Utilizing Smartphone Magnetometers for Magnetic Field Tracking and Signal Processing in the Context of Biomedical Engineering

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***Abstract*— This paper investigates the accuracy of smartphone magnetometers for magnetic field recording and analysis using signal processing techniques. Through experimental calibrations, we provide insights into the physics of magnetism, sensor calibration procedures, and signal processing methodologies. We successfully calibrated a smartphone sensor, demonstrating its sensitivity, in addition to accurately calculating the smartphone's position within a magnetic field grid. Our findings show that modern magnetometers possess the necessary sensitivity, resolution and accuracy to be valuable in certain biomedical applications.**

Keywords*— *Magnetism, Helmholtz, spiral coil, signal processing, magnetometer

I. Introduction

This paper explores the use of a smartphone's magnetometer to capture magnetic field data, which is subsequently analyzed using advanced signal processing techniques in Python and MATLAB. By using the high precision of modern smartphone devices, we aim to prove that data obtained from such smart devices can be effectively used for tracking and location-based tasks, yielding useful results that aid both research and industry.

Magnetic tracking plays a significant role in biomedical engineering, as this method can be applied in areas such as surgical navigation, where the precise location of instruments is crucial to the success and safety of different clinical procedures. To explore magnetic tracking from a research perspective, a certain level of knowledge in magnetism is necessary, as well as comprehensive knowledge in signal processing and sensor behaviors.

In our experiments, various magnetic layouts were used to locate and calibrate the smartphone magnetometer, culminating in the placement of the smartphone inside a magnetic field grid. Through these calibrations and processing of the resulting signal data, we aimed to accurately calculate the location of the smartphone. The following sections of this paper delve into the principles of magnetism, our chosen calibration method, signal processing techniques including their results, and the implications of our experiments for the application of magnetic field tracking in the wider field of biomedical engineering.

II. Theory

A. *Principles of magnetism*

Understanding the basic principles of magnetism is crucial to the interpretation and the analysis of the measurement data taken from the smartphone's magnetometer. The magnetic field, also known as a B-field, is a physical field that influences moving electric charges, currents and magnetic materials. It causes a force perpendicular to the velocity of a moving charge and to the magnetic field itself. A permanent magnet's field pulls on ferromagnetic materials such as iron and attracts or repels other magnets.

Electromagnetism is the interaction that occurs between electrically charged particles via electromagnetic fields. It is a combination of electrostatics and magnetism, which are two very closely intertwined phenomena. Maxwell's equations are a set of partial differential equations governing the laws that describe the behavior of electric and magnetic fields and their interaction with charged particles.
One of the fundamental principles derived from Maxwell's equations is the Biot-Savart law shown below (1).

$$B = \frac{\mu_0 \times N \times I}{2 \times R} \tag{1}$$

With μ_0, the magnetic permeability of vacuum, I the current through a coil, N the number of windings per coil, R the radius and distance of coils. This equation establishes a mathematical relationship between electric currents and the magnetic fields they produce. This law precisely quantifies the magnetic flux density generated by a constant current in a conductor in [T]. The earth's magnetic field can be measured at around 50μT, whereas small permanent magnets' flux density can be measured between 10mT and 100mT.

B. *Calibration with a Helmholtz Coil*

A Helmholtz coil [3] is a configuration of two circular magnetic coils placed symmetrically and separated by a distance h, same as the radius R of the coils. This results in a uniform magnetic field in the center of the space between the two coils. The Helmholtz configuration, with current flowing in the same direction, generates a homogenous magnetic field in the center. Equation (2) allows us to calculate the magnetic field density in the center, and subsequently use the value as a reference for our measurements.

An anti-Helmholtz or Maxwell configuration is when the equal current in the coils is flowing in opposing directions, resulting in a magnetic field strength of 0 in the center. The configuration of the field can be observed by placing a small permanent magnet at the center of the coils. If the magnet experiences a torque, the configuration is in Helmholtz, and if the magnet is configured in the Maxwell configuration, the magnet is in a gradient field and experiences an attractive force.

$$B = \frac{\mu_0 \times 8 \times N \times I}{\sqrt{125} \times R} \tag{2}$$

C. Spiral Coil Configuration

To obtain the optimal configuration of a lightweight magnetic field generator, the spiral coil configuration requires the coils to be manufactured on a printed circuit board (PCB). For this design, the number of layers must be determined, as well as the width and thickness of the track. The arrangement used for this experiment was four coils, laid in a 2x2 grid, seen in Fig. 1. As power dissipation can be an issue, the maximum current injected is limited to 2A.

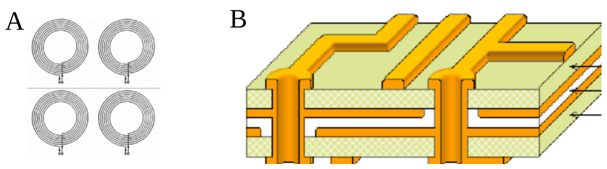

Fig. 1. **A. Spiral coil configuration laid in a 2x2 grid. B. Layer view of the configuration [2]**

Using a derivation of the Biot-Savart Law (3), the magnetic flux density at the surface of the spiral coil can be calculated.

$$B = \frac{4 \times \mu_0 N \times I}{2(b-a) \times \log\left(\frac{b}{a}\right)} \tag{3}$$

D. Integrated Sensors Technology

Integrated sensors in smartphones have been developed to perform many tasks, with a focus on precision and effectiveness. Magnetometers are a vital sensor inside modern smartphones, as these help in navigation, orientation, and other such location-reliant services. An internal chip contains a 3-axis magnetometer and provides the magnetic strength along the *x*, *y* and *z* axes of the smartphone. One of the most important types of sensors are Hall Effect sensors [4] that operate by producing an output voltage as the magnetic field that passes through the sensor changes in strength. The sensitivity of these integrated sensors tends to range from 10μT to several Tesla. Consequently, there are 2 types of Hall effect sensors – horizontal Hall devices (HHD) that are responsible for B_z, while vertical Hall devices (VHD) are responsible for B_x and B_y [5].

Hall effect devices are highly relevant in biomedical engineering and in the wider field of medicine technology. In biomedical applications, Hall sensors are used for precise position sensing of invasive surgical tools such as insulin pumps or pacemakers, where accurate positioning data is crucial to the health and safety of a patient. Additionally, these sensors are also used in magnetic resonance imaging (MRI) systems to detect magnetic field gradients, ensuring precise imaging results.

As mentioned previously, these sensors are present in both smartphones and cutting-edge biomedical devices and allows us a unique opportunity to gain valuable insights from everyday devices that can be highly beneficial to enhancing their application in biomedical applications.

E. Tracking of the magnetometer

The Biot-Savart Law also provides the magnetic field components B_x, B_y and B_z along the *x*, *y* and *z* axes. Combining these components results in the total magnetic field. The method used in this project for magnetic tracking is applying a lookup table (LUT) that contains the magnetic field strength for each coil at each position inside a defined volume. There are two ways to design such mappings, either by simulations or by measurements. Once a lookup table is generated, five measurements of the magnetic field strength are needed: one with no coil activated and one for each of the four individual coils. In this way, the offset can be removed, leading to a measured magnetic field strength $B_i(X)$ of coil *i* at the unknown position $X = [x, y, z]$. Eventually, the position of the sensor is found by minimizing the difference between $B_i(X)$ and the reference value $B_i^r(X')$ of the mapped magnetic field strength.

III. Methods

A. Initial magnetometer data acquisition and analysis

The first step was to enter the field of sensors, particularly to understand and process signals from the magnetometer. The data we obtained throughout all the project was from the Phyphox [1] app on our smartphone, an Apple iPhone 14 Pro. Initially, we gathered data from the magnetometer sensor, for which we compensated the earth's magnetic field. To estimate the sensor's resolution, we then calculated the standard deviation of the signal and plotted both the raw signal and the signal shifted by one standard deviation on the same graph. Using this method, we could estimate the resolution of the sensor by distinguishing the two curves. Additionally, we applied an averaging on the signal to filter the noise.

B. Three-axes magnetometer calibration

After this little introduction, we continued with the calibration of the three-axis magnetometer in our smartphone which we would need for further measurements. We calibrated the magnetometer using the Helmholtz pair of coils which generate a controlled and homogenous magnetic field in the center. Before we exposed the sensor to the magnetic field, we identified the approximate location of the magnetometer inside the smartphone. We achieved this by scanning the phone's surface with a small permanent magnet and observing the resulting peaks in the real-time data of the absolute magnetic field. Now, we were prepared to insert the smartphone inside the pair of coils, considering the magnetometer to be in the center of the setup, shown in Fig. 2. We aligned the smartphone along the y-axis, so changes in the magnetic field along x and z are minimal. A voltage source was used to apply a certain voltage which generated the magnetic field. In total, we did four measurements with changing voltages and noted the resulting currents. After the second measurement, we swapped the cables, so the orientation of the current changed. With four different current values, we calculated the reference magnetic field B_{ref}. With this method, the magnetometer was calibrated within the range of -1mT to +1mT to ensure accurate measurements for magnetic fields within this specified range with the smartphone.

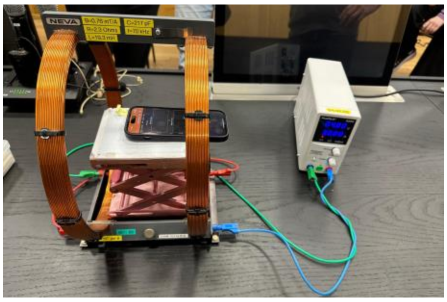

Fig. 2. **Helmholtz coil configuration connected with banana cables to a voltage source.**

C. Characteristics of the Printed Circuit Board (PCB)

Furthermore, we used a Printed Circuit Board (PCB) as a lightweight magnetic field generator. We calculated key properties of the PCB based on standard PCB technology standards. The number of turns per coil, the magnetic flux density at the center of the spiral, as well as the power dissipation were calculated to better understand the design of the PCB.

D. Magnetic field tracking with the four-coil setup

After all these steps, our smartphone was exposed to the magnetic field induced by the four coils in a 2x2 grid configuration, visible in Fig. 1, without us knowing the position. The setup of this experiment is shown in Fig. 3 . The four coils are declared with the letters A, B, C and D. A pre-programmed sequence that was already implemented for us, sequentially activated and deactivated each coil. This cycle was repeated for several seconds. Next, we started processing the signal by smoothing the data with a rolling window average and then taking the differences between consecutive smoothed values. Indices where the difference was below an implemented threshold were identified as part of a plateau. We extracted the start and end indices of each plateau region to calculate the median value of the magnetic field for each plateau region between given start and end indices. Finally, we computed the mean of the medians for each type of plateau (A, B, C, D and no coil) across repeated experiments, resulting in four values for each axis, namely *x*, *y*, *z* and the *absolute* one. All signal processing techniques using Python can be found in the GitHub repository [6].

E. Determining smartphone coordinates

The last step was to find the coordinates for the location of the smartphone. A MATLAB project was provided which included several files implementing the theory described earlier. One of the files was a discrete lookup table that was mapped with already calculated norms. Entering the raw magnetic data after signal processing yields the coordinates of our magnetometer.

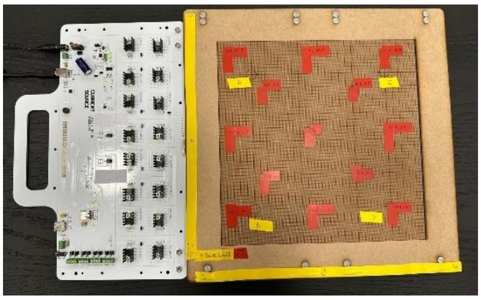

Fig. 3. **2x2 grid PCB setup for generation of the magnetic field.**

IV. RESULTS

We first analyzed the magnetometer data to estimate the sensor's resolution. The raw signal and the signal shifted by one time the standard deviation is shown in Fig. 4. The two curves are distinguishable, so the sensor's resolution can be estimated. In numbers, the standard deviation of the signal was calculated to be 0.149µT, indicating the sensor's ability to detect small changes in magnetic field strength. According to Phyphox literature [1], the standard deviation is reported to be 0.17µT, suggesting that our sensor's performance is very close to expected values.

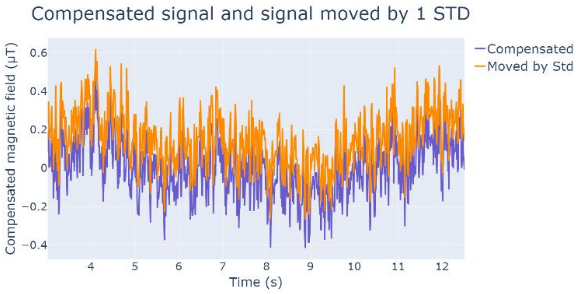

Fig. 4. **Plot of the raw signal of the magnetometer together with the signal shifted by one time the standard deviation.**

Next, the magnetometer was calibrated using a Helmholtz coil setup, with measurements taken at different voltages. With this data, we could calculate the reference magnetic field and plot it alongside the measured magnetic field against the current as shown in Fig. 5. It demonstrates a reasonable correlation between the measured and calculated magnetic field values. The high correlation, as indicated by the R value of 0.9999995 confirms that the calibration was highly accurate.

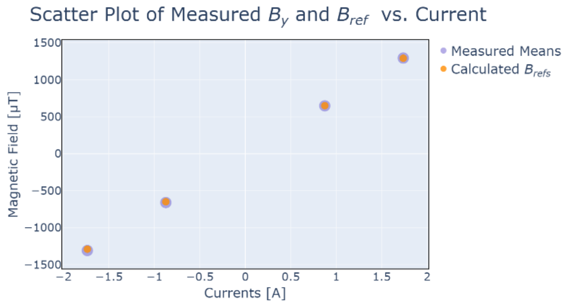

Fig. 5. **Reference magnetic field B_{ref} plotted alongside the measured magnetic field against the current.**

The number of turns per coil was determined based on the physical dimensions and spacing requirements, resulting in 75 turns per coil. Further, we calculated the magnetic flux density at the center of the spiral coil which was 11mT with the formula mentioned in chapter C. The power dissipation of the printed circuit board turned out to be 17.2W.

Finally, we determined the unknown position of the smartphone. The data obtained from the experiment is plotted in Fig. 6, showing the progression of the *absolute* magnetic field as well as the magnetic field in all three axes *x*, *y* and *z*. In addition, the repeated experiments are indicated in different colors. There are five completely repeated cycles, from which the plateau regions were processed to obtain the values of interest listed in Table 1. Using the provided MATLAB script, we found the following calculated position of the smartphone:

x = *20.5cm*, y = *14cm* and z = *4.5cm*.

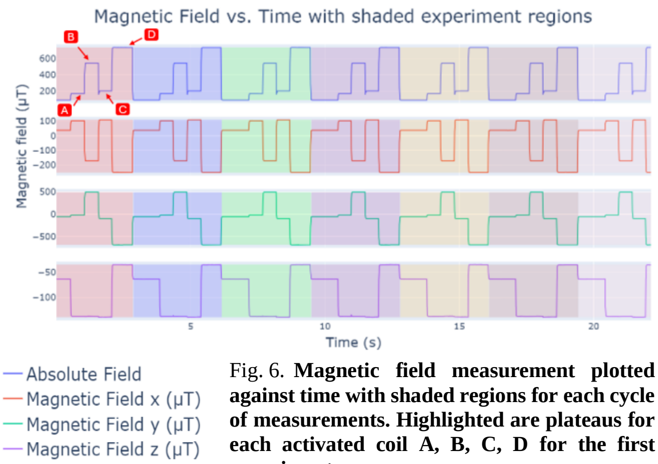

Fig. 6. **Magnetic field measurement plotted against time with shaded regions for each cycle of measurements. Highlighted are plateaus for each activated coil A, B, C, D for the first experiment.**

	Means of magnetic field measurements			
	x [mT]	*y [mT]*	*z [mT]*	*Absolute [mT]*
No coil	***0.0379***	***-0.0539***	***-0.0634***	***0.0914***
Coil A	***0.102***	***-0.0177***	***-0.138***	***0.172***
Coil B	***-0.173***	***0.496***	***-0.138***	***0.543***
Coil C	***0.109***	***-0.0990***	***-0.139***	***0.202***
Coil D	***-0.251***	***-0.689***	***-0.0349***	***0.733***

Table 1. **Calculated means of magnetic field measurements for each type of plateau (A, B, C, D and no coil) across repeated experiments.**

V. Discussion

In this project, we successfully calibrated the three-axis magnetometer in an Apple iPhone 14 Pro using a Helmholtz coil setup. We dove into the field of signal processing by analyzing the sensor data. Additionally, we ensured accurate magnetic field measurements since the resulting data of the magnetometer was well within the calibrated range of -1mT to +1mT. Therefore, the sequential activation of the four coils provided consistent magnetic field measurements and the computation of these signals allowed us to determine the position of the magnetometer inside the smartphone with reasonable precision.

Despite the successful parts of this project, there are some limitations that must be considered. First, the fact that a voltage source was used to generate the magnetic field with the Helmholtz pair of coils. With a voltage source, the current is not perfectly constant as the resistance changes due to heating of the copper wires, potentially resulting in variations of the magnetic field. These variations are a possible source of error in the calibration part. Another limitation is the alignment of the magnetometer inside the magnetic field. On one hand, the shape of the smartphone doesn't allow proper alignment. On the other hand, the setup makes it difficult in general to achieve perfect alignment. Although the signals along the x and z axes were minimal, this could affect the accuracy of the magnetic field measurements and subsequently the position determination.

Future experiments should use a current source instead of a voltage source for the calibration to ensure a constant current and a more stable magnetic field. Additionally, the alignment of the magnetometer can be improved to further reduce the signals detected in the x and z axes, for example by using a more precise mounting setup for the smartphone. However, our experiment highlights the potential for using the characteristics of magnetic fields for tracking, but also emphasizes the importance of proper signal processing and accurate calibration for reliable performance.

VI. Conclusion

In conclusion, the experiments outlined in this paper show a great potential for the use of magnetic tracking in the field of biomedical engineering. Applying calibration, we have demonstrated the sensor's capacity of detecting even small changes in magnetic fields, proving a high sensitivity and resolution. However, there are some significant limitations to consider that influence the accuracy of some measurements, such as the reliance on a voltage source for calibration or the lack of a repeatable mounting setup for the smartphone. Despite these sources of inaccuracies, we believe that our findings show a promising outlook for magnetometer-based tracking in healthcare.

Acknowledgment

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