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Investigation of the Metrological Properties of Magnetic Field Sensors Used in Popular Smartphones for the Shoe Size Determination System

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Abstract: This article presents a study on the metrological properties of smartphone magnetometers and their application in determining the correct shoe size. The research focuses on using magnetometers in smartphones to measure the magnetic field generated by magnetic markers placed inside shoes. To measure foot dimensions, smartphone embedded position sensors and image analysis were employed to determine key foot parameters accurately. Measurements were conducted under controlled conditions using triaxial Helmholtz coils, which generated a precise magnetic field. Linearity, sensitivity, offset, and measurement uncertainty were evaluated in several popular smartphones. The results indicate that the accuracy of magnetometer measurements depends on the quality of the smartphone. Electromagnetic interference, especially in cheaper devices, can introduce noise that affects data quality. Extended averaging periods help reduce noise and improve measurement accuracy. Smartphone magnetometers can be effectively utilized for precise magnetic field measurements, provided the device is calibrated correctly and the measurement method is appropriately adjusted. Certain limitations, such as noise from electromagnetic interference and its impact on data quality, remain challenging. Nonetheless, the study's findings are promising, especially in applications such as shoe sizing systems, where accurate measurements of the inside of the shoe are essential for a proper fit of the shoe to the foot.

Keywords: smartphone magnetometers, magnetic field measurement, shoe size fitting system, magnetometer accuracy, magnetic field sensors, foot dimension analysis

1. Introduction

Magnetometers in smartphones are compact sensors that measure magnetic fields. Their primary function in smartphones is to act as digital compasses, assisting with navigation and orientation. However, their application extends beyond basic compass functions, contributing to various sophisticated features and research areas.

The fundamental technology behind smartphone magnetometers is based on detecting the Earth's magnetic field. This allows the device to determine its orientation relative to the Earth's magnetic poles, which is crucial for navigation applications. These sensors have evolved considerably over time, becoming more accurate and reliable, making them indispensable in modern smartphones for accurate directional information, especially when integrated with other sensors like GPS and gyroscopes [1, 2].

Apart from navigation, magnetometers in smartphones support augmented reality (AR) applications. They provide essential orientation data that, when combined with accelerometers and gyroscopes, allow AR applications to offer immersive, spatially aware experiences. This integration is fundamental in gaming, educational, and commercial AR applications [3, 4].

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In scientific research, smartphone magnetometers have been utilized in geomagnetic studies. They offer a cost-effective and widely accessible means to collect geomagnetic data on a global scale. Researchers have developed methodologies to use the data from these sensors in large-scale geomagnetic surveys, contributing to the understanding of Earth's magnetic field variations [5, 6].

Furthermore, in the health sector, smartphone magnetometers have been innovatively used. For instance, they have been used in remote monitoring and diagnostic applications. By detecting magnetic fields generated by certain medical devices or processes, these sensors can aid in patient monitoring and diagnosis remotely, which is particularly valuable in telemedicine and remote healthcare services [7, 8].

Additionally, magnetometers play a role in indoor positioning systems. In environments where GPS signals are weak or non-existent, such as inside buildings, magnetometers can assist in determining the orientation and movement of a smartphone. This is particularly useful in large indoor spaces like shopping malls, airports, and museums, where navigation assistance can significantly enhance the visitor experience [9, 10].

The online clothing trade market (e-commerce) is one of the most dynamically developing industries in recent years, which was especially visible during the Covid-19 pandemic and related legal solutions, the so-called lockdowns. One of the biggest problems in the industry is the rate of return of orders due to incorrect determination of the size of the clothes worn compared to the manufacturer's sizes. One of the proposals to solve this problem was an innovative shoe measurement and fitting system implemented by Efiter Sp. z o.o. as part of the project POIR.01.01.01-00-0359/19 "Innovative system for measuring and adjusting shoe size", enabling a real comparison of the buyer's foot with the dimensions of the inside of the shoe. The key aspect of the system was the measurement of the magnetic field generated by the permanent magnet in the shoe. Due to the assumption of simplifying the implementation of the system and reducing its cost for users, it was decided to base magnetic field measurements on magnetometers available in devices that almost everyone has today – smartphones. The key aspect for determining the uncertainty of the method is to determine the metrological parameters of popular smartphones.

The key role in assessing the suitability of using magnetometers in smartphones is played by the metrological properties of these phones. On their basis, it can be indicated how useful it can be for smartphones in various applications such as in [1–10]. Odenwald compared two phones from one manufacturer for use as a radioactivity and magnetic field meter [5]. Ouyang and Abed-Meraim compared the use of 3 phones in measuring the magnetic field, but only for the Earth's magnetic field [11]. Koblischka and Koblischka-Veneva used one phone and two tablets to measure the Earth's magnetic field [12]. There are no studies described in the literature on a broader group of smartphones checking the metrological properties in a wide range of magnetizing fields. Therefore, the authors decided to conduct research on the linearity, sensitivity, offset and uncertainty of sensor readings built into smartphones.

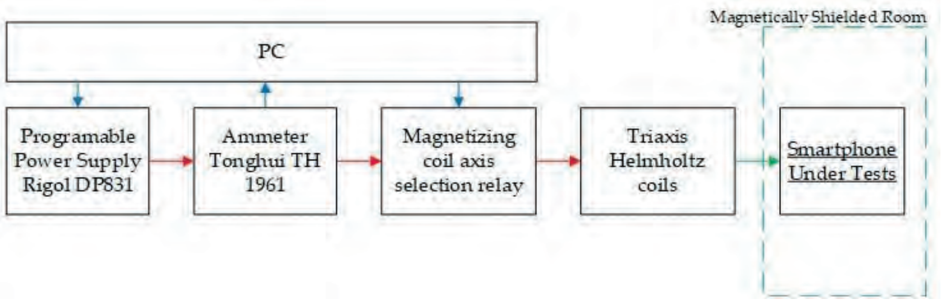


Fig. 1. Schematic block diagram of the experimental setup
Rys. 1. Schemat blokowy układu eksperymentalnego

2. Research motivation

The shoe fitting system requires precise measurement of both the interior of the shoe and the foot. The project aimed to utilize smartphones for both types of measurements. The goal was to create a system that would be easily scalable and cost-effective (by purchasing passive magnetic markers), rather than developing a dedicated measuring device. The foot measurement was conducted using the smartphone's camera and position sensors. Based on a series of photos, a reference pattern (an A4 sheet of paper), and knowledge of the anthropometric model of the foot, the key dimensions of the foot were determined. The measurement of the shoe's interior involved the use of magnetic markers placed inside the shoe and the magnetic field sensor in the smartphone. The magnetic field sensor enables the measurement of the magnetic induction vector at a single point. By using the camera to observe a stationary pattern, it is possible to determine the device's position accurately. This allows for the collection of multiple measurements of the magnetic induction vector at various points. The measurement uncertainty of the magnetic field is crucial for accurately determining the dimensions of the shoe's interior, and consequently, for fitting the shoe to the foot.

3. Experimental setup

The measurements were conducted using a setup that included triaxial Helmholtz coils, which generated a magnetic field of known value in three perpendicular directions, along with a control system. The current value was set by a PC through a programmable power supply RIGOL DR831, which powered the individual coils via a switching circuit. The exact current value in the coils was measured by a Tonghui TH 1961 ammeter and transmitted to the computer. The magnetic field measured by the smartphone sensor was read using the Phyphox app and stored in the phone's memory, along with a timestamp, enabling synchronization of the results (Fig. 1.). To avoid the influence of external interference, the smartphone and the Helmholtz coils were placed in a magnetically shielded room (Fig. 2.).

The goal of this research was to assess metrological properties of magnetometers available in most common smartphones on the market. The most popular smartphone models in Poland in 2019 were tested. The parameters of the smartphones are presented in Table 1.

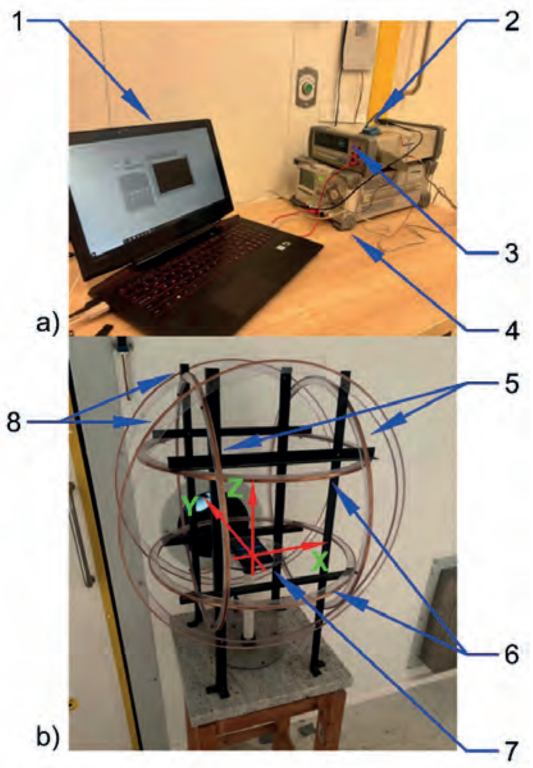


Fig. 2. The experimental setup: a) Photography of the experimental setup outside the magnetically shielded room, b) Photography of the experimental setup inside the magnetically shielded room: 1 – PC computer, 2 – Switching circuit: magnetizing coil axis selection relay, 3 – Tonghui TH 1961 ammeter, 4 – Programmable power supply RIGOL DR831, 5 – Individual Helmholtz coils (X axis), 6 – Individual Helmholtz coils (Z axis), 7 – Smartphone under test, 8 – Individual Helmholtz coils (Y axis)

Rys. 2. Układ eksperymentalny: a) fotografia układu eksperymentalnego na zewnątrz pomieszczenia ekranowanego magnetycznie, b) fotografia układu eksperymentalnego wewnątrz pomieszczenia ekranowanego magnetycznie: 1 – Komputer PC, 2 – Przekaźniki cewek Helmholtza (do wybór osi magnesowania), 3 – Amperomierz Tonghui TH 1961, 4 – Zasilacz programowalny RIGOL DR831, 5 – Cewki Helmholtza (oś X), 6 – Cewki Helmholtza (oś Z), 7 – Testowany smartfon, 8 – Cewki Helmholtza (oś Y)

4. Measurements results

Studies were conducted with a stepwise increasing magnetic field for each axis in range from –300 µT up to 300 µT. After stabilizing each value, measurement results from the smartphone's magnetometer were collected for 20 s. This allowed for the measurement of linearity, sensitivity, offset and measurement uncertainty.

The measurement uncertainty was determined for 50 samples measured over 0.5 s with a sampling frequency of 0.01 s. To determine the uncertainty, the type B method was applied under the assumption of a normal distribution [14]:

$$u(B) = \sqrt{\frac{\sum_{j=1}^{n}\left(B_j - \bar{B}\right)^2}{n-1}} \tag{1}$$

The application of the type A method would be possible if the sample size were greater than 100. This would make the uncertainty of the mean value equal to:

$$u(\bar{B}) = \sqrt{\frac{\sum_{j=1}^{n}\left(B_j - \bar{B}\right)^2}{(n-1)n}} \tag{2}$$

However, in practical application, this would be difficult because the smartphone would need to remain stationary for at least one second, which is hard to achieve since it is necessary to collect magnetic field measurement results at multiple points. The Table 2 provides the values of expanded uncertainty for the confidence level $p = 95.4$ % and $k = 2$ given by equation:

$$U = k \cdot u(B) \tag{3}$$

The measured measurement uncertainty was significantly greater than the resolution of the AK09918 sensor, which is $Re = 0.15$ µT/LSB.

Tab. 1. Key parameters of the smartphones tested in the study [13]
Tab. 1. Kluczowe parametry smartfonów testowanych w badaniu [13]

Trade name	Manufacturer model name	Magnetometer manufacturer	Magnetic sensor type	Price (PLN)
Samsung Galaxy S10	SM-G973	AKM	AK09918	2950
Samsung Galaxy A80	SM-A805F	AKM	AK0991x	1950
Apple iPhone 11	A2111	unknown	unknown	3600
Xiaomi Mi Note 10	CC9	AKM	AK0991x	2150
Redmi Note 8	Redmi Note 8	AKM	AK0991x	750
Huawei P30	ELE-L29	AKM	AKM09918	2250
OnePlus 6	A6000	AKM	AK0991x	1850

Tab. 2. Expanded uncertainty values for magnetic field measurements at a confidence level of 95.4 % with coverage factor k = 2
Tab. 2. Wartości niepewności rozszerzonej dla pomiarów pola magnetycznego na poziomie ufności 95 % przy współczynniku rozszerzenia k = 2

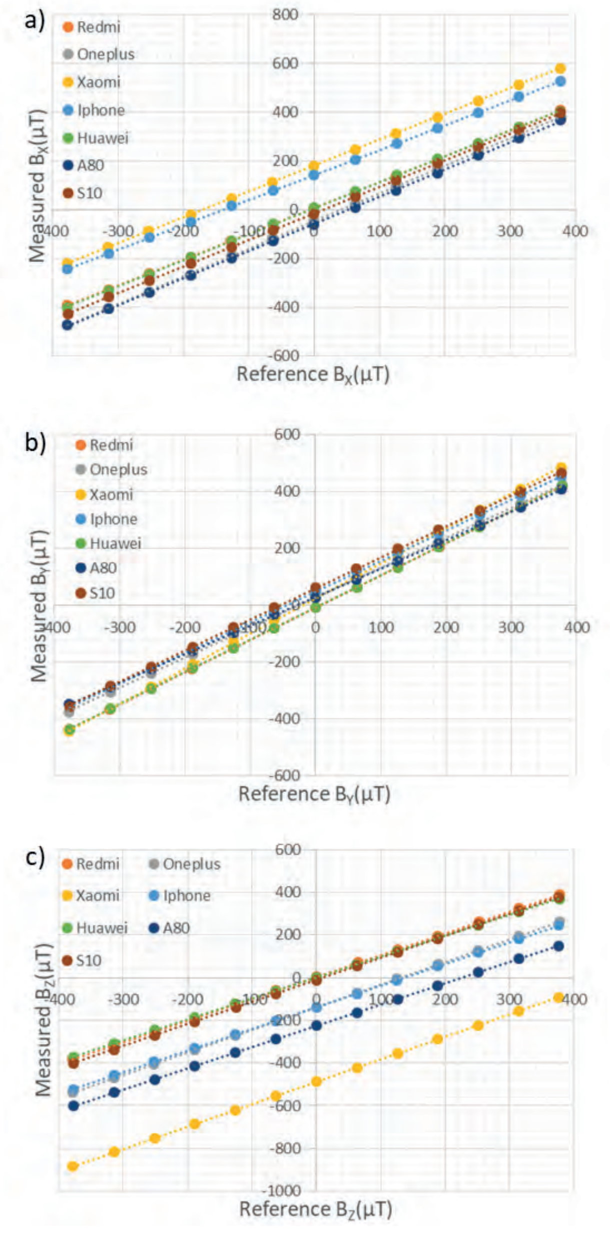
	Redmi	Oneplus	Xaomi	iPhone	Huawei	Samsung A80	Samsung S10
U_X (µT)	1.64	1.85	1.53	0.35	0.45	1.46	0.81
U_Y (µT)	1.62	1.62	1.60	0.33	0.57	1.58	0.73
U_Z (µT)	1.62	1.72	1.63	0.49	0.53	1.98	0.78

Tab. 3. Sensitivity values of smartphone magnetometers across different magnetic field intensities
Tab. 3. Wartości czułości magnetometrów smartfonów przy różnych natężeniach pola magnetycznego

	Redmi	Oneplus	Xaomi	iPhone	Huawei	Samsung A80	Samsung S10
Sensitivity Se_X (µT/µT)	1.06	1.13	1.06	1.02	1.07	1.11	1.09
Sensitivity Se_Y (µT/µT)	1.13	1.06	1.05	1.08	1.13	1.00	1.09
Sensitivity Se_Z (µT/µT)	1.02	1.06	1.05	1.02	0.98	1.00	1.03

Tab. 4. Offset values of smartphone magnetometers across different magnetic field intensities
Tab. 4. Wartości offsetu magnetometrów smartfonów dla różnych natężeń pola magnetycznego

	Redmi	Oneplus	Xaomi	iPhone	Huawei	Samsung A80	Samsung S10
Offset Off_X (µT)	6.86	-47.16	180.53	142.60	5.35	-57.48	-15.64
Offset Off_Y (µT)	-8.26	26.80	24.34	48.76	7.78	28.85	58.13
Offset Off_Z (µT)	3.39	-138.10	-487.05	183.94	0.67	225.93	-11.51



Subsequently, to evaluate linearity, sensitivity, and offset values, measurements were conducted under a stepwise increasing magnetic field. The parameters of linear regression were then estimated, where the slope represented sensitivity, the intercept indicated the offset, and the coefficient of determination (R^2) quantified linearity. For each specified magnetic field value, the measurements were averaged over a period of 20 seconds. An R^2 value of 1 was achieved for all devices (Fig. 3.). The sensitivity values are presented in one Tab. 3, while the offset values are provided in Tab. 4.

The sensitivity values for all tested smartphones are close to 1; however, calibration is necessary to achieve more accurate results. In all devices, except for the iPhone, the same sensor was used. Therefore, it is likely that sensitivity variations may exist within the same model. Calibration of sensitivity is challenging without a reference magnetic field source.

The offset values vary significantly depending on the direction. The Redmi and Huawei devices exhibit the lowest offset values, which may indicate some form of compensation. In many applications, the offset is not critical, as changes in the magnetic field are more important than its absolute value.

5. The Use of Smartphones for Measuring the Interior Dimensions of Shoes

The assumptions of the shoe interior measurement method involve determining the position of a magnet using the measurement of a constant magnetic field. This would make it possible to determine the positions of magnets placed at characteristic points of the shoe, and consequently, to measure its size.

The magnets used have two poles, providing five degrees of freedom: position (X, Y, Z) and two rotation angles, due

Fig. 3. The results of experimental measurements of the of magnetic field sensors used in popular smartphones. Subfigures present measurements along different axes: a) X, b) Y, c) Z
Rys. 3. Wyniki pomiarów eksperymentalnych czujników pola magnetycznego zastosowanych w popularnych smartfonach. Poszczególne wykresy przedstawiają pomiary wzdłuż różnych osi: a) X, b) Y, c) Z

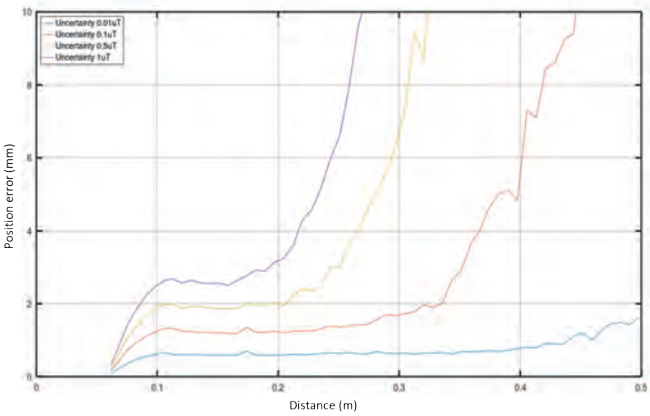


Fig. 4. The dependence of error on distance for different values of magnetic field measurement uncertainty

Rys. 4. Zależność błędu od odległości dla różnych wartości niepewności pomiaru pola magnetycznego

to axial symmetry. Therefore, to determine the position of a magnet in space, it is necessary to measure the magnetic field induction vector at least at two points. If more magnets were placed in the shoe, the number of required equations would increase, assuming no interaction between them.

The developed analytical equations allow for accurate modeling of the B vector distribution in space around a vertical point dipole m. Optimization using the differential evolution method involves determining the positions of four vertical dipoles m based on the measurement of the B vector at 10 points. A more detailed analysis of this approach, including the use of Finite Element Method (FEM), can be found in [15].

The error in determining the position of the standard was examined in relation to the measurement uncertainty of the magnetic field induction vector, and the results are presented in the graph in fig. 4.

The error in position was estimated for uncertainty ΔB, and distance R using the Nelder-Mead algorithm according to equation (4):

$$\vec{B} = \frac{0.3}{R^5}\left(\vec{r}\cdot\vec{M}\right)\vec{r} - \frac{0.1}{R^3}\vec{M} \tag{4}$$

where $\vec{M}$ represents the magnetic moment vector, $\vec{r}$ is the direction vector, and R is the magnitude of $\left|\vec{r}\right|$, corresponding to the distance.

The studies demonstrated the maximum magnetic field measurement uncertainty at level 0.1 µT needed to ensure results with the desired uncertainty (maximum 2 mm error) within the area corresponding to the shoe size (230–300 mm).

Achieving an uncertainty level of 0.15 µT would be possible by averaging over 100 magnetic field measurements; however,

Tab. 5. Dependence of position determination error on magnetic induction measurement uncertainty

Tab. 5. Zależność błędu określenia położenia od niepewności pomiaru indukcji magnetycznej

B measurement uncertainty *U*(µT)	Position error in distance 230–300 mm (mm)
0.01	0.66
0.1	1.34–1.5
0.5	2–6.6
1	> 10

this would require moving the phone to several positions and then keeping it stationary for at least one second. In practice, this would be difficult to implement.

6. Conclusions

Measurements demonstrated a significant increase in noise levels due to the propagation of electromagnetic interference within the smartphone, contributing to greater measurement uncertainty. It was generally observed that more expensive devices exhibit lower levels of interference. For the development of applications that rely on magnetic field measurements, proper calibration, including offset correction and sensitivity adjustment, is essential. Improved accuracy can be obtained through extended averaging periods. Achieving dynamic measurements of a constant magnetic field with uncertainty levels below 1 µT is feasible only with high-end smartphones. The research indicated that the use of smartphones for sophisticated magnetic field distribution analysis is limited by the uncertainty associated with magnetic field measurements, which appears to vary between different models. While smartphones are equipped with advanced sensors, the lack of standardization hinders the ability to fully exploit their potential. Determining the position of a magnetic reference in a shoe with an error margin that allows for the determination of size, which changes every 5 mm, using a smartphone without peripheral devices is not feasible. The use of additional sensors would be necessary to enable averaged magnetic field measurements at several points and to minimize the impact of interference originating from the smartphone's internal components.

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Badanie właściwości metrologicznych sensorów pola magnetycznego stosowanych w popularnych smartfonach dla systemu określania rozmiaru buta

Streszczenie: W artykule przedstawiono wyniki badań metrologicznych właściwości magnetometrów wbudowanych w smartfony oraz ich zastosowanie w precyzyjnym określaniu rozmiaru obuwia. Badania koncentrują się na wykorzystaniu dostępnych w smartfonach magnetometrów do pomiaru pola magnetycznego generowanego przez markery magnetyczne umieszczone wewnątrz obuwia. Do pomiaru wymiarów stopy, użyto czujniki położenia wbudowane w smartfony oraz analizę obrazu w celu dokładnego określenia kluczowych parametrów stopy. Pomiary przeprowadzono w kontrolowanych warunkach wykorzystując trójosiowe cewki Helmholtza generujące precyzyjne pole magnetyczne. Oceniono liniowość, czułość, offset i niepewność pomiaru w kilku popularnych smartfonach. Wyniki wskazują, że dokładność pomiarów magnetometru zależy od jakości smartfona. Zakłócenia elektromagnetyczne, szczególnie w tańszych modelach, mogą wprowadzać szum, który obniża jakość zbieranych danych. Wydłużenie czasu uśredniania pomiarów pomaga zredukować szumy i poprawić dokładność pomiarową. Magnetometry smartfonów mogą być skutecznie wykorzystywane do precyzyjnych pomiarów pola magnetycznego, pod warunkiem ich prawidłowej kalibracji i odpowiedniego dostosowania metody pomiarowej. Ograniczenia, takie jak zakłócenia elektromagnetyczne i ich wpływ na jakość danych, stanowią wyzwanie. Niemniej jednak wyniki badania są obiecujące, szczególnie w systemach doboru rozmiaru obuwia, gdzie dokładne pomiary wnętrza buta są niezbędne do prawidłowego dopasowania buta do stopy.

Słowa kluczowe: magnetometry w smartfonach, pomiar pola magnetycznego, system dopasowania rozmiaru obuwia, dokładność magnetometru, czujniki pola magnetycznego, analiza wymiarów stopy

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