Performance Analysis of Magnetic Indoor Local Positioning System

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PERFORMANCE ANALYSIS OF MAGNETIC INDOOR LOCAL POSITIONING SYSTEM

by
KYLE WROBLE

A thesis submitted to the Graduate College in partial fulfillment of the requirements for the degree of Master of Science in Engineering (Computer) Electrical and Computer Engineering Western Michigan University June 2015

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ABSTRACT

As of the writing of this paper, there is no standard technique for implementing Indoor Position Systems (IPS) in one building or another, as each technique has its own advantages and drawbacks. The best IPS implementations often employ the use of multiple techniques within a building in order to maximize precision. This paper explores the most popular IPS techniques in use today, and highlights their strengths and weaknesses. After analyzing the pros and cons of each approach, it becomes clear that magnetic positioning is a useful tool for creating an accurate, reliable positioning system. Throughout this paper, the feasibility of the implementation of magnetic localization in an indoor positioning system is explored. The conclusion of this research is that while magnetic positioning can be used as a solo solution for an indoor positioning system, it is best utilized as a supplement to other methods of indoor localization.
We have seen that computer programming is an art, because it applies accumulated knowledge to the world, because it requires skill and ingenuity, and especially because it produces objects of beauty.

— Don Knuth

ACKNOWLEDGMENTS

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Kyle T. Wroble
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INTRODUCTION

In the following pages, I will state the research question posed by this paper, as well as explain the purpose and importance of this research. At the onset, the theme of this thesis began as a study of all indoor positioning methods to determine the most effective one to implement throughout our university’s engineering campus. Considered approaches included the use of Bluetooth, RFID, geomagnetic positioning, UWB, WiFi fingerprinting, and Google’s project Tango. As research continued, the candidates for study were reduced to geomagnetic positioning and project Tango. Extensive research was done on both topics. The favored subject of the research was project Tango, but the release timeline of the Tango did not match up with deadlines for thesis. Research continued on geomagnetic positioning until the discovery of position calculation using artificially generated magnetic fields.

1.1 PURPOSE

In this day and age, it is a trivial matter for anyone with a smart-phone to locate and navigate themselves using the Global Positioning System (GPS). That is, however, provided that they are in an environment that is able to communicate with GPS satellites. When the user is outdoors and/or the device has an unobstructed path to the satellite, GPS works as intended. It is when the user steps into a building and obstructs the clear path to the satellite that GPS fails as a positioning system. For these cases, a secondary method of localization is needed. The systems used in determining a user’s position within a structure are often referred to as Indoor Positioning Systems (IPS), and the service that they provide is referred to as indoor localization. These terms will be used throughout the paper when describing these two concepts.

1.2 RESEARCH QUESTION

At the onset, the theme of this thesis began as a study of all indoor positioning methods to determine the most effective one to implement throughout our university’s engineering campus. Considered approaches included the use of Bluetooth, RFID, geomagnetic positioning, UWB, WiFi fingerprinting, and Google’s project Tango.
As research continued, the candidates for study were reduced to geomagnetic positioning and project Tango. Extensive research was done on both topics. The favored subject of the research was project Tango, but the release timeline of the Tango did not match up with deadlines for thesis. Research continued on geomagnetic positioning until the discovery of position calculation using artificially generated magnetic fields.

The experiment performed for the thesis involved the construction of a large solenoid to produce and control a magnetic field. Using a separate sensor equipped with a compass and magnetometer, the components of the magnetic field could be quantified. Due to the nature of magnetic field propagation, the magnitudes of these components could be easily translated into distance measurements from the sensor. If three or more solenoids were operating in the system, and were frequency controlled by a multiple access signal architecture, then trilateration can be employed to determine relative position.

1.3 Importance

The importance of accurate positioning within the confines of a structure is not be be understated. Nearly every modern structure is poorly suited to make use of GPS to provide fine positioning throughout a building. Often there is no line of sight to one GPS satellite, let alone the 3 required for adequate for accurate positioning. When accurate, reliable positioning is required within the confines of a structure, specialized indoor positioning systems are necessary.

The applications of a sophisticated indoor positioning system are numerous. This technology is already being used by supermarkets to track users throughout the store to deliver targeted advertisements [1]. Another proposed application of this technology comes in the form of deployable emergency indoor location systems [15].
BACKGROUND

This section details the roots of indoor positioning systems, and describes a number of methods used in the past and present.

2.1 IPS TECHNIQUES

The concept of Indoor Positioning Systems, or IPS, is one that is seen many approaches. While the implementation of the Global Positioning System (GPS) has become an accepted and standardized system, IPS technology is constantly evolving and adapting as new technology is introduced and new techniques are discovered. There is no standard technique for implementing IPS in one building or another, and each technique has its own advantages and drawbacks. Outlined below are a few technologies that are used to detect an object’s position indoors.

2.1.1 Bluetooth

With Bluetooth receivers being a common fixture on nearly every phone and mobile device these days, it makes sense to implement this technology in an IPS system in some capacity. As Bluetooth is more about proximity and less about position or orientation, it is most commonly used as a sort of an indoor proximity solution as opposed to an indoor positioning system [6]. What’s more, Bluetooth tags have limited range as well as poor predictability. Common fixtures within buildings such as walls and obstacles can occlude the signal, which throws off the locational accuracy. In order to achieve a functional navigation system with Bluetooth alone, tags would need to be placed relatively close together with a clear path to every point of interest. While perhaps not the best choice when looking for positional accuracy, Bluetooth can still be utilized in a supplementary capacity in an IPS system.

2.1.2 RFID

There are actually two forms of RFID that can be used in an IPS system: active RFID and passive RFID. With both implementations of an RFID location system, it is required that special RFID scanners be placed throughout the facility
to be traversed. An RFID tag, either active or passive, is then affixed to the person or object that needs to be tracked.

The main difference between active RFID and passive RFID when it comes to a location system is the minimum distance that the tag must be from the scanner in order to determine position. Passive RFID tags contain no power source, and thus relies on the scanner to transmit power to it. Once energized, the RFID tag can transmit its code to the scanner which can then determine its position. Because of this design, the passive RFID tag is limited in the distance it can be from the scanner in order to be energized. This distance is dependent on the frequency operation of the RFID system and is usually classified as low frequency (LF), high frequency (HF), or ultra-high frequency (UHF). LF typically only operates within a range of 10 cm, HF reads within 1 m, and UHF can read as far as 12 m [3].

In contrast, the active RFID tag supplies its own power, and thus can transmit its signal to the scanners from much farther away. With both active RFID and passive RFID, the positional accuracy is limited to the number of scanners installed in the facility [10]. If an acceptable level of accuracy is to be achieved, a considerable infrastructure investment in tags and scanners would have to be made up front.

2.1.3 Global Positioning System

The Global Positioning System (GPS) boasts tremendous accuracy and precision in wide-open, outdoor settings, but its performance falls off almost completely indoors. As GPS relies on line of sight to the satellites to do the positioning calculations, it is all but useless in enclosed buildings.

2.1.4 Inertial Navigation

A particularly interesting method of indoor positioning comes in the form of inertial navigation. Also referred to as deduced reckoning, inertial navigation helps to determine the position of an object by using measurements of previously determined position of an object along with the speed and direction of the object. Here is a set of equations to describe the heading and coordinates of a wheeled object using inertial navigation [5]:

\[
\Delta \Theta = 2\pi \times \frac{R_W}{D} \times \frac{T_1 - T_2}{T_R} \quad (1a)
\]

\[
\Delta x = R_W \times \cos \Theta \times (T_1 + T_2) \times \frac{\pi}{T_R} \quad (1b)
\]

\[
\Delta y = R_W \times \sin \Theta \times (T_1 + T_2) \times \frac{\pi}{T_R} \quad (1c)
\]

In the equations above, \( \Delta \Theta \) is the change in heading, while \( \Delta x \) and \( \Delta y \) represent the change in the coordinates. \( T_1 \) and \( T_2 \) represent encoder ticks on drives one and two respectively, \( R \) represents the radius of each drive wheel, \( D \)
represents the separation between the wheels, and represents the number of encoder ticks in a full rotation of a wheel.

Because inertial navigation estimates position from a known starting position from heading and speed measurements, it is subject to error. What’s more, because each position measurement is relative to the last, errors are cumulative [5]. To lessen the effect of drift and cumulative error, inertial navigation measurements are run through a filter of some sort, typically a Kalman filter.

An example of applied inertial navigation is the navigation systems in submarines. When the submarine is in stealth mode or otherwise unable to utilize other methods of navigation and positioning, the inertial navigation system must be relied upon to provide accurate predictions of position. Such sophisticated systems are cumbersome and expensive, and thus are only used in applications where other navigation methods are unsuitable [4]. Since inertial navigation is subject to cumulative errors, it is recommended that another positioning system be working in tandem with any inertial navigation system for the sake of accuracy [5].

2.1.5 Geomagnetic Positioning

A promising method of mapping and traversing the interiors of buildings involves the measuring of magnetic flux density. Termed geomagnetic indoor localization, this method of indoor positioning exploits the properties of the earth’s magnetic field to accurately calculate the position of an object [17].

Magnetic flux density is defined as the magnitude of a magnetic B field over a surface. The types of surfaces that allow this technique to calculate position are man-made objects such as certain building materials. If the construction of a building remains static over a period of time, so too will the magnetic flux measured in a particular location of a building remain the same. This property of magnetic fields makes geomagnetic indoor localization an attractive option for businesses looking to map the interior of their buildings.

One downside of this method is that the magnetic anomalies must be measured and mapped ahead of time before they can provide useful positional data. However, once the magnetic anomalies have been measured and mapped to a static floor plan, no additional hardware or time investment is necessary to maintain the system. Furthermore, the accuracy of position measurements scale with the resolution of the fingerprint data.
THEORY

This chapter describes the theory behind the design of this thesis experiment. Also, the fundamentals of magnetic fields and signal processing are described. Previous works involving indoor positioning using artificially generated magnetic fields are introduced, and their findings explained.

3.1 POSITION CALCULATION

After measurements have been gathered from one or more of the technologies described above, the position must then be calculated. There are a number of methods to calculate the position of an object, and the method used depends on the technologies used and what kind of measurements they produce.

3.1.1 Trilateration

Trilateration is essentially a more complicated version of triangulation. Instead of measuring angles to a location from a fixed baseline, it measures the distance to the point directly. GPS is the most popular example of trilateration in practice.

In order to calculate the 2-dimensional position of an object via trilateration, the distance to 3 separate locations is required (GPS measures this distance by measuring the time of arrival of the GPS signal to an object.) Once the distance from the object to a location is known, a circle with a radius of that distance can be imagined around the point of measurement. Along the circumference of this circle is all the possible locations of the object. When a circle is drawn around a second point of reference with a radius of its associated distance to the object, it is seen that the circles now intersect at 2 points. These are now the possible locations of the object. When a third reference point is introduced, the appropriate circle drawn around the point will create an intersection area of the three circles. The center of this intersection is the estimated position of the object and is referred to as the error ellipse [2].

The IPS methods that use trilateration are those that gather data in the form of Time of Flight (TOF), or the amount of time a signal takes to propagate from transmitter to receiver. These measurements can be used to calculate distance to the object. With the distances to three receivers calculated, a po-
position estimation can be made based on the error ellipse formed by the three measurements [6].

3.1.2 Kalman Filter

In order to apply dead reckoning for positioning with any kind of accuracy, a filter is required to separate the inertial measurements of interest from the noise. A Kalman filter is known as an optimal estimator in that it separates the desired parameters from noisy observations [11]. A Kalman filter is described in equation (2):

\[
x(k + 1) = F(k)x(k) + G(k)u(k) + v(k)
\]  

where \(x(k)\) is the dimensional state vector, \(u(k)\) is the dimensional known input vector, and \(v(k)\) is an unknown zero mean white process noise with covariance as described in equation (3):

\[
Q(k) = E[v(k)v(k)']
\]  

State Estimation: In order to understand Kalman filter processing, we can partition it into several stages with physical interpretation:

Initial State:
Start with known \(\hat{x}(k|k), u(k), P(k|k)\)
and new measurement \(z(k+1)\)

State Prediction:
\[
\hat{x}(k + 1|k) = F(k)\hat{x}(k|k) + G(k)u(k)
\]  

Measurement Prediction:
\[
\hat{z}(k + 1|k) = H(k)\hat{x}(k + 1|k)
\]  

Measurement Residual:
\[
v(k + 1) = z(k + 1) - \hat{z}(k + 1|k)
\]  

Updated State Estimate:
\[
\hat{x}(k + 1|k + 1) = \hat{x}(k + 1|k) - W(k + 1)v(k + 1)
\]  

where is the Kalman Gain as defined in the state covariance estimation section.

State Covariance Estimation:
Continuing the partitioning of Kalman filter stages, we use \(e\) to estimate the state covariance:

State prediction covariance:
\[
P(k + 1|k) = F(k)P(k|k)F(k)' + Q(k)
\]  

Measurement prediction covariance:
\[
S(k + 1) = H(k + 1)P(k + 1|k)H(k + 1)' + R(k + 1)
\]
Filter Gain:

\[ \mathbf{W}(k+1) = \mathbf{P}(k+1|k)\mathbf{H}(k+1)'\mathbf{S}(k+1)^{-1} \]  

(10)

Updated state covariance:

\[ \mathbf{P}(k+1|k+1) = \mathbf{P}(k+1|k) - \mathbf{W}(k+1)\mathbf{S}(k+1)\mathbf{W}(k+1)' \]  

(11)

By combining equations (4) through (11), we can perform the covariance calculations as such:

\[ \mathbf{P}(k+1|k+1) = \mathbf{F}(k)[\mathbf{P}(k|k-1) \]  

\[ - \mathbf{P}(k|k-1)\mathbf{H}(k)'[\mathbf{H}(k)\mathbf{P}(k|k-1)\mathbf{H}(k)'] \]  

\[ + \mathbf{R}(k)^{-1}\mathbf{H}(k)\mathbf{P}(k|k-1)] \]  

(12)

This amalgamation of Kalman filter equations (4) through (11) is called the Riccati equation [11] and is described in equation (12).

3.1.3 NLoS and Multipath

The concepts of Non-Line-of-Sight (NLoS) reception and multipath interference are often mentioned when dealing with the transmission of signals. Whenever a signal is projected through space, it is possible for that signal to be reflected off of the surfaces that it comes in contact with. The signal can arrive at the desired receiver in several ways. If there is a line of sight from transmitter to receiver, then the direct signal can reach the receiver.

If reflective surfaces are encountered along the way, then reflected signals can be received as well. If there is no line of sight between transmitter and receiver, then the direct signal can not be received, but a reflected signal still might be. If there is only one received signal, and it is a reflection of the direct signal, then that is termed NLoS reception. In the case that a direct signal is received along with the reflected signals, it is classified as multipath interference [14].

NLoS reception and multipath interference each come with their own challenges to overcome in terms of signal processing. In the case of NLoS, problems arise in terms of measurement errors which are not easily mitigated. The measurement error is termed the path delay, which is the difference in the length of the path taken by the reflected signal and the potential direct route between transmitter and receiver [14].

3.2 Signal Architectures

As the number of signals that require processing increase, it becomes ever more critical to choose a suitable signal architecture. Three of the most common methods of multiple-access signal architecture are time division, frequency division, and code division.
3.2.1 Time Division Multiple Access (TDMA)

In this signal architecture, each signal source generates a signal during its assigned time slot. Since only one source is producing a signal at a given time, the sensor can distinguish which source is producing the observed signal, provided all sources are synchronized to a common clock [15].

3.2.2 Frequency Division Multiple Access (FDMA)

This signal architecture has each signal source producing a sinusoidal signal at a unique frequency. The sensor can identify the signal from each beacon by way of frequency selective filtering [15].

3.2.3 Code Division Multiple Access (CDMA)

This signal architecture technique is designed to accommodate systems with a large number of signal sources while still maintaining low overall signal frequency content. In the CDMA structure, all sources produce signals at all times. However, each source reverses the polarity of its signal according to a pseudo-random code. Each source contains a pseudo-random code, which is a sequence of 1’s and −1’s. Each element of the sequence is referred to as a chip, and the number of chip periods per second is called the chipping rate. The entire code sequence must be sampled in order to identify the individual source. The sources are linked to each other to ensure that all chip transitions occur at the same time and the codes remain aligned. The sensor is also synchronized with the sources, so as to allow for the proper measurements to take place at the end of each chip period.

The most successful and well known implementation of the CDMA signal architecture is the Global Positioning System (GPS). The pseudo-random codes used in GPS are called Gold codes and are so named because of their ability to be grouped into special sets [15]. The Gold codes used in GPS are sequences of 1,023 bits with periods of one millisecond, and are used to determine the identity of a satellite [18].

3.3 Magnetic Localization

There are two ways of utilizing magnetic fields for indoor positioning. One leverages the anomalies caused by disturbances of earth’s magnetic field to perform positioning. This method, termed geomagnetic localization, is akin to localization methods such as those that use existing WiFi signals to determine position. When signals are relatively static, such as the magnetic anomalies caused by perturbations of earth’s magnetic field, the methodology known as “fingerprinting” can be applied to construct a positioning system.

The other method involves the use of artificially generated magnetic fields. In order to artificially generate magnetic fields, coils of current carrying wire
are deployed in key locations around the building. On the receiving end, the strength of the magnetic field from each coil is measured. Since the exact coordinates of the coils are known, trilateration can be used to estimate position based on the magnetic field measurement from each [13]. This is the method we will be exploring for the remainder of the paper.

3.3 Magnetic Localization

3.3.1 Fundamentals of Magnetic Fields

A magnetic field is described as a vectorial physical quantity. It can be observed as a force on a magnet, magnetized matter, or Lorentz forces. There is also a relationship between electricity and magnetism. For the purposes of theory, if a straight wire of infinite length has a current flowing, then magnetic forces are generated. This magnetic force is proportional to the current intensity I, inversely proportional to the distance from the wire r, and tangential to the circular field lines surrounding the wire [9].

In order to measure the strength and direction of a magnetic force, it is important to mention two ways of describing a magnetic field. One vectored quantity $H^*$ is used to describe the magnetic field strength. H is measured in terms of amperes per meter and shows the direction and strength of a magnetic field at a given point. Another way that is often used to describe magnetic fields is the B-field, which is measured in teslas and newtons per meter per ampere [12]. The B-field is also known as magnetic induction and is proportional to the field strength H [9].

The distance from the center of an electromagnetic coil can be reliably estimated by examining the the Biot-Savart law. This law is used to compute the magnetic field created by an excited circular loop of wire.

$$dB = \frac{\mu_0 I dl \times \hat{r}}{4\pi r^2}$$  \hspace{1cm} (13)

Prigge [15] derived from the Biot-Savart law the following equation to describe the vector magnetic field at a given point in space:

$$B = \frac{\mu_0 N I a}{4\pi r^3}$$  \hspace{1cm} (14)

where $\mu_0 = 4\pi \times 10^{-7}$ V·A/m

N is the number of turns in the coil

I is the current through the coil

$a = \pi r_0^2$

and $r_0$ is the coil’s loop radius.

3.3.2 Position Estimation Using Magnetic Fields

The magnetic indoor local positioning system (MILPS) proposed in [8] contained a series of reference stations of electrical coils. These reference stations
generated the periodic magnetic fields that were to be measured by a mobile magnetic field sensor. If the mobile station equipped with the magnetic field sensor measured the field strength of at least three reference coils, then the position could be estimated by way of trilateration. Moreover, combining the calculated static position with kinematic data from passive sensors provides an accurate measure of an object’s heading and speed.

Unlike the signals used in traditional active positioning systems such as UWB or WiFi, the MILPS generates periodic magnetic fields at the reference stations. Due to the nature of magnetic field propagation, this system is not susceptible to None Line of Sight (NLoS) errors or multipath effects.

The MILPS designed for this paper designed a reference station as a 140 turn coil of wire wrapped around a 50 cm diameter core. A current of 12A was then run through the wire, generating a magnetic field to be measured by a mobile station. In order to properly measure the three vector components of the magnetic field, three magneto-resistive transducers were aligned orthogonally to each other and affixed to the mobile station. The sensor data was then read into Matlab for further analysis.

Before the reference coils were excited with current, measurements were taken with the mobile station to account for any interfering magnetic signals. In addition to the earth’s magnetic field, the mobile station also picked up electromagnetic interference from the building’s power lines. In order to account for these interferences, the coils’ current direction was switched so as to measure the magnetic field by difference [8].

Measurements were performed at three different distances to the reference station: 4.20 m, 12.6 m, and 16.6 m. While the fields measured at 4.20 m and 12.6 m yielded a favorable signal-to-noise ratio (SNR), the SNR dropped off dramatically at 16.6 m [8]. This is due to the magnetic field strength being inversely proportional to $r^3$ as shown in Equation 14.

In the end, the MILPS system was able to achieve positioning accurate to a few centimeters when sensors were close to the reference point, but struggled to maintain accuracy when distance to the reference point exceeded 10 m. As far as active positioning systems go, it is a flexible and cost effective solution.

3.3.3 Advantages

There are many advantages to leveraging artificially generated magnetic field to construct an indoor positioning system:

- No line-of-sight restrictions. A magnetic field easily penetrates most obstacles, so line of sight is not required in order to do position estimation.

- Drift free estimates. The position estimation happens in real-time, using the most up to date information about the magnetic field.

- Building wide coverage. Given enough beacons, a positioning system using ELF magnetic fields can cover the entirety of a building.
• Accuracy on the order of a few centimeters and degrees at 10 Hz. When eddy field noise and ferromagnetic distortion is accounted for, magnetic positioning systems can be extremely accurate.

• Small, low power magnetic sensor. The magnetometers in most smartphones are sufficient to gather the required magnetic measurements.

• Potential for no FCC restrictions. While electromagnetic emissions are generated by this system, they are at frequencies below where the FCC regulates [15].

3.3.4 Challenges

A magnetic positioning system using ELF magnetic fields brings with it two fundamental challenges to overcome: short range and sensitivity to certain materials.

3.3.4.1 Sensitivity to Materials

When a magnetic field comes into contact with conductive materials, eddy field noise can be the result. When the time-varying magnetic fields interact with conductive materials, the result can be an induction of current through the conductor. These currents then create magnetic fields of their own, thus introducing errors into the position estimates [15].

Additionally, interaction with ferromagnetic objects cause an additional type of error. The ELF magnetic field causes the domains within the ferromagnetic material to grow or shrink, thus producing a net magnetic field. This net magnetic field throws off the field measurements even further.

3.3.4.2 Short Range

Equation 14 demonstrates that strength diminishes rapidly with distance. Thus, many beacons are required to ensure complete coverage of a building. However, as the number of beacons increases, the signal structure and position solution algorithms must change to accommodate the increased complexity [15].

3.3.5 Sensor Unit

The sensor unit is comprised of three sensors oriented orthogonally to measure the vector magnetic field. The sensors contain semiconductors, which generate a voltage proportional to the magnetic field amplitude along a particular axis [15]. The three raw voltage measurements are then sent through an A/D converter. These values are then passed to the detection process to estimate the strength of the magnetic field from each beacon. To correct for eddy field noise, the value estimates for each beacon are run through an eddy correction technique. From these corrected values, an estimate for sensor position and attitude is produced. Finally, this position estimate is combined with the
beacon magnetic field estimates to correct for distortion due to ferromagnetic materials.

3.3.6 Beacons

The beacons consist of a coil of wire, a power amplifier, and an electronics box. The coil consists of 80 turns of wire wrapped around a 36cm core. The coil has measured inductance of 4 mH and a resistance of 1.2 Ω.

The power amplifier forces a 2 A current through the coil with a polarity specified by the signal structure. It is controlled by way of the electronics box module.

The electronics box controls the power amplifier and maintains synchronization with the beacon network. Each electronics box contains an HC11 microcontroller which is programmed with its own pseudo-random code. When the sync signal is received from the beacon network, the electronics box outputs the next chip in the sequence. Each chip is a command to be sent to the amplifier to produce the appropriate polarity of current through the coil.

With the two most common multiple access signal architectures, as the number of beacons increases, so does the frequency content of the signal. This in turn results in an increase in eddy noise. As the amount of eddy noise increases, the positional accuracy decreases [15].

3.3.7 Beacon Network

All beacons in this prototype system are networked to each other via category 5 cable to a central timekeeping source. This is to ensure that all beacons stay synced up relative to each other. The timekeeping source produces a repeating sequence of 63 pulses, with the rising edge of each pulse signaling the start of the next chip in each beacon’s pseudo-random sequence. All pulses have a width of 10 µs, with the exception of the first pulse, which has a width of 100 µs. This is done to mark the beginning of the sync sequence in order to ensure all beacons start their pseudo-random sequence at the same time.

The timekeeping source also serves an additional purpose in providing communication between all beacons and the monitor PC. Two lines, “ToBeac” and “FromBeac”, are used to provide two-way communication between the monitor PC and the beacons. The timing box converts signals sent from the monitor PC to the beacons, and vice-versa. A limited number of command were programmed into the prototype system, mainly for diagnostic purposes [15].

3.3.8 Sensor Box

The magnetic field sensing is done by the three Honeywell magneto-resistive transducers affixed to the sensor box. They are only sensitive to magnetic fields in one axis, so the vector measurement of the magnetic field can be captured.
The specific sensors used were the Honeywell HMC1001 one-axis sensor and the HMC1002 two-axis sensor.

After the magnetic measurements are captured, the 3 voltage values are amplified, sent through a first order low pass filter, and finally passed through an A/D converter to be digitized. The A/D conversion process is controlled by an HC11 microcontroller within the sensor box. This process occurs approximately 1.5 ms after the sync timing pulse arrives. The A/D conversion is done at this point in the chip period so as to allow the beacon fields to stabilize to their final values [15].
EXPERIMENTAL CONSTRUCTION

In this section, the method of experimentation is outlined. First, the specifications of the experimental construction for both the beacon and the sensor unit are described. Next, the construction process of the beacon and test environment is detailed. The code to control the beacon operation as well as interpret the magnetic field data is included.

4.1 OVERVIEW

The design of the experiment is rather simple. The experimental construction consists of a magnetic beacon and a sensor unit. The magnetic beacon design is based off the work done by Prigge [15]. Beacon construction consists of an air coil electromagnet connected to a relay unit. This relay is controlled by an Arduino, which sends the appropriate control signals to the relay to open and close it at an extremely low frequency. This produces distinct peaks and valleys in magnetic field strength.

Throughout the operation of the relay-controlled electromagnet, magnetometer readings are logged and indexed accordingly. Measurements of the differences between the peaks and valleys of the vectored quantity can then be used to calculate the net magnetic field as produced by the magnet.

4.2 MAGNETIC BEACON

The first step in construction of the beacon was gathering the materials necessary for the electromagnet. In order for the electromagnet to be considered for use in an indoor positioning system, it would have to be capable of producing a substantial magnetic field. This called for a gauge of magnet wire that could withstand a current of at least 2A. It was decided that 16 gauge magnet wire struck an appropriate balance between price and current rating. The electromagnet used in this experiment was a 120 turn coil of 16 gauge wire with a diameter of 10 inches. It was measured to have an inductance of 7.22mH. It was connected to a voltage source which was configured to run a specific amount of current.
4.3 SENSOR UNIT

A smart-phone served as the sensor unit for this experiment. The phone used was the OnePlus One and is shown below in Figure 4.1.

![OnePlus One](Image)

Figure 4.1: OnePlus One

Modern smart-phones such as the OnePlus One contain a multitude of sophisticated sensors in order to determine certain conditions such as orientation, pressure, ambient light, acceleration, proximity, and magnetic field strength.

An app named “Sensor Fusion” was used to quantify and log measurements of all the smart-phone’s internal sensors. The sensor fusion app contains a module that collects data from the smart-phone’s on-board magnetometer. It can measure the strength and direction of the magnetic field in the area. Each axis of the magnetometer measures the field strength in micro-Teslas (μT) along that particular axis. The three vector quantities can then be used to calculate a scalar field strength which is proportional to the distance from the source of the magnetic field.

![OnePlus One: Teardown](Image)

Figure 4.2: OnePlus One: Teardown

As can be seen in the teardown of the OnePlus One in Figure 4.2, the sensor board contained within the OnePlus One in Figure 4.3 is remarkably small and compact.
The method used in this experiment to gather and parse magnetic field data is a marked improvement to the method used by Prigge [15] in terms of scalability and practicality. As most modern smart-phones contain sensor suites along the same level of sophistication as the OnePlus One, it is almost unnecessary to construct a proprietary sensor unit.

4.4 ASSEMBLED

Below is the full experimental setup which consists of the electromagnet, variable current source, electromagnetic relay, and Arduino powered by an external battery.
4.5 TEST BENCH

The test environment consisted of 14 marks each spaced 3 inches apart starting at 12 inches away from the center of the coil. Throughout the collection process, the relay, which controlled current flow through the electromagnet, was set to toggle on and off at determined intervals.

Figure 4.5: Test Bench

The phone was centered at each mark and set to collect the magnetic field strength data for ~ 5 seconds.

4.6 SUMMARY

This chapter described the design and construction process of the experimental prototype. The magnetic beacon design was heavily inspired by Prigge’s [15] beacon prototype, being constructed of similar materials but differing dimensions. In designing the method of magnetic field measurement, cues were taken from Shala and Rodriguez [16] who leveraged the capabilities of modern smart-phones to navigate via Wi-Fi.
EXPERIMENTAL DEMONSTRATION

In this section, the results of experimentation are stated and analyzed. First, we explore the results obtained from the simulations of magnetic beacons and discuss how they can be used in the experimental process. Next, we analyze simulation vs experimental data for magnetic field behavior as distance is varied. Finally, the process of running the experiment and collecting the data is outlined.

5.1 RAW DATA

The sensor fusion app collected and logged magnetic field strength along each of the 3 axes. These data logs were fed into a MATLAB script which parsed the magnetic field strength data for analysis. Figure 5.1 graphs the magnetic field data of all three axes during a test trial.

![Figure 5.1: Magnetometer Data: 3-axes](image)

The individual components of the magnetic field vector are shown below in Figure 5.2, Figure 5.3, and Figure 5.4.
Figure 5.2: Magnetic Strength at 12” - X-axis

If the sensor traveled perfectly along the test bench, the Y component should fluctuate very little. This measurement was factored into the final magnitude measurement to account for the drift due to human error.

Figure 5.3: Magnetic Strength at 12” - Y-axis

The Z component measurement sees the greatest difference between the control measurement and the coil-excited measurement due to most of the magnetic field from the coil being oriented along this axis.
Figure 5.4: Magnetic Strength at 12” - Z-axis

Figure 5.5: Magnetic Strength at 12” - Vector

Figure 5.5 above depicts the total magnitude of the vectored quantity. The difference between the peaks and the valleys depict the net magnetic field strength produced by the coil at 12 inches from center.

5.2 FILTERING

The graph of the raw vector magnitude, especially as the distance from the coil is increased, displays significant noise at the peaks and valleys. This makes it difficult to obtain a meaningful measurement with which to calculate the net magnetic field strength from the coil.
The decreasing of the SNR can be witnessed by comparing the magnitude graph at 12 inches in Figure 5.5 to the vector magnitude graph for 24 inches in Figure 5.6.

In order to more accurately extract useful data from the noise, the dataset from each trial is passed through a Savitzky-Golay filter. This serves the purpose of smoothing the data and increasing the SNR [7].

From this smoothed data, the average value of the valleys is gathered and subtracted from the average value of the peaks. In performing this calculation on all trials, the standard deviation from the theoretical values can be calculated.

5.3 THEORETICAL VS. EXPERIMENTAL

When all experimental values are properly accounted for, they can finally be compared to the theoretical model of magnetic field strength vs. distance.
5.3 THEORETICAL VS. EXPERIMENTAL

As evidenced by Table 5.1, magnetic field strength is an extremely accurate predictor of distances up to 36 inches from the source, as accuracy is within an inch.

Even at the end case of 51”, magnetic field strength was still an acceptable predictor for distance, with a standard deviation of 5.4768 inches.
Table 5.1: Theoretical vs Experimental

<table>
<thead>
<tr>
<th>Distance (inches)</th>
<th>Field Strength (uG)</th>
<th>Field Strength (uG)</th>
<th>Distance (inches)</th>
<th>Std. Deviation (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>21.4730</td>
<td>24.3613</td>
<td>11.5057</td>
<td>0.4943</td>
</tr>
<tr>
<td>15</td>
<td>10.9942</td>
<td>11.6006</td>
<td>14.7339</td>
<td>0.3970</td>
</tr>
<tr>
<td>18</td>
<td>6.3624</td>
<td>7.0155</td>
<td>17.4231</td>
<td>0.4648</td>
</tr>
<tr>
<td>21</td>
<td>4.0066</td>
<td>4.3308</td>
<td>20.4623</td>
<td>0.4840</td>
</tr>
<tr>
<td>24</td>
<td>2.6841</td>
<td>3.2837</td>
<td>22.4401</td>
<td>0.8210</td>
</tr>
<tr>
<td>27</td>
<td>1.8852</td>
<td>2.0639</td>
<td>26.1969</td>
<td>0.8180</td>
</tr>
<tr>
<td>30</td>
<td>1.3743</td>
<td>1.7057</td>
<td>27.9156</td>
<td>1.0928</td>
</tr>
<tr>
<td>33</td>
<td>1.0325</td>
<td>1.0877</td>
<td>32.4320</td>
<td>1.0418</td>
</tr>
<tr>
<td>36</td>
<td>0.7953</td>
<td>0.8223</td>
<td>35.6021</td>
<td>0.9911</td>
</tr>
<tr>
<td>39</td>
<td>0.6255</td>
<td>0.9713</td>
<td>33.6790</td>
<td>1.9275</td>
</tr>
<tr>
<td>42</td>
<td>0.5008</td>
<td>0.9550</td>
<td>33.8699</td>
<td>3.0638</td>
</tr>
<tr>
<td>45</td>
<td>0.4072</td>
<td>0.7709</td>
<td>36.3752</td>
<td>3.8475</td>
</tr>
<tr>
<td>48</td>
<td>0.3355</td>
<td>0.8029</td>
<td>36.3752</td>
<td>4.9953</td>
</tr>
<tr>
<td>51</td>
<td>0.2797</td>
<td>0.5296</td>
<td>35.8860</td>
<td>5.4768</td>
</tr>
</tbody>
</table>

Figure 5.10 visualizes the accuracy falloff at higher distances.

5.4 Summary

It is clear from the experimental results that magnetic fields are well suited for a role in an indoor positioning system. The nature of magnetic field propagation through space and various mediums make it well suited for close indoor environments. Furthermore, the measurable and formulaic correlation of field strength to distance from the source makes it an attractive option for many positioning systems.

In addition, because the experimental results followed so closely to the theoretical model, it is possible to calculate the magnetic beacon specifications necessary to cover a given environment. For example, in order to provide coverage in a 10’x10’x10’ room, with beacons at all 8 corners of the room, each beacon would need to produce a magnetic field strong enough to be discerned in the center of the room. Referring back to Equation 14, the distance to the midpoint of the room is entered in for r to form the following equation:

\[
B = \frac{\mu_0 N I a}{73.6\pi} \tag{15}
\]
According to the experimental results, the signal to noise ratio breaks down when the magnetic field strength is around 3 $\mu$G. Substituting this value in for $B$, as well as a value of 5 A for $I$, the equation becomes:

$$N_a = 110.4$$  \hspace{1cm} (16)

Using the conservative value for $N$ of 120, and recalling that $a = \pi r_0^2$, the equation simplifies to:

$$r_0^2 = \frac{0.92}{\pi}; r_0 = 0.54\text{m}$$  \hspace{1cm} (17)

This equates to beacon over a meter in diameter. Since this is a bit on the larger side, several adjustments can be made to reduce the footprint necessary of the beacon. A higher resolution magnetometer and/or filtering and processing algorithm would allow the system to more accurately measure magnetic fields under 3 $\mu$G. Also, running more current through the coil and/or increasing the number of turns in the coil would decrease the necessary size of the beacon. Additionally, a higher density of beacon distribution would reduce the requirements of each beacon. Prigge recommends dense beacon configurations in a lattice [15].
CONCLUSIONS

The main objectives of this thesis were: research and identify an effective solution for indoor positioning, test the relationship between the strength of an artificially generated magnetic field and the distance from the source of the magnetic field, and determine the suitability of magnetic localization for environments with a high probability of electromagnetic interference.

In the research stage of this thesis project, several IPS methods were considered. For a time, the objective of the thesis experiment was to implement and test an IPS solution using geomagnetic localization. After magnetic localization using artificially generated magnetic fields was researched, geomagnetic localization was dropped in favor of this newly discovered method.

In the theory section of this paper, the properties of magnetic fields, as well as the equations that describe them, were given. Further attention was given to the application of artificially generated magnetic fields for the purposes of indoor localization.

In the experimental stage of this thesis, an experiment was performed to examine the relationship between magnetic field strength from an electromagnet, and the distance from the electromagnet’s center. The equations that link these two quantities held true up to a certain distance, at which point the SNR became too weak.

6.1 LIMITATIONS

As with all indoor positioning systems, magnetic localization has its limitations. While the nature of magnetic field propagation allows the fields to be detected through obstacles, the strength of the field drops off rapidly with increased distance. At a certain point, the SNR drops to an unusable level. The solution to this is to decrease the distance between beacons in the coverage area, but this increases cost, eddy field noise, and ferromagnetic errors. However, by utilizing the CDMA signal architecture and a suitable position calculation algorithm, sufficient beacon density can be achieved without sacrificing performance.
RECOMMENDATIONS

Many would benefit from increased research and experimentation on the concept of magnetic localization. In order to bring this positioning method to the masses, a standard for the magnetic beacons, sensor unit, and beacon network must be established. A few suggested avenues for improvement include:

- Improve the calibration procedure to better filter out electromagnetic interference.
- Perform analysis so as to determine the optimal number of beacons per unit volume.

There is already a high demand for accurate positioning systems indoors, and potential future applications not yet realized. Prigge argued that a magnetic indoor positioning system could be used in emergency settings to provide location info to emergency workers [15]. Magnetic beacons could be retrofitted to install in emergency vehicles and provide indoor location services to buildings on the fly.

Additional applications can be found in the field of marketing. Retail markets have a strong desire to deliver targeted marketing to customers while they are within their establishment. Precise indoor positioning allows marketing to happen on an aisle to aisle basis, by offering special deals and coupons on the products nearest to the customer. Such work is already being done in this sector by the likes of IndoorAtlas, a company specializing in geomagnetic indoor positioning [1].

Technology has improved a great deal since the work done by Prigge [15]. What once was a complicated and cumbersome sensor box, can now be replaced with an app gathering data from a modern smartphone. Combining today’s technology with Prigge’s approach certainly is an exciting proposition.
APPENDICES

What follows are some of the resources and figures that were too cumbersome to make it into the main matter.

8.1 MATLAB - XYZ MAGNETOMETER COMPONENTS

```matlab
%% import all data from text file
In_B = importdata('BField_18_in.txt'); % Please the text file name
In_data = In_B.data;

%% obtain data of Magnetic field in 3-dimension(X,Y,Z)
X = In_data(:,1);  % separate those data of Magnetic field into X,Y,and Z
Y = In_data(:,2);
Z = In_data(:,3);

%% smooth the resultant graphs
X_sm = sgolayfilt(X,4,101);
Z_sm = sgolayfilt(Z,2,101);

%% acquire the length of data
len_In = length(In_data);
len_X = length(X);
len_Y = length(Y);
len_Z = length(Z);

%% set up the time interval
time_In = 0:1/len_In:1-1/len_In;
time_X = 0:1/len_X:1-1/len_X;
time_Y = 0:1/len_Y:1-1/len_Y;
time_Z = 0:1/len_Y:1-1/len_Y;

%% Plot the graphics
figure
plot(time_X',X,'linewidth',2)
xlabel('Time','fontsize',10)
ylabel('Magnetic Field(uG)','fontsize',10)
title('X Component','fontsize',14)
grid on
```
figure
plot(time_X',X_sm,'linewidth',2)
xlabel('Time','fontsize',10)
ylabel('Magnetic Field(uG)','fontsize',10)
title('X Component (smooth)','fontsize',14)
grid on

figure
plot(time_Y',Y,'linewidth',2)
xlabel('Time','fontsize',10)
ylabel('Magnetic Field(uG)','fontsize',10)
title('Time VS Magnetic','fontsize',14)
grid on

figure
plot(time_Z',Z,'linewidth',2)
xlabel('Time','fontsize',10)
ylabel('Magnetic Field(uG)','fontsize',10)
title('Time VS Magnetic','fontsize',14)
grid on

figure
plot(time_Z',Z_sm,'linewidth',2)
xlabel('Time','fontsize',10)
ylabel('Magnetic Field(uG)','fontsize',10)
title('Z Component (smooth)','fontsize',14)
grid on

% plot X Y Z
figure
plot(time_In',In_data,'linewidth',2)
xlabel('Time','fontsize',10)
ylabel('Magnetic Field(uG)','fontsize',10)
title('Time VS Magnetic','fontsize',14)
legend('X','Y','Z')
grid on

8.2 MATLAB - THEORETICAL VS EXPERIMENTAL

%% Parameters
Uo=4*pi*1e-7;
% Coi diameter 10" = 25.4cm=0.254m
Coil_diameter=0.254;
Ro=Coil_diameter/2;
% F=pi+Ro^2
\[ F = \pi R_0^2; \]
\[ N = 120; \]

\% Simulation
% Distance VS Magnetic Field
\r = 0.3:0.001:1.3;
\r_len = length(r);
\T = zeros(\r_len,5);
n = 0;
theta = 0;
for I = 1:0.5:3
    n = n + 1;
    \T(:,n) = Uo*N*I*Ro^2/((4*r.^3));
end
figure
plot(r*39.3701, \T(:,1)*10^6, 'linewidth', 2)
title('Distance vs. B-Field Strength')
xlabel('Distance(in)', 'fontsize', 12);
ylabel('Magnetic Field(uG)', 'fontsize', 12);
legend('simulation');
grid on
hold on
str = 'BField_%d_in.txt';%data file format
BvD = zeros(51);
BvDt = zeros(51);
D = zeros(51);
Sq = zeros(14);
Sd = zeros(14);
k = 1;
% reading data from each text file
for i = 12:3:51
    filename = sprintf(str, i);
    \% import all data from text file
    In_B = importdata(filename);
    In_data = In_B.data;
    \% separate into vector components
    X = In_data(:,1);
    Y = In_data(:,2);
    Z = In_data(:,3);
    \% acquire the length of data stream
    len_In = length(In_data);
    Q1 = int32(len_In/4);
    Q3 = int32(len_In*3/4);
    \% calculate vector magnitude
    B = zeros(len_In, 1);
    for n = 1:len_In
        B(n, 1) = (X(n, 1)^2 + Y(n, 1)^2 + Z(n, 1)^2)^(1/2);
    end
```
B_sm = sgolayfilt(B,2,101); % smooth the data
B_middle = B_sm(Q1:Q3); % trim off edges of data stream
[sortedB,sortingIndices] = sort(B_middle,'descend'); % sort data
len_B = length(sortedB);
% calculate difference from baseline
Maximum = mean(sortedB(1:50));
Minimum = mean(sortedB(len_B - 50:len_B));
Strength = Maximum - Minimum;
disp(i);
BvD(i) = Strength;
BvDt(i) = Uo*N*Ro^2./(4*(i*0.0254)^3)*10^6;
D(i) = 39.37*(10^6*Uo*N*Ro^2./(4*Strength))^(1/3);
Sq(k)=(i-D(i))^2;
for j=1:k
    Sd(k) = Sd(k)+Sq(j);
end
Sd(k)=(Sd(k)/k)^(1/2);
disp(Sd(k));
k=k+1;
end
x = 12:3:51;
y = BvD(x);
disp(BvD(12));
scatter(x, y);
hold off
figure
x=12:3:51;
y = Sd((x-12)/3+1);
scatter(x,y);
title('Distance vs. Accuracy')
xlabel('Distance(in)','fontsize',12);
ylabel('Standard Deviation(in)','fontsize',12);
```
8.3 EXPERIMENTAL DIAGRAM


