Indoor localization Using a Magnetic Flux Density Map of a Building

Feasibility study of geomagnetic indoor localization

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Abstract— **The need for indoor localization has become increasingly important in recent years for a number of applications. Magnetic flux density fluctuations, caused by reinforced concrete or metal objects, are common in indoor environments. Originally, these fluctuations were considered to be harmful for localization because they can cause electromagnetic interference in sensitive sensors like a compass. However, in many papers it is suggested that these interference patterns can be mapped and used to achieve indoor localization. During this research, tests were performed to determine how feasible geomagnetic indoor localization is for a handheld smartphone device. Pattern matching, a technique often used by radio-frequency based localization technologies, will be used to determine the position of such a device. Advantages of this technology are discussed and possible obstacles are exposed.**

Keywords - Indoor localization; Pattern matching; Magnetic flux density; Geomagnetic indoor localization

I. INTRODUCTION

Since the emergence of the global positioning system, outdoor localization has become a part of our everyday lives. Though the system has proven its worth for outdoor localization in recent years, it falls short when localization is required in an indoor environment, as discussed by Mautz [1]. The ability to locate a person or a device in an indoor environment has become increasingly important for a number of applications.

Since the need for indoor localization systems arose, many technologies have been developed and tested, and it has become apparent there is no overall solution based on a single technology [1]. Studies by Boles and Lohmann [2] and Mouritsen *et.al.* [3] have shown that animals use local anomalies in the Earth's magnetic field to orientate themselves. In recent years, the idea emerged that the same principle can be used for indoor self-localization, termed geomagnetic indoor localization.

Static and low frequency magnetic fields both natural and man-made are present everywhere around us in an indoor environment, as shown by Yamazaki and Keita [4]. The steel reinforced concrete structure of a building and other metal objects cause fluctuations in the Earth's magnetic field. Originally, these fluctuations were considered to be harmful for localization because they can cause electromagnetic interference in sensitive sensors like a compass. However, in many papers it is suggested that these interference patterns can be mapped and used to achieve indoor localization [5] [6] [7] [8] [9] [10].

The goal of this research is to determine how feasible geomagnetic localization is for a handheld smartphone in an indoor environment. Different hardware platforms will be tested, to determine if magnetic flux density measurements are platform independent and localization can be achieved with each platform. This paper wants to validate stated results from other papers using a handheld smartphone.

This paper will first explain the earth's magnetic field in Section II. Second, it will discuss how pattern matching can be done using this magnetic field in Section III. Afterwards, it will describe the used hardware and address the problem of hardware variances in section IV. Section V and VI describe the core of this paper; the indoor magnetic flux density and fingerprinting. In Section VII, interference of objects is discussed and tested. The last part includes the localization measurement model in Section VIII followed by test results in Section IX. The paper in concluded in Section X.

II. EARTH'S MAGNETIC FIELD

Earth's magnetic field originates from currents produced by highly conductive liquid iron spinning inside the outer core. The magnetic field that originates from these currents is called the magnetic B field. The magnitude of the magnetic B field over a surface is described as magnetic flux density and is measured in weber per square meters Wb/m^2, tesla T or gauss G (1 Wb/m^2 = 1 T = 10000 G). In this research, tesla is used, as it is the current official unit defined by the SI system. The magnetic B field itself can be affected or distorted by natural or manmade objects that cause interference. The magnetic B field at the earth's surface ranges from 25 to 65 µT.

Magnetic flux density can be measured by a magnetometer to determine magnetic north. It is important to note that magnetic north is not the same as true north. True north or geographical north is the direction the North Pole is located along the earth's rotational axis. Magnetic north refers to the geomagnetic pole position which is not located along the earth's rotational axis. The angle between magnetic north and true north is called magnetic declination.

 ISBN: 978-1-61208-309-4

Magnetic declination can differ from place to place and changes over time.

Earth magnetic field is described by seven parameters. The total intensity *F* consisting of a north *X*, an east *Y* and a vertical *Z* component. The horizontal intensity *H*, which consist only of the north *X* and the east *Y* components. Inclination *I* describes the angle between *H* and *F*. Declination *D* describes the angle between magnetic north and true north.

Antwerp, the city where this investigation took place has a positive declination of 0° 19', an inclination of 66° 25' and an average magnetic flux density of 48.73 µT. These values can be found using Google maps.

III. GEOMAGNTIC PARTERN MATCHING

Pattern matching is a technique that incorporates measurement data to overcome the cumulative error of an estimated position, as shown by Weyn [11]. While this technique is often used in radio-frequency (RF) based localization technologies, it is very suited for geomagnetic localization, as shown by Storms [5].

The pattern matching process consists of two phases: an offline calibration or training phase and an online tracking or localization phase. During the offline training phase a database is build, containing measurements of the magnetic flux density at predefined positions in a building. This database is called the fingerprint as it is often unique for each building. These measurements will serve as reference points during the localization phase. During the localization phase, the currently measured magnetic flux density by a smartphone is compared to all measurements stored in the fingerprint database. If the current measurement matches a measurement in the fingerprint database it is highly probable that the user will be at the position that corresponds to this fingerprint measurement. Using statistical algorithms the most likely position can be determined.

IV. MAGNETOMETERS

Magnetometers are capable of measuring the three components of earth's magnetic field (x, y and z), relative to their own spatial orientation. Today magnetometers are standard sensors in almost every smartphone, which makes them suitable candidates to use for localization.

For this research two magnetometers on two different platforms were used. A Honeywell HMC5843 3-axis digital compass on a Shimmer 9 dimensions-of-freedom Kinematic Sensor [12]. A AK8973 3-axis magnetometer used on a Huawei Sonic U8650 smartphone [13]. The behavior of each individual sensor was tested to determine if measurements are platform independent.

The first test was conducted in an indoor bedroom apartment were both sensors were individually placed on a wooden table, away from any possible interference factors like metal objects or electronic devices. The sensor would send data back via Bluetooth to a computer were all data was recorded. Both sensors were placed on the table facing true north, which was found using outdoor reference points and Google maps.

Table 1 shows the average magnetic flux density of the first test. Test results show that magnetic flux density measurements are not the same for both sensor platforms. This can be expected, both sensors each have a unique electronic and metal composition, which might distort sensor readings. These distortions are called hard iron effects and are caused by the internal structure of the sensor [14]. Compensation for these hard iron effects is needed. If no compensation for hard iron effects would be done and we use a different sensor for both offline training and online localization phase, we might have an inconsistency between the 2 data sets. Thus, compensating for hard iron effects is crucial for geomagnetic indoor localization.

TABLE 1. SHIMMER SENSOR AND SMARTPHONE AVERAGE MAGNETIC FLUX DENSITY OF STATIC TEST

	Shimmer Sensor	**Smartphone**
x (µT)	-1.05	0.50
y (µT)	7.34	19.19
z (µT)	-57.61	-41.50
Norm (µT)	58.09	42.32

Hard iron characteristics can be found by rotating the sensor round the x, y and z axis. If no hard iron effects are present, rotating a magnetometer 360 degrees and plotting the resulting data as y-axis versus x-axis, will result in a circle centered around (0, 0). Figure 1 and 2 show the resulting circles of the x-y rotation of the smartphone and the Shimmer sensor before compensating for hard iron effects and after. Table 2 shows the compensation values for each axis of both sensors.

TABLE 2. HARD IRON COMPENSATION VALUES FOR BOTH SENSORS

	Shimmer Sensor	**Smartphone**
Correction X (µT)	15.00	3.67
Correction Y (µT)	7.25	0.16
Correction Z (µT)	-11.25	4.52

After compensating both sensors for these hard iron effects by subtracting the compensation values from the raw data, the first test was repeated and the results are shown in Table 3. We can now see that both sensors give very similar measurements at the same position.

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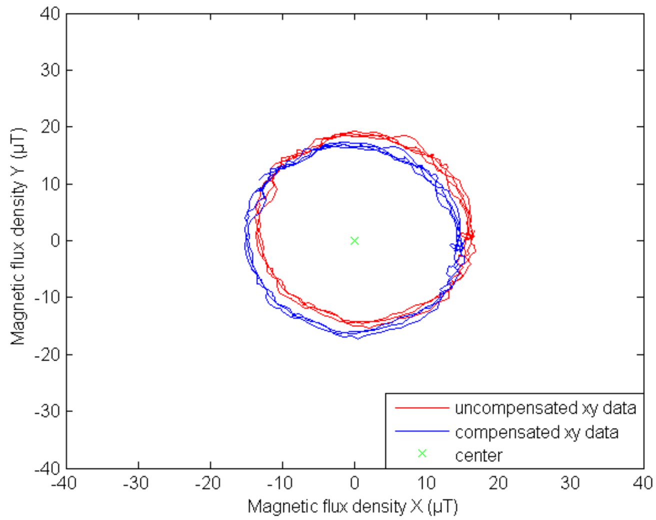

Figure 1. Smartphone hard iron compensation

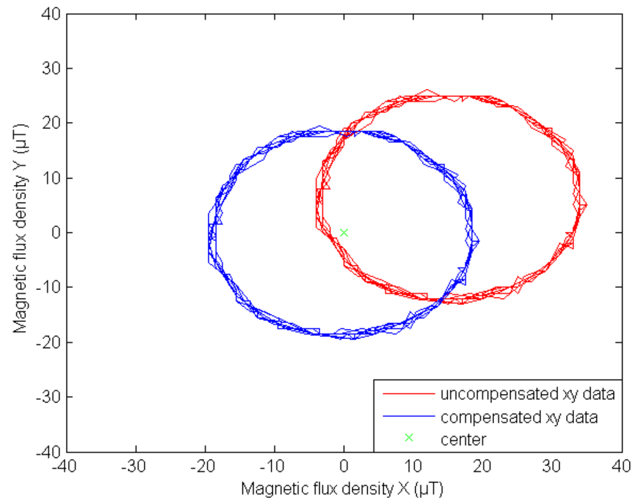

Figure 2. Shimmer sensor hard iron compensation

TABLE 3. SHIMMER SENSOR AND SMARTPHONE AVERAGE MAGNETIC FLUX DENSITY OF STATIC TEST AFTER HARD IRON COMPENSATION

	Shimmer Sensor	**Smartphone**
x (μT)	-0.33	-0.8
y (μT)	17.12	18.01
z (μT)	-45.97	-44.46
Norm (μT)	49.06	47.98

Often, magnetometers are also calibrated to compensate for the presence of external metal or electronic distortions, called soft iron effects. For this research, this is an undesired calibration as the goal of geomagnetic localization is to measure and map these distortions.

If we do not look at the previous test data, we would expect the smartphone to have a higher variance because of its more advanced electronic composition, which might influence the sensitive magnetometer. The test showed that the shimmer sensor had a slightly larger variance, which was unexpected. Additional tests were conducted were all receivers of the smartphone were turned on in an attempt to maximize the variance. Table 4 shows the magnetic flux density measurements of the smartphone with receivers disabled and enabled. Note that the Bluetooth receiver was enabled in both scenarios as it would send back the data. Although variance in the data rose slightly when both receivers were activated, it would not significantly affect our measurements.

TABLE 4. SMARTPHONE MAGNETIC FLUX DENSITY VARIANCE TEST RESULTS

	Wi-Fi and GPS disabled		**Wi-Fi and GPS Enabled**	
	Mean (μT)	Std	Mean (μT)	Std
x	15.07	0.47	15.14	0.48
y	2.35	0.43	2.43	0.54
z	-32.94	0.49	-32.91	0.55
Norm	36.31	0.50	36.32	0.56

As the focus of this research will be handheld smartphones, tests were conducted to see if human hand contact would significantly affect measurements. During the offline calibration phase measurements might be taken with or without contact by a human hand. Magnetic flux density measurement were taken with and without contact by human hand and results are presented in Table 5. The test results show that there was no significant change between both scenarios.

TABLE 5. SMARTPHONE MAGNETIC FLUX DENSITY VARIANCE TEST RESULTS

	No Human Hand Contact		**Human Hand Contact**	
	Mean (μT)	Std	Mean (μT)	Std
x	14.33	0.55	14.48	0.48
y	1.21	0.50	0.93	0.55
z	-33.80	0.52	-33.32	0.52
Norm	36.74	0.54	36.35	0.51

V. INDOOR MAGNETIC FLUX DENSITY

While indoor environments pose good candidates for indoor geomagnetic localization, magnetic flux density measurement must be stable over long periods of time. Li *et. al.* [7] conducted experiments were indoor magnetic flux density was measured in different environments. The results show stable magnetic flux density measurements over a 24 hour period. The experiments were repeated 3 months later and no significant chance was detected.

To achieve indoor localization, it is important that magnetic flux density measurements change considerably from position to position. If the magnetic flux density measurements do not change considerably, the fingerprint might not contain enough information to overcome the cumulative error of the estimated position and indoor localization cannot be achieved [1].

A dynamic test was performed to see if magnetic flux density measurements would vary inside two hallways. The Shimmer sensor was placed on an office chair and was elevated to a height of 1.2m. This height is similar to a user holding a smartphone. The elevation also made sure there was as little interference as possible from the chair itself.

The chair was moved at a constant velocity (0.3 m/s) through the hallway. The speed is not always constant as human error is inevitable. The first hallway was expected to have changing measurement value because of the reinforce concrete floor and metal furniture in the rooms next to the hallway. The second hallway was expected to have less varying measurements because of the wooden floor and the absence of metal furniture.

Figure 3 and Figure 4 show the measurements of the x, y and z components taken through the first hallway and the second hallway respectively. The test results show changing magnetic flux density measurements for hallway A. These peaks and drops in magnetic flux density allow us to identify certain areas inside the hallway and accordingly allow for localization. The measurements of hallway B tell a different story, there are no peaks or drops to identify certain areas, which makes accurate localization improbable.

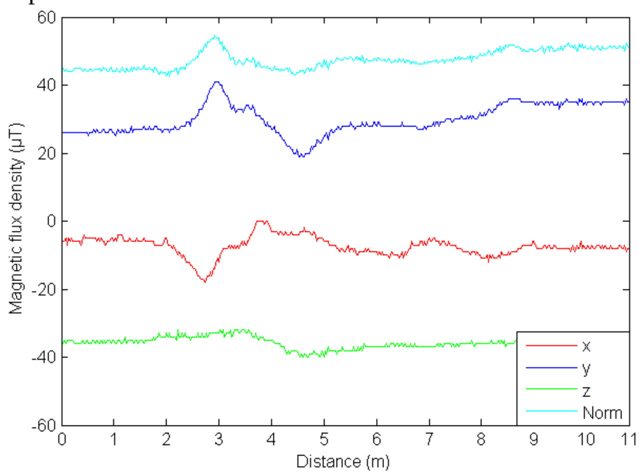

Figure 3. Magnetic flux density dynamic tests of hallway A

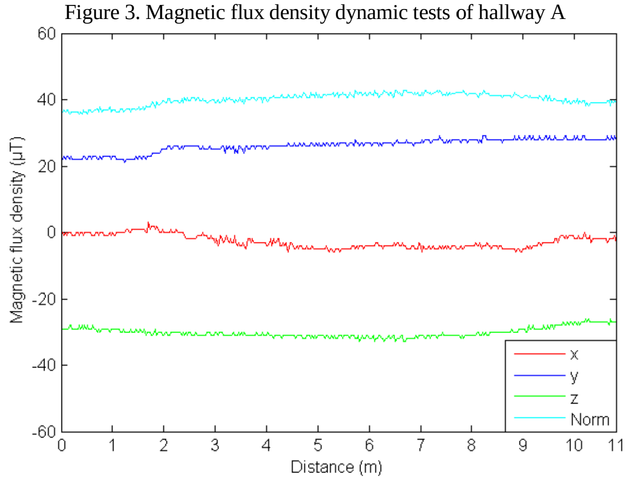

Figure 4. Magnetic flux density dynamic tests of hallway B

VI. Indoor Magnetic Flux Density Fingerprinting

As stated before, pattern matching will be used to achieve indoor localization. This technique requires the recording of a magnetic flux density fingerprint. During this research, an application is developed that allows a user to record such fingerprint. The user loads a map of the desired location in the application. The application will then define measurement positions at the selected resolution. The user selects a desired position, then walks to the coordinates of this position with the magnetometer and starts recording a desired amount of magnetic flux density measurements. It is important that the orientation of the magnetometer does not change during the fingerprinting process as the magnetometer will measure magnetic flux density relative to its own orientation. When all positions are measured, the fingerprint is finished and can either be exported for analysis or used for localization.

The application was used to record a fingerprint of 3 different locations: the ground floor of a suburban house (14 x 16 m), the second floor of a city centered apartment (9 x 12 m) and the second floor lab of the university campus (6 x 19 m). These locations were chosen because they represent different distinct environments were indoor localization might be required. It was important that all locations had multiple rooms and had a medium to large size (+20 m2). Figure 5 shows the recorded fingerprints of the suburban house. The color map shows the magnetic flux density measurements of the normalized x, y and z components taken at 1 m spacing. Areas that remained white were places were no fingerprint measurement could be obtained because of built in cabinets, wardrobes or other furniture.

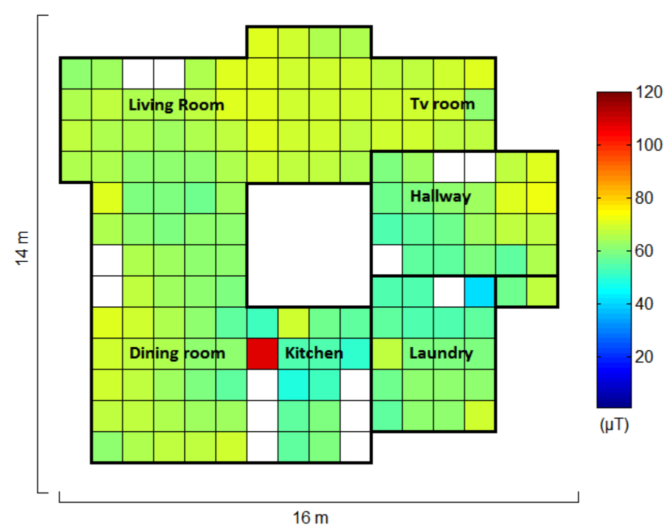

Figure 5. Magnetic flux density fingerprint ground floor suburban house. A big metal stove was located between the dining room and the kitchen. A high magnetic flux density was measured at that location (red square)

The fingerprint in Figure 5 shows that the magnetic flux density characteristics change from position to position. A test was done to determine if these characteristics are unique for an indoor environment. A fingerprint was taken of a garden (4 x 6 m) and a small part of a street (5 x 15 m). Figure 6 shows the obtained fingerprint of the street. The outdoor results are very different from the indoor results. The magnetic flux density characteristics don't change significantly with position. Tables 5 and 6 show the magnetic flux density standard deviation of the recorded measurements for both the indoor and the outdoor fingerprints. The indoor environments clearly have more varying measurements that the outdoor environments.

TABLE 5. MAGNETIC FLUX DENSITY STANDARD DEVIATION OF RECORDED INDOOR FINGERPRINTS

	Suburban house	Apartment	Lab
x (µT)	5.70	5.49	6.99
y (µT)	4.63	5.52	4.84
z (µT)	5.11	4.65	8.08

TABLE 6. MAGNETIC FLUX DENSITY STANDARD DEVIATION OF RECORDED OUTDOOR FINGERPRINTS

	Garden	Street
x (µT)	1.45	3.53
y (µT)	1.28	3.30
z (µT)	0.55	2.65

VII. METAL AND ELECTRONIC OBJECT INTERFERENCE

Indoor environments are places where objects are often moved or replaced. When objects are moved after the initial fingerprinting phase, they can cause undesired inconsistencies between the fingerprint data and real word circumstances.

Tests were conducted to investigate these interferences. Three objects were tested, a perforator, a mobile phone and a hard drive. These objects were chosen because they can represent normal household objects which are often moved within an indoor environment. These different size objects were moved at a constant speed towards a Shimmer sensor to investigate the range and magnitude of the interferences. Figure 6 shows the results of the hard drive test. Magnetic flux density changes drastically as the hard drive moves closer to the sensor. As can be expected the change in magnetic flux density was less significant for the smaller objects. Table 7 shows the interference range of all objects.

Test results show that the size and magnetic composition of the object determines the range and magnitude of the interference. Small size objects only caused interference at a maximum range of ±15 cm, while larger objects cause interference at ±25 cm. While small objects have a negligible influence for a room sized environment, the interference of larger objects cannot always be ignored.

TABLE 7. METAL AND ELECTRONIC OBJECT INTERFERENCE TESTS RESULTS

	Perforator	Phone	Hard Drive
Average velocity (cm/s)	1.48	1.66	1.37
Start of interference (s)	29	24	23
Interference range (cm)	12	15,1	23,5

Fingerprint tests were conducted to confirm these findings. A fingerprint was taken from a small bedroom (3.5 x 3.5 m). Magnetic flux density measurements of the x, y and z component were taken at 0.5 m spacing. Figure 7 shows the interior setup of the room and the resulting magnetic flux density fingerprint of the normalized x, y and z components. As can be seen form this fingerprint, the two speaker cause a clear magnetic flux density interference pattern. The size of this distortion is rather large as speaker are often constructed with strong magnets inside them. After taking the first fingerprint one of the speakers was moved to a different location within the room and a new fingerprint was taken. Figure 8 shows the new interior setup and the resulting new fingerprint. The interference pattern of the moved speaker is clearly visible in the new fingerprint. These test results give an example of how the repositioning and removal of objects inside a room can form an obstacle for indoor geomagnetic localization. When the interior setup of a room changes significantly, a new fingerprint should be taken.

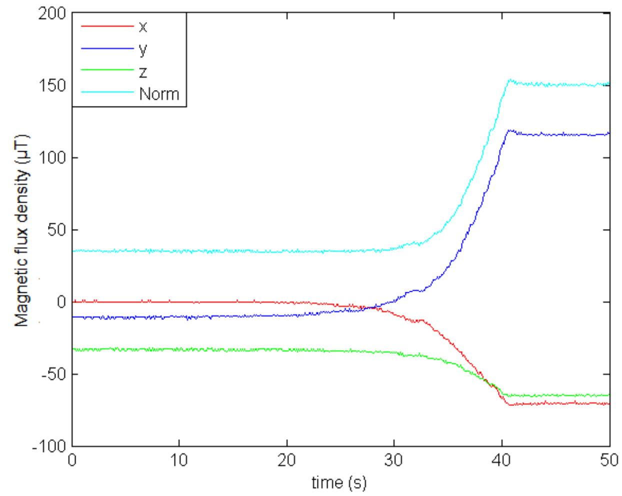

Figure 6. Metal and electronic object interference tests of the hard drive

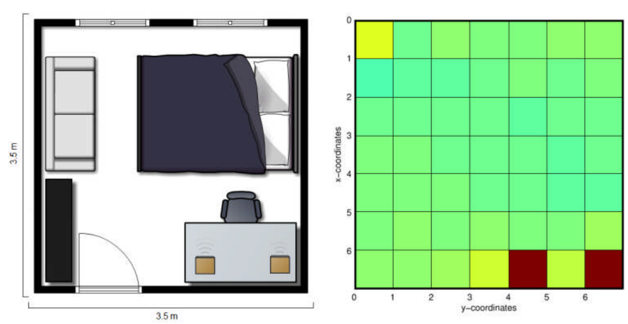

Figure 7. Magnetic flux density fingerprint of bedroom (speaker on original position)

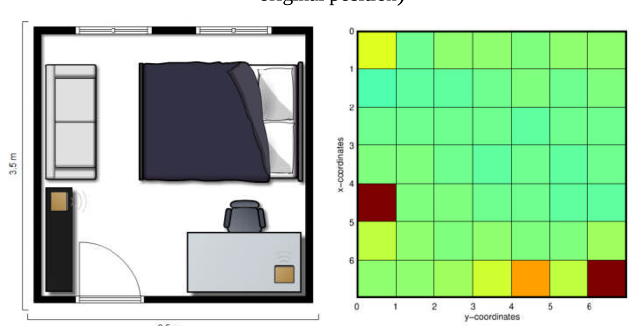

Figure 8. Magnetic flux density fingerprint of bedroom (speaker on new position)

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VIII. GEOMAGNETIC INDOOR LOCALIZATION MEASUREMENT MODEL

All previous results suggest that magnetic flux density measurements can be used to achieve indoor localization. It is important to note, that the quality of the localization often depends on the number of measured components that can be used as reference points [1]. Having many values to compare can obviously increase the chance of finding the right position. The number of components that can be recorded by a magnetometer is rather small. Only the x, y and z components of the Earth's magnetic field can be measured. There are some practical considerations to be made during the localization and fingerprinting phase to use these three components.

As stated before, a magnetometer will measure the magnetic flux density components relative to its own orientation. So, to use the three components requires that the orientation of the sensor is exactly the same during fingerprinting and localization phase. This is a requirement that cannot easily be met. A user will walk around in different directions and the orientation of the device will follow along with him. The way the user holds the device is also never the same. Determining the orientation of the device will be key to using all three components. If no information is available about the orientation of the device in either one of these two phases, we can only use the normal of the measured x, y and z components. This would bring the amount of components to be used for localization to only one.

To resolve this issue, a tilt compensated magnetometer can be used [14]. Such magnetometer uses accelerometers to detect the vertical orientation of the device by measuring the force of gravity. Tilt compensation will allow us to calculate the z component of the magnetic field. Using tilt compensation allows us to use two components, the z component and the norm of the x and y component [7]. To use all three components the horizontal orientation of the device needs to be known. To determine the horizontal orientation the magnetometer can be used as a compass. A compass can determine the direction of the magnetic north and can thus determine the horizontal orientation of the device. However, to do this the user has to manually point the device to a reference point on the map e.g. true north. By defining a reference point the horizontal orientation can be determined [11]. This research showed that indoor environments can cause interference in compass measurements. These interferences are called soft-iron effects. Compensation has to be done to remove these interferences to get an accurate heading [14]. It is important to note, that when soft-iron compensation is done, there needs to be clear distinction between the compensated data and the raw data. Orientation requires soft-iron compensation while localization requires no soft-iron compensation.

All aforementioned information can be combined to define a measurement model for geomagnetic indoor localization. Defining a measurement model can provide a technology interface for sensor fusion systems [11]. Algorithm 1 describes the measurement model. The measurement model is used to find the probability of a position x_t given a measurement z_t.

Although magnetic flux density measurement remain stable over long periods of time, moving metal objects like a lift cause variations in these measurements [7]. These sources of error can cause a mismatch in the magnetic flux density measured at the same position. The accumulated error can be modeled as a Gaussian kernel distribution. The standard deviation of this distribution has to represent the maximum variation that can be expected. The standard deviation was set to 2 µT as this was the maximum standard deviation reported by Li et. al 2 m from a lift [7].

Algorithm 1: Geomagnetic Measurement Model (z_t, x_t)

get z_t^+ from fingerprint for x_t
if $eCompass_{tiltCompensation}$ and $eCompass_{HeadingCompensation}$ then
    $w_x = w_x \,.\, p(z_t^x \mid x_t)$
    $w_y = w_y \,.\, p(z_t^y \mid x_t)$
    $w_z = w_z \,.\, p(z_t^z \mid x_t)$
else if $eCompass_{tiltCompensation}$ then
    $w_{xy} = w_{xy} \,.\, p(z_t^{xy} \mid x_t)$
    $w_z = w_z \,.\, p(z_t^z \mid x_t)$
else
    $w_{norm} = w_{norm} \,.\, p(z_t^{norm} \mid x_t)$
end if
$w_{total} = w_x . w_y . w_z . w_{norm}$
return w_{total}
with:
$p(z_t \mid x_t) = \frac{e\,(\Phi_{Measurement} - \Phi_{fp})}{2\sigma^2}$ σ = 2 µT

IX. GEOMAGNETIC INDOOR LOCALIZATION FEASIBILITY RESULTS

The measurement model defined in Algorithm 1 was used to investigate the feasibility of geomagnetic indoor localization. To test the feasibility, each individual fingerprint position and its accompanying magnetic flux density measurements was used as a test position. Each test position was compared to all measurement positions in the fingerprint using the measurement model described in Algorithm 1. The measurement model would give a high weight to fingerprint positions that had magnetic flux density measurements similar to the test position. The weight represents the likelihood of the user being at position x_t given the measurement z_t. The final estimated position x_t was calculated as the weighted average of all fingerprint positions [11], using Equation 1. Positions with a high probability will contribute more to the final estimated position.

$$x_t = \frac{\sum_{i=1}^{N} w_t^i x_t^i}{\sum_{i=1}^{N} w_t^i} \tag{1}$$

The coordinates of the final estimated position are compared to the real coordinates of the test position and the error is stored. The process will be repeated for all measurement positions within the fingerprint. The maximum, minimum and average errors for every location were determined. The amount of estimated positions that were within 1 m and the amount of estimated positions that were in the same room was also determined. Table 8 shows the results that were obtained from the three fingerprints that were recorded.

TABLE 8. GEOMAGNETIC FEASIBILITY RESULTS

	Suburban house			Apartment			Lab		
Components	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Avg (m)	4.8	4.3	3.1	3.7	3.3	2.5	4.5	3.4	2.5
Min (m)	0.1	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0
Max (m)	9.3	9.4	8.8	7.2	7.4	7.0	10.5	11.3	11.8
< 1m (%)	4	9	17	7	13	23	9	20	32
room (%)	10	18	44	21	31	49	73	74	82

It is clear from the results that using three components gives the best localization results and results deteriorate as fewer components are available. The maximum and minimum errors stay relatively the same for all amounts of components. All localization results were combined to form a cumulative density function in Figure 9.

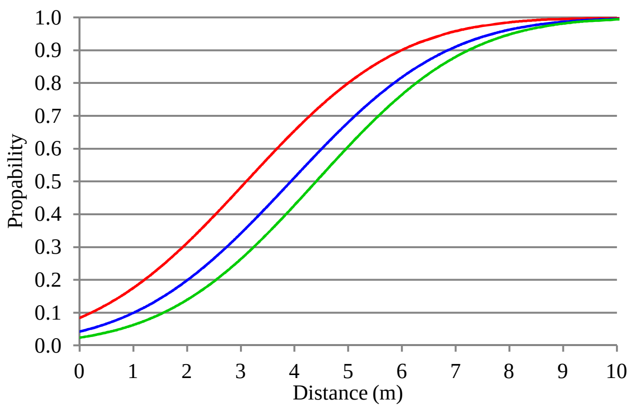

Figure 9: Cumulative density function, error of localization using 3 (red), 2 (blue) and 1 component (green).

Table 9 shows the results of the same test, only now the room of the test position was known. Only measurement position in the same room as the test position would have to be compared to test position. Test results were significantly better, even using only one component could achieve localization close to 1 m. These results indicate that geomagnetic localization might be more suited for localization within a room.

TABLE 9: GEOMAGNETIC FEASIBILITY RESULTS WHEN ROOM WAS KNOWN

	Suburban house			Apartment			University lab		
Components	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Avg (m)	1.4	1.0	0.8	1.4	1.0	0.6	2.2	1.4	0.9
Min (m)	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
Max (m)	3.2	2.8	2.3	5.2	3.9	2.1	5.4	5.2	3.7
< 1m (%)	30	47	67	35	50	74	21	42	61

Figure 10 shows the cumulative density function when the room was known.

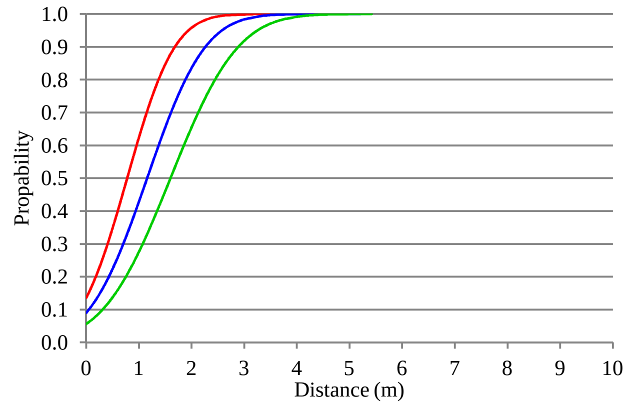

Figure 10: Cumulative density function, error of localization using 3 (red), 2 (blue) and 1 component (green) when the room was known

Although previous results give a good indication of how feasible geomagnetic indoor localization can be, they are largely theoretical. To verify these findings, a more practical test was done. A route was recorded through the suburban house. On this route, magnetic flux density measurements were taken at the same position where fingerprint measurements were taken. The position could not be exactly the same as human error is inevitable. Figure 11 shows the recorded magnetic flux density for the route and the fingerprint.

The results show that the recorded measurements are not exactly the same. The average correlation coefficient between the route and the fingerprint x, y and z measurements is 0.93 which means that both recordings are very similar. The recorded route was estimated within the environment using Algorithm 1. Figure 11 shows the original route (blue) and the estimated route (red). First the route was estimated when nothing about the room was known, later when the room of the measurement was known. Table 10 shows the localization results of both scenarios.

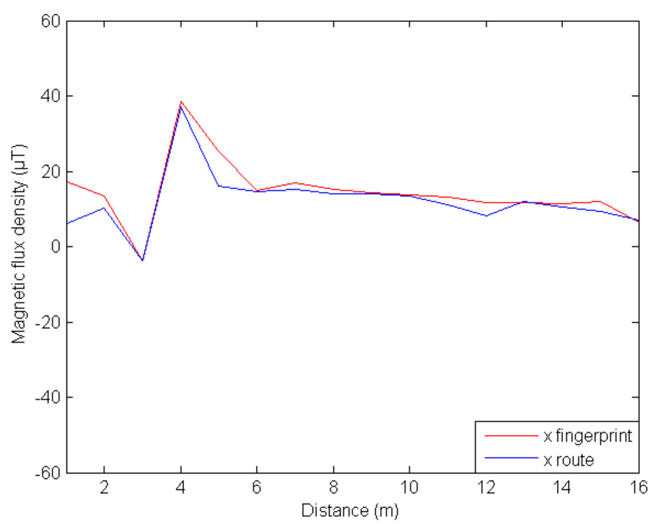

Figure 11: Magnetic flux density x measurements from fingerprint and route

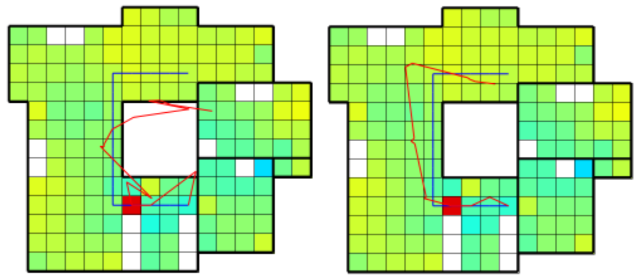

Figure 12: Suburban house route results for 3 components when room was not known (left) and when the room was known (right), blue line is the recorded route and red the estimated route.

TABLE 10: ROUTE ESTIMATION RESULTS

	Global			Room known		
Components	**1**	**2**	**3**	**1**	**2**	**3**
Avg (m)	2.1	2.1	1.4	1.3	1.1	0.9
Min (m)	0.2	0.1	0.0	0.0	0.0	0.0
Max (m)	4.22	4.2	4.5	3.1	2.6	2.0
< 1m (%)	13	13	38	43	43	62
room (%)	25	31	56	/	/	/

This practical test confirmed the original findings. Localization is very dependent on the amount of components that can be used and results are superior when room sized localization is required.

X. CONCLUSIONS

Geomagnetic localization has some big advantages compared to other indoor localization technologies. No dedicated hardware infrastructure is needed, as magnetic fields are present all around us. Magnetic flux density measurements are platform independent as long as hard-iron calibration is applied. Magnetic flux density measurements remain stable over long periods of time. Magnetometers are build-in sensors in almost every smartphone on the market which makes them very suited as a localization sensor.

During this research, many test have been performed to determine how a magnetic flux density map can be used to achieve indoor localization. Possible obstacles are exposed and theoretical feasibility results were produced. Test results show that the quality of localization is strongly depended on the number of components that were used. When three components are used, geomagnetic localization performs reasonably well. When only one or two components are used the feasibility results decrease rapidly. Although these results might not be sufficient for a standalone technology, geomagnetic localization can be applied in a sensor fusion system. A sensor fusion system combines all available sensor measurement data on the platform to estimate the position of the user. Results were poor when global localization was needed but showed promising results when the room was known. In a sensor fusion system other more suited technologies might be used for global localization while geomagnetic localization can be used to determine the most likely position within a room.

While this research touches on many aspect of geomagnetic localization, further research is still required. Using the three components of the Earth's magnetic field is crucial to achieve proper localization results. To use these three components in a real life localization application, a tilt/heading compensated magnetometer must be developed. Determining the maximum variance of such a magnetometer of such a magnetometer under all circumstances is crucial.

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 ISBN: 978-1-61208-309-4