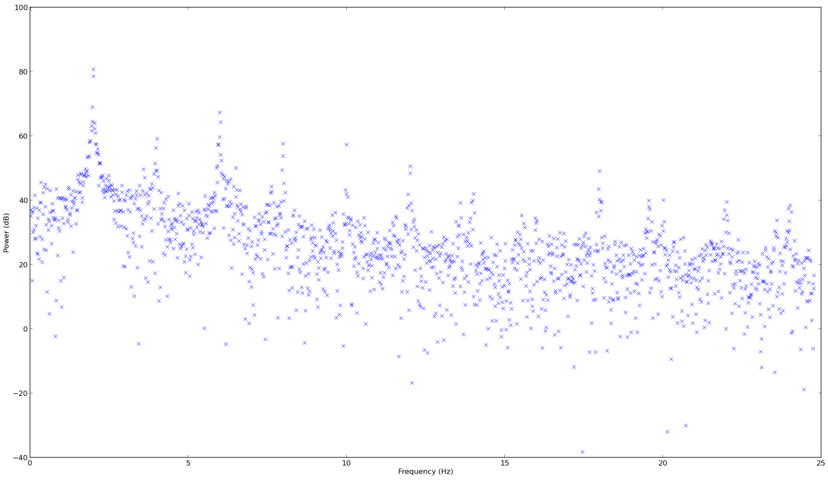


Figure 4.3: 2 Hz square wave frequency response

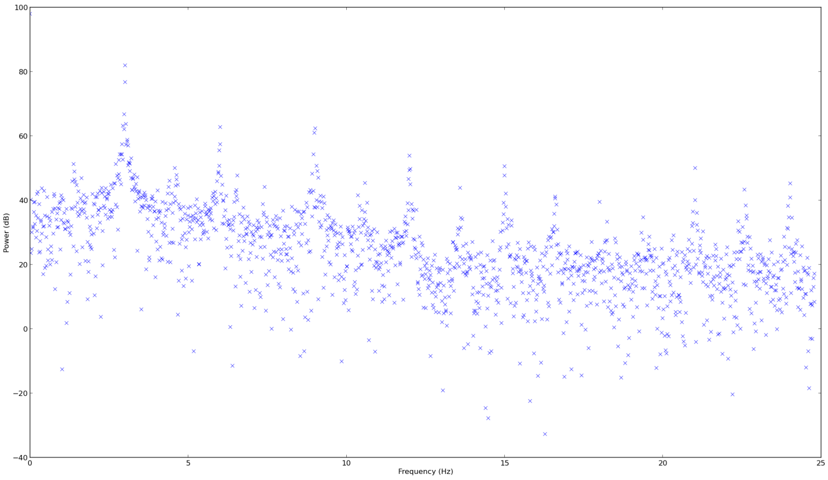


Figure 4.4: 3 Hz square wave frequency response

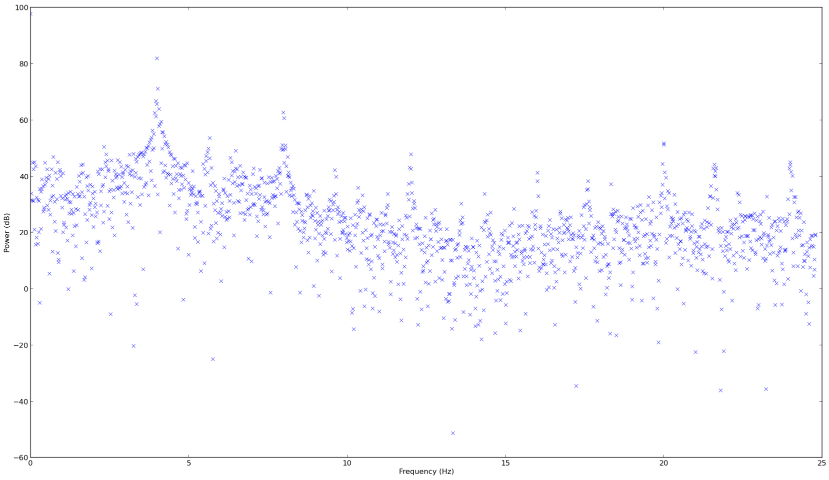


Figure 4.5: 4 Hz square wave frequency response

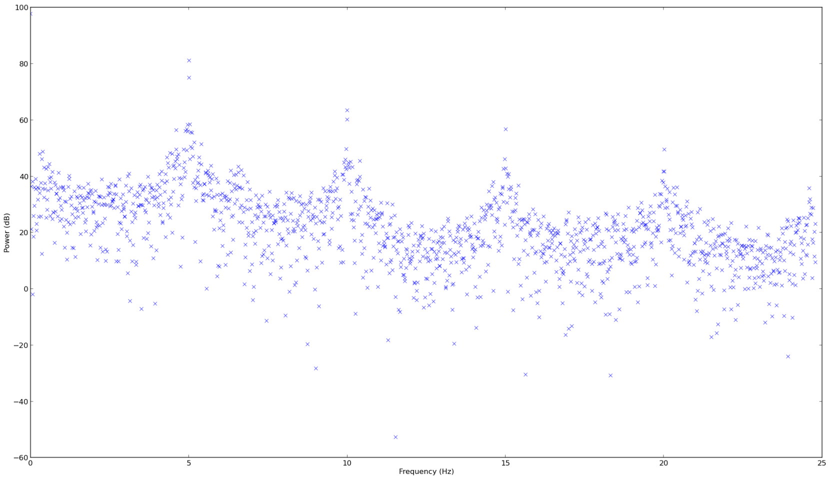


Figure 4.6: 5 Hz square wave frequency response

As expected the spectral content of signals 2 to 5 Hz,figures 4.3, 4.4, 4.5 and 4.6, show a big peak at the fundamental frequency followed by a series of peaks at multiple frequencies. Square waves are formed by overlapping sinusoids multiple of the original frequency. The shape will be closer to the ideal square wave the more odd harmonics are present. In order to achieve an approximate square wave shape at least the 3rd and 5th harmonics should be found.

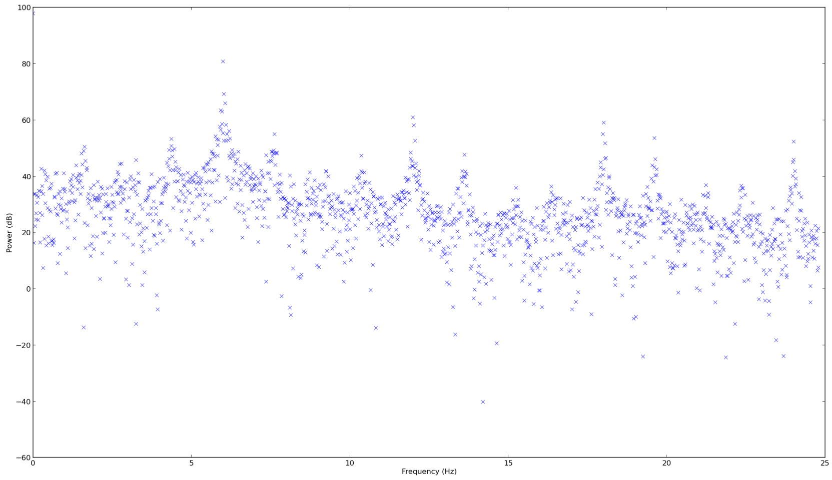


Figure 4.7: 6 Hz square wave frequency response

Taking into account the 50 Hz sampling rate the 5th harmonic can only be considered until the 25 Hz limit. This means the highest fundamental frequency that can be used is 5 Hz. At 6 Hz the 5th harmonic is lost and with it the shape of the wave,as seen in 4.7, furthermore several frequency peaks appear due to aliasing of the increasing amount of frequencies past 25 Hz.

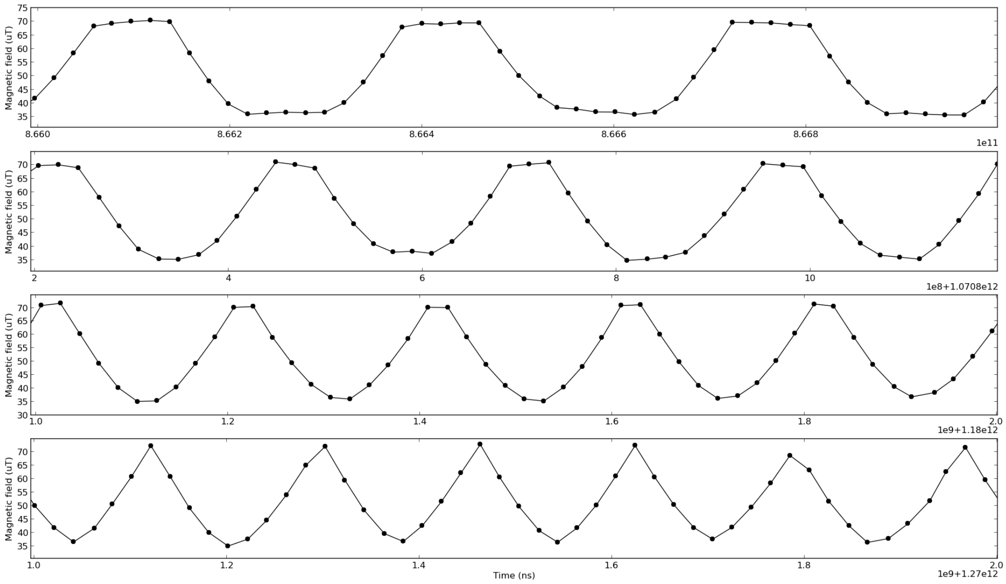


Figure 4.8: Signals:3 Hz, 4 Hz, 5 Hz, 6 Hz (top to bottom)

A perfect sinusoid should have only one peak at its fundamental frequency, however even sinusoidal waves show harmonic content due to distortion caused by sampling process and field generation.

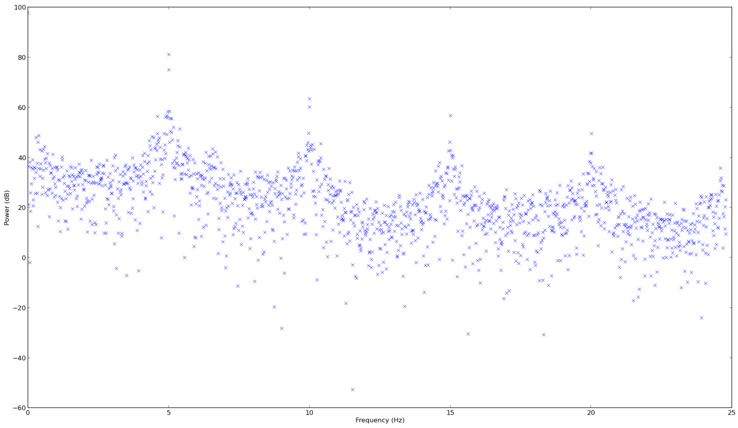


Figure 4.9: Square wave 5Hz frequency spectrum

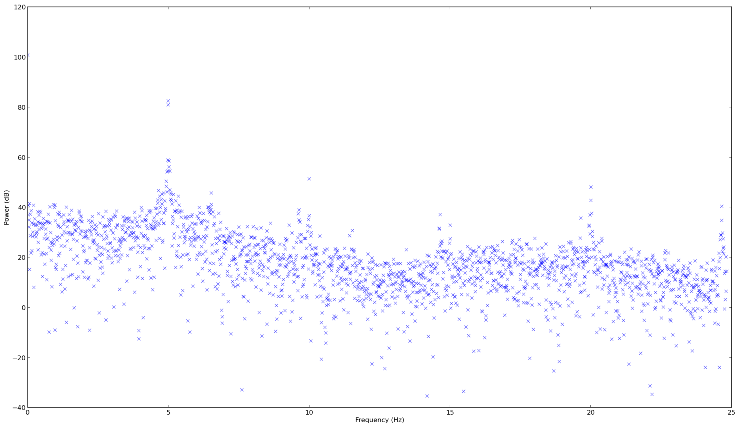


Figure 4.10: Sine wave 5 Hz frequency spectrum

In this particular case, it is possible to see how the sinusoid and square wave spectrum are similar with the power of the harmonics in the sinusoid being just lower.

Another factor to take into account is the magnetometer position on the smartphone itself. Given its positioning, discrepancies in the measured magnetic field magnitude can occur when crossing the field in different positions, getting higher readings the closest the left side is to magnetic sources.

Figure 4.11: Magnetometer position

4.3 Android Application and Procedure

The first step is the detection of the artificially generated magnetic field. The application needs to be able to detect being in the presence of the magnetic reference which as an example is being modulated by a square wave. It achieves this by monitoring the derivative between samples.

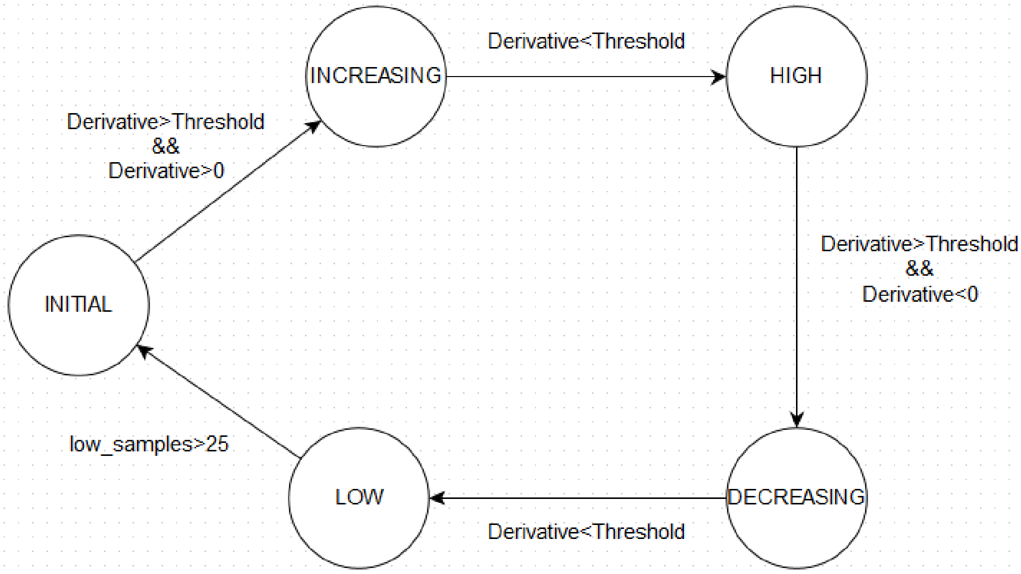


Figure 4.12: State diagram

The detection is made by searching for a high peak in the derivative between magnetic field samples, it then follows a state machine-like behaviour, as seen in diagram 4.12, analysing the derivative to identify the periodical repeating states: rising to peak, peak level, decreasing to ambient and ambient level. When this behaviour is observed a set of times it is assumed the smartphone is in the presence of the coils' alternating field.

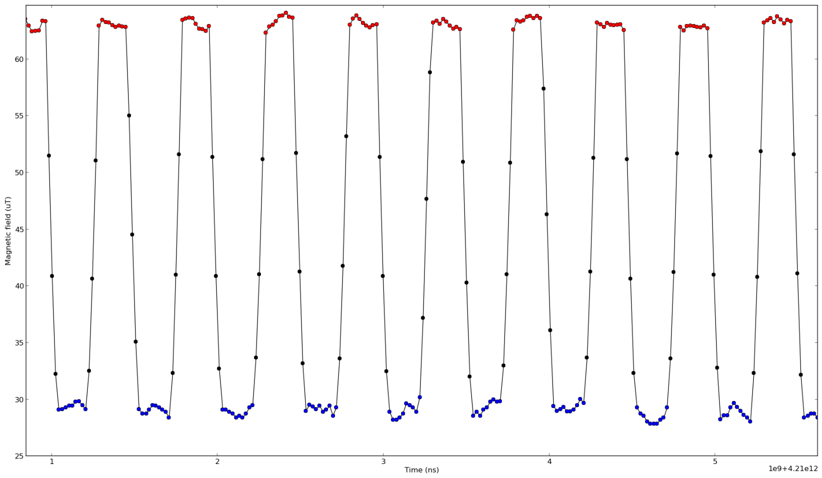


Figure 4.13: High(red) and low(blue) level detection performed by the application

The procedure consists of passing the smartphone across the area between the coils getting its orientation by calculating the angle between itself and the interference. It is important to notice the magnetic field between the coils is the conjunction of the field generated by the coils and the environmental field in the same zone. In order to get rid of the ambient level the magnetic field is modulated with a square wave. The application saves the magnetic field value of each axis when in the ambient state (LOW) and calculates an average of what the environmental influence is. When it reaches the peak level state (HIGH) it deducts the ambient magnetic field from the measurement. This isolates the magnetic field being generated and then this 3 axis magnetic field values are used by trigonometric functions to calculate the device orientation relative to field. Pairs of these orientations measurements enable the computation of the angle variation.

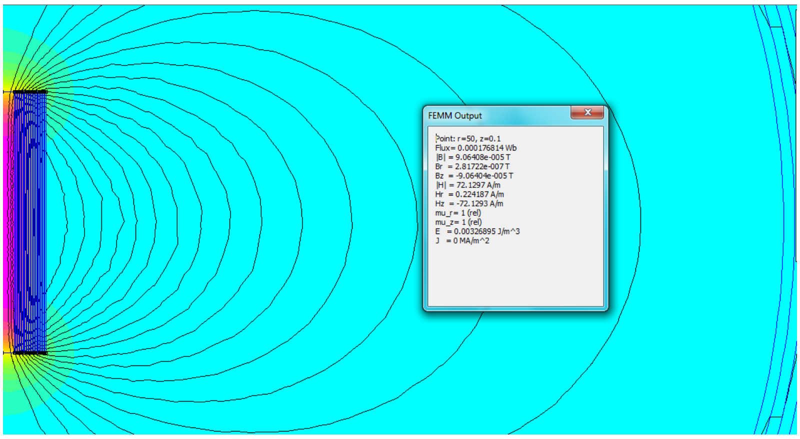
Even though it is a simplistic approach it should be enough to give some insight on the possibility of achieving a valid measurement of an angle variation with this method.

Chapter 5

Results

5.1 Solenoid design

As far as solenoid design is concerned two main prototypes are considered. A larger version that generates a field of $90\mu T$ at 50 cm without using a ferromagnetic core.

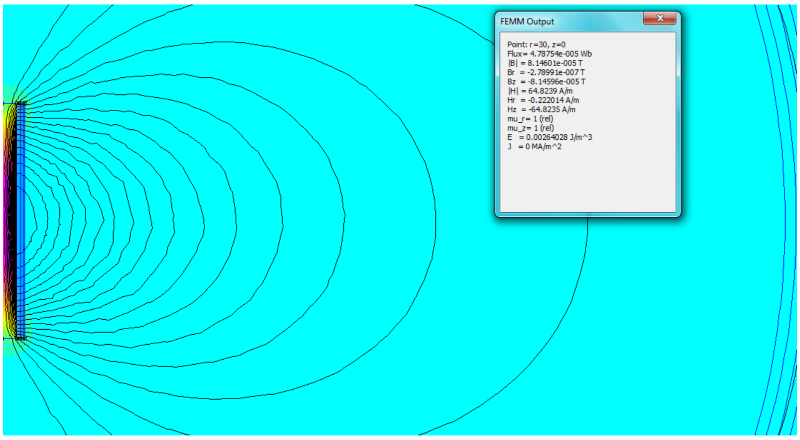


```
Point: r=50, z=0.1
Flux= 0.000176814 Wb
|B| = 9.06408e-005 T
Br  = 2.81722e-007 T
Bz  = -9.06404e-005 T
|H| = 72.1297 A/m
Hr  = 0.224187 A/m
Hz  = -72.1293 A/m
mu_r= 1 (rel)
mu_z= 1 (rel)
E   = 0.00326895 J/m^3
J   = 0 MA/m^2
```

Figure 5.1: Air core solenoid design simulation

It is 30 cm long, has a 2.5 cm radius and 25 layers of 250 turns of AWG 12 wire. A current of 2 A is considered.

A more compact version that makes use of a M-27 silicon steel core to achieve a similar field on same point in space.



```
Point: r=30, z=0
Flux= 4.78754e-005 Wb
|B| = 8.14601e-005 T
Br  = -2.78991e-007 T
Bz  = -8.14596e-005 T
|H| = 64.8239 A/m
Hr  = -0.222014 A/m
Hz  = -64.8235 A/m
mu_r= 1 (rel)
mu_z= 1 (rel)
E   = 0.00264028 J/m^3
J   = 0 MA/m^2
```

Figure 5.2: M-27 core solenoid design simulation

The former being 15 cm long, a 2 cm radius, and 5 layers of 150 turns of AWG 18 wire. A current of 3 A is considered.

5.2 Experimental

A 2 Hz square wave was used to modulate the generated magnetic field.

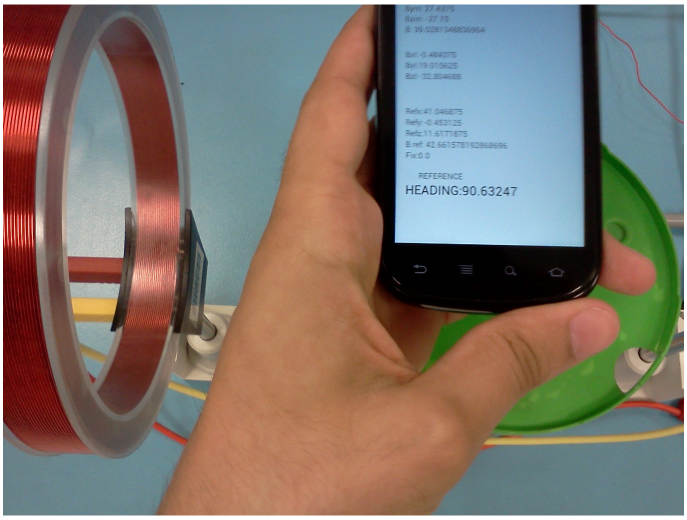


Figure 5.3: Perpendicular crossing

In order to test the output of the application the smartphone was rotated inside the magnetic field between the coils. For reference directions 0 , 90 , 180 and -90 degrees the following results were obtained by setting the smartphone in said directions for approximately 1 minute.

Perpendicularity to the field can be achieved in two different positions that should yield 90 and -90 degrees.

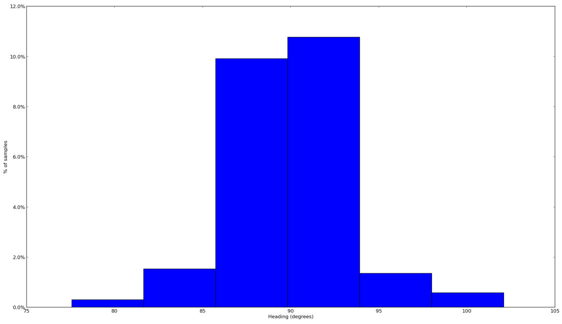


Figure 5.4: Perpendicular position(90 degrees)

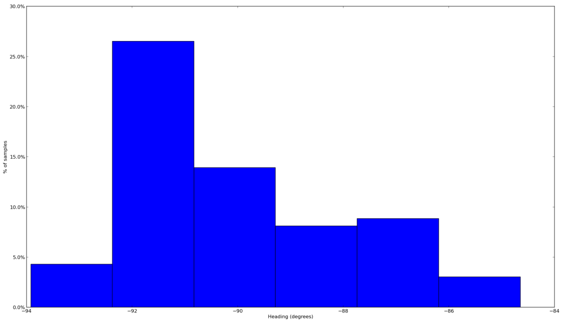


Figure 5.5: Perpendicular position (-90 degrees)

Parallel to the field there are also two possible positions (0 and 180 degrees).

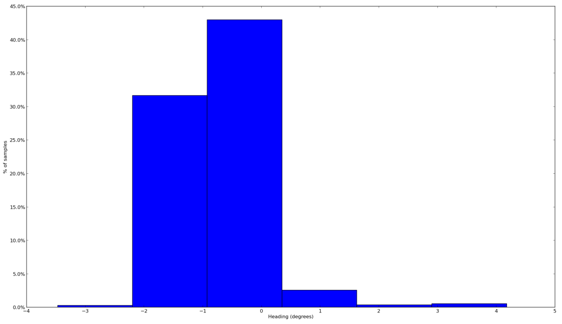


Figure 5.6: Parallel position (0 degrees)

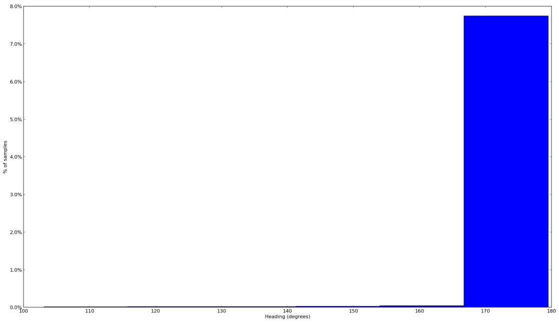


Figure 5.7: Parallel position (180 degrees)

There is a significant variation around the expected values and also the variation between directions is not the same. This could be explained by the non uniformity of the field and position of the magnetometer on the smartphone. A rotation around the smartphone's center leaves the magnetometer in a different region of the field resulting in these deviations.

5.3 Discussion

The results regarding solenoid design show that it is possible to generate a magnetic field that should be big enough to some applications. However generating a magnetic field for big distances requires high power, a big design and a significant amount of material. Even though the solenoid seems like an inefficient solution for generating the magnetic field in large scale problems its use could still be situational in some scenarios.

Using the magnetic field to acquire further information regarding heading looks promising taking into account the results without any advanced signal processing methods and optimization. The bigger problem could be generating a field uniform enough to achieve precise results.

Chapter 6

Conclusions

6.1 Objectives and achievement

Getting back to the objectives proposed for this work most of them were at least partially achieved.

Review technologies and principles of indoor positioning: A review of several principles used for distance measurement and positioning was made. An overview of a variety of technologies used in indoor tracking systems was done, with the most important alternatives listed and also some examples of said technology applications.

Magnetic antenna design suitable for reference points in indoor tracking systems: A study exploring the possibility of a solenoid as a magnetic reference was elaborated covering magnetic field calculations and expressing the variables parametrization. Some guidelines were given for the choice of a possible magnetic core. Simulation were presented to corroborate calculations and predict magnetic core influence. The resources for further material characterization and testing were also proposed for a more reliable and optimal choice.

Developing an Android application that can identify multiple reference points on a blueprint: An android application was developed that can identify the presence of the magnetic reference. It detects the high and low magnetic field level and calculates the magnetic field influence. Finally it computes the smartphone orientation to the aforementioned field.

Heading and displacement correction for indoor tracking solutions: Even though the application calculates the angle between smartphone and field, and two of this measurement can produce a angle variation to be used for gyroscope correction.

6.2 Future work

Regarding the specific area of magnetic references various different ways offer room for innovation and improvement. On the smartphone side further study into sensor event handling can result in higher and steadier sampling while also reducing CPU usage. The main objective being, the highest possible sampling rate with the minimum amount of deviation in time between samples.

This could be achieved by further investigating native sampling and how android handles the sensor interruptions. When all the software optimizations are achieved, no further improvements can be obtained on this particular area. The bottleneck lies only on the hardware side and constitutes a system limitation.

As far as the magnetic reference is concerned in this work the solenoid was explored as such, however other methods and creative solution can be studied. Working on different coil configurations may further improve the performance and create more alternative approaches to this problem. Innovative ideas like using magnetic paint among other magnetic materials also look like interesting ways of improving the range of strategies using magnetic fields as references for indoor tracking.

Finally filtering algorithms, detecting algorithms and methods of evaluating the validity of a magnetic measurement can be researched in order to turn this approach much more robust and reliable. Implementing a signature on the field for unique recognition or even transmitting a message using the magnetic field is also a task worth mentioning.

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