A Uniformed DC Magnetic Generator Using Ferromagnetic Slot Cage by Geomagnetism Distortion Cancellation

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ABSTRACT A widely uniform and highly ambient robust DC magnetic field generator for precise motion sensors using inertial measurement units (IMUs) is newly proposed in this paper. Chronic problems such as low uniformity of magnetic field and geomagnetic disturbance of conventional Helmholtz, Merritt, Rubens, Lee-Whiting, and Tetra coils can be significantly mitigated by the proposed uniform DC magnetic field generator (UFG). Different from the previous air coils, the proposed UFG adopts a core-cage so that a strong and uniform DC magnetic field distribution can be generated inside the cage and that the UFG may be quite magnetically robust to ambient changes such as geomagnetic field and ferromagnetic objects. A dedicated power supply was developed for providing not only a DC current to generate the required magnetic field but also an exponentially decaying AC current to demagnetize the residual magnetic field in the core-cage. Design procedures for the UFG are fully established, considering the manufacturing cost, performance, and mechanical robustness for commercialization. Detailed designs of the UFG for magnetic field generation, enhancing uniformity, geomagnetic cancellation, and demagnetizing of the UFG are provided. Experimental results verified by a 30 cm \(\times\) 30 cm \(\times\) 30 cm prototype UFG showed that the geomagnetic field inside the UFG was significantly attenuated by 22 dB while the DC magnetic field uniformity \((\theta_t < 5.0^\circ)\) was achieved over 85% of the total volume of 27,000 cm\(^3\).

INDEX TERMS Uniform DC magnetic field generator, inertial measurement units (IMU), terrestrial magnetism sensor, geomagnetic field, residual magnetic field.

I. INTRODUCTION

Kinetic motion captures are becoming emerging technologies and widely used in various applications such as rehabilitations, virtual realities, computer graphics, remote controls, exercise analyses, and bio-electromagnetic experiments. To accurately track and analyze dynamic movements of joints of human or target objects, several sensor techniques such as optical, magnetic, mechanical, and inertial measurement units (IMUs) have been developed in two past decades.

Among them, optical sensors, which collect spatial information from reflective markers with multiple high-resolution cameras, have been widely used due to their fast sampling and high resolution [1], [2]. The optical sensor methods, however, lead to several problems such as long preparation and analysis time, large measurement space, occlusion among reflective markers, and high cost. For these reasons, the optical sensor methods need many reflective markers, expensive high-resolution cameras, and post-process to convert two-dimensional (2D) information of each camera to three-dimensional (3D) integrated spatial information [3], [4], [5]. For convenient and cost effective solutions, the marker-less
optical sensor methods, which do not require wearing any equipment for motion captures, have been introduced [6], [7]. These methods, however, still have the problems such as large measurement space and low measurement resolution. Moreover, it is difficult to recognize accurate behavior or gestures of patient because visibility is not ensured due to the use of many assistive devices for rehabilitation. Magnetic sensors are often used, but measurement errors may significantly increase when ferromagnetic objects, e.g., iron, ferrite, and nickel, are close to the magnetic sensor due to magnetic field distortion [8], [9].

To solve the inherent demerits for the conventional sensors mentioned above, IMU sensors are the most widely used methods because they do not require visible distance between the sensor and the object to be measured. The IMU sensors generally include linear acceleration sensors, gyro sensors, and terrestrial magnetism sensors [10], [11], [12], [13], [14], [15]. In IMU, geomagnetic field can be used for the terrestrial magnetism sensors as a reference. However, the geomagnetic field inside buildings, factories, or houses may be severely distorted and therefore cannot be used as a reference for precise motion captures.

To generate uniform AC and DC magnetic field in a volume, there may be several possible coils, e.g., Helmholtz, Merritt, Rubens, Lee-Whiting, and Tetra coils as well as sheet current loops [16], [17], [18], [19], [20], [21]. However, the magnetic field inside these coils may be substantially affected by a distorted geomagnetic field as well as ferromagnetic objects near the coils because they are all air-coil. Therefore, active compensation feedback control methods, which adopt additional coils to cancel the geomagnetic field and additional magnetic sensors near main coils, have been suggested [22], [23]. However, it is not highly practical due to high complexity, high cost, and low reliability of the whole systems. On the other hand, magnetic shielding systems with ferromagnetic materials may be utilized for the calibration of high-sensitive sensors and bio-electromagnetic research [24], [25]. However, manufacture cost is too high, and a uniform magnetic field generation is not considered for motion sensors.

For simultaneously generating uniform DC magnetic field and implementing magnetic shielding, an innovative uniform DC magnetic field generator (UFG) for precise motion capture using IMUs is proposed in this paper, as shown in Fig. 1. Contrary to the conventional air-coils, the proposed core-cage type UFG is composed of four-sided core-bars and two-sided core-plates to generate a uniform DC magnetic field inside the core-cage. Hence, the UFG is robust to ambient changes such as geomagnetic field and ferromagnetic objects. Moreover, a dedicated power supply system is introduced to supply not only a DC current to generate a uniform DC magnetic field, but also an exponentially decaying AC current to demagnetize a residual magnetic field in the core-cage. Based on the fundamental principle and contents of the UFG [26], all the detail design procedures and analytical analysis

![FIGURE 1. Overall configuration of the proposed motion capture systems.](image-url)

are fully established, considering manufacturing cost, performance, and mechanical robustness for commercialization, and verified by experiments with 30 × 30 × 30 cm³ size of a UFG prototype. Experimental results showed that the geomagnetic field inside the UFG was significantly attenuated by 22 dB while the DC magnetic field uniformity (θ ≤ 5.0°) was achieved over 85% of the total volume of 27,000 cm³.

II. DESIGN OF UNIFORM DC MAGNETIC FIELD GENERATORS

In this section, the operating principle of the proposed UFG is thoroughly explained using solenoid coils, and the proposed UFG is analyzed based on an equivalent magnetic circuit. To develop the uniformed DC magnetic field generation, an optimized winding distribution of the proposed UFG is suggested by a finite-element-method (FEM) analysis. The electrical and mechanical design guidelines for the UFG are developed and an experimental prototype is established. A dedicated power supply for the UFG is built, and that provides an appropriate DC current and AC current for magnetizing and demagnetizing the UFG. It is assumed in this paper that the UFG operates under an uneven geomagnetic field distribution and that core materials have high permeability and ideally linear characteristics without any residual magnetic field.

A. BASIC PRINCIPLE OF THE PROPOSED UFG

In general, conventional coils such as Helmholtz, Merritt, Rubens, Lee-Whiting, and Tetra coils can be regarded as a sort of a solenoid air coil, as shown in Fig. 2(a). As well known, a uniform magnetic field distribution inside the solenoid air coil can be obtained if the length l₀ of the coil is much larger than its diameter D₀, maintaining coil winding is evenly distributed and has the same diameter, as follows:

\[ B_y \equiv B_x x_0 + B_y y_0 + B_z z_0 \to |B_y(x, y, x)| \equiv B_y \]

\[ \therefore B_x = B_y = 0 \text{ for } |y| < l_0/2, |x| < D_0/2, \]

and \[ |z| < D_0/2, \] (1)
where $x_\alpha$, $y_\alpha$, and $z_\alpha$ are unit vectors, and all sorts of solenoid coils in Fig. 2(a)-(c) are assumed to be satisfied to (1) in this section for simplicity of analysis.

These simple solenoid coils can be represented as an equivalent magnetic circuit, as shown in Fig. 2(d), where $\mathcal{R}_i$ and $\mathcal{R}_o$ are the magnetic reluctance inside the coil and outside the coil, respectively. Then, magnetic flux $\phi_s$ can be simply determined as follows:

$$\phi_s = \frac{N_i I_s}{\mathcal{R}_{in} + \mathcal{R}_{out}}.$$  (2)

For the case of Fig. 2(a), because effective area of the outer coil $A_{eff}$ is much larger than coil cross section area $A_0 = \pi (D_o/2)^2$, $\mathcal{R}_i$ becomes much larger than $\mathcal{R}_o$. Then, magnetic flux density the magnetic flux $\phi_s$ of the air coil for Fig. 2(a) is determined as follows:

$$\phi_s \approx \frac{N_i I_s}{\mathcal{R}_{in}} \rightarrow B_s = \frac{N_i I_s}{A_0 \mathcal{R}_i} = \frac{\mu_o \mu_r A_0}{A_0} \frac{N_i I_s}{I_o}.$$  (3a)

$$\therefore \mathcal{R}_i \gg \mathcal{R}_o, \quad \mathcal{R}_i = \frac{I_o}{\mu_o A_0}, \quad \mathcal{R}_o = \frac{I_o}{\mu_o A_{eff}}$$

for solenoid air coil  (3b)

In (3), $\mu_r$ is the permeability for the air, and $N_i$ and $I_o$ are the number of the coil turn and the source current flowing into the coil from a power supply, respectively.

In contrast with the solenoid air coil in Fig. 2(a), a uniform magnetic field distribution inside the in-core solenoid coil, which includes a ferromagnetic material inside the solenoid, as shown in Fig. 2(b), can be obtained even if the length $l_o$ of the coil is not much larger than its diameter $D_o$. Thus, magnetic flux density can be obtained from $\mathcal{R}_i \ll \mathcal{R}_o$, as follows:

$$\phi_s \approx \frac{N_i I_s}{\mathcal{R}_i} \rightarrow B_s = \frac{N_i I_s}{A_0 \mathcal{R}_i} = \frac{\mu_o A_0}{A_0} \frac{N_i I_s}{I_o},$$  (4a)

$$\therefore \mathcal{R}_i \ll \mathcal{R}_o, \quad \mathcal{R}_i = \frac{I_o}{\mu_r A_0}, \quad \mathcal{R}_o = \frac{I_o}{\mu_o A_{eff}}$$

for in-core solenoid coil  (4b)

where $\mathcal{R}_o$ can be much larger than $\mathcal{R}_i$ because the relative permeability of the core $\mu_r$ is about 2,000 ~ 5,000 and $A_{eff}/A_0$ is nearly 20 ~ 50.

In this way, the magnetic flux density is drastically increased by virtue of the core inside the coil, and this magnetic flux increment is the desired solution in this paper. However, this in-core solenoid coil cannot be utilized for a uniform magnetic field generation because IMUs cannot be placed inside the coil but outside the coil, where no uniformed magnetic field distribution is obtained. For this reason, an out-core solenoid coil, i.e., core-cage coil, is proposed in this paper, as shown in Fig. 2(c). Contrary to the in-core solenoid coils, the inside of the solenoid coil is empty, and the outside is covered with cores so that IMUs can be placed inside solenoid coil to be exposed to uniformed magnetic field distribution for motion captures.

In a similar fashion to the in-core solenoid coil from (4), a uniform magnetic field distribution inside the out-core solenoid coil can be obtained as follows:

$$\phi_s \approx \frac{N_i I_s}{\mathcal{R}_i} \rightarrow B_s = \frac{N_i I_s}{A_0 \mathcal{R}_i} = \frac{\mu_o N_i I_s}{I_o},$$  (5a)

$$\therefore \mathcal{R}_i \gg \mathcal{R}_o, \quad \mathcal{R}_i = \frac{I_o}{\mu_r A_0}, \quad \mathcal{R}_o \approx \frac{I_o}{\mu_o A_{eff}}$$

for out-core solenoid coil  (5b)

where $\mathcal{R}_i$ can be much larger than $\mathcal{R}_o$ because of outer core. It is noteworthy that the magnetic field for the solenoid air coil (3a) is the same as that for the out-core solenoid coil (5a).

In addition to these advantages, the out-core coil can be magnetically robust to ambient changes such as geomagnetic field and ferromagnetic objects near the coil because the out-core structure provides a magnetic shield against external disturbances, which will be discussed in the next sections.

B. MAGNETIC ANALYSIS OF THE PROPOSED UFG

Based on the proposed out-core solenoid coil, an innovative UFG, which reflects several practical design issues for its commercialization, is newly introduced for the patient’s hand motion capture using IMUs, as shown in Fig. 3. The proposed UFG includes core-cage having a number of core-bars as well as two core-plates, and multiple-wound coils.

For the highly precise motion captures using IMUs with the proposed UFG, the design requirements for the
UFG should be satisfied to overcome the chronic drawbacks of conventional coils [16], [17], [18], [19], [20], [21] as follows:

1) Low angular error of DC magnetic field in y-axis ($\theta_t < 1^\circ$) to limit maximum hand motion capture error under 2 mm when the longest finger length of users is 10 cm, i.e., maximum motion capture error $\approx$ a longest length $\times$ an angular error.

2) High occupation ratio of evenly distributed DC magnetic field area to total volume for large space utilization. (>85 %)

3) Magnetic robustness to ambient changes because active compensation methods used in the conventional coils lead to complex additional systems, which result in expensive cost as well as low reliability.

4) Good penetrability and visibility to the inside of the UFG for measurement convenience.

For the determination of the magnetic field inside the proposed core-cage of the UFG, a simplified core-cage model which illustrates the magnetic resistances of Fig. 3 is derived, as shown in Fig. 4(a). It is assumed that the hole of the left-side core-plate for patient’s hand is negligible for simplicity of analysis because the air gap of the hole is too small, compared to the airgap inside the core-cage. Based on Fig. 4(a), an equivalent magnetic circuit model of the proposed UFG can be obtained, as shown in Fig. 4(b), where $N_s$ is the number of coils turns and $I_s$ is the source current from a power supply. When the same core material is used for both core-bars and core-plates, the magnetic reluctances of core-bars on one side of the core-cage $\mathcal{R}_b$ and core-plate $\mathcal{R}_p$, respectively, can be derived as follows:

$$\mathcal{R}_b = \frac{l_b}{\alpha_b\mu_o\mu_r A_b} = \frac{l_b}{\alpha_b\mu_o\mu_r w_b h_b},$$

$$\mathcal{R}_p = \frac{w_p}{\mu_o\mu_r A_p} = \frac{w_p}{\mu_o\mu_r h_p t_p},$$

where $t_b$ and $t_p$ are the thickness of the core-bars and core-plates, respectively, and $l_b$ and $w_p$ are the length of the core-bars and core-plates, respectively. For these reluctance equations of (6), detail parameter descriptions are shown in Fig. 5. Especially, $\mathcal{R}_b$ in (6) is the effective area ratio of the core-bars, which can be defined in this paper, as follows:

$$\alpha_b \equiv \frac{N_{bs} w_{bs} t_b}{w_b h_b} = \frac{N_{bs} w_{bs}}{w_b}.$$  

In (7), it is assumed that $\alpha_b$ is determined about two thirds to meet one of the system requirements, i.e., the high penetrability and visibility to the inside of the UFG for user convenience.

Then, the magnetic flux $\alpha_s$ and magnetic flux density $B_s$ inside the core-cage can be derived from Fig. 4 as follows:

$$\phi_s = \frac{N I_s}{\mathcal{R}_o + (\mathcal{R}_b + \mathcal{R}_p)/4} \equiv \frac{N I_s}{\mathcal{R}_o} \Rightarrow B_s = \frac{\phi_s}{A_o} = \frac{\mu_o N s I_s}{l_o},$$

where $\mathcal{R}_p > \mathcal{R}_b \ll \mathcal{R}_o$, $A_o = \frac{l_o}{\mu_o A_o} \equiv \frac{l_b}{\mu_o h_p t_p} \equiv 1$ for system user requirements in this paper. Therefore, the required magneto-motive force,
FIGURE 6. The proposed edge-concentrated coil structure to get more evenly distributed DC magnetic field.

i.e., ampere-turns $N_s I_s$ for the given flux density, can be straightforwardly found as follows:

\[ N_s I_s \approx \frac{B_s I_o}{\mu_o}. \] (9)

C. IMPROVED UFG USING EDGE-CONCENTRATED COIL

To achieve the first and second requirements, which are the low angular error of the DC magnetic field in the $y$-axis ($< 1^\circ$) and the high occupation ratio of the evenly distributed DC magnetic field area to the total volume (85%), the evenly distributed coil winding structure may not be satisfied with these requirements. Then, the DC magnetic field becomes weak at the end of the core-bars due to the uneven corner effects. As a remedy for this problem, an edge-concentrated coil to strengthen the weak magnetic field to the corners is newly adopted in the proposed UFG design, as shown in Fig. 6.

As shown in Fig. 7, a comparative evaluation was conducted by 3D FEM analysis for the simple evenly distributed coil and the proposed edge-concentrated coil. The size of the core-cage and ampere-turns are the same for both cases, and coil winding density from side to the center for the proposed edge-concentrated coil is steadily decreased. Thus, the edge-concentrated coil generates an additional magnetic field to compensate the weakened magnetic field at the corners. As identified from Fig. 7(a)-(b), magnetic field uniformity, which is defined as the ratio of maximum-to-minimum flux density difference to average flux density, is improved by two times for the edge-concentrated coil of 0.75% over the evenly distributed coil of 1.48% for $y$-axis direction at $z = 0$ cm case.

To expand 3D volume point of view, a 3D DC magnetic field uniformity has been evaluated for 30 cm $\times$ 30 cm $\times$ 30 cm size, as shown in Fig. 7(c)-(d). As a result, because the measured range of the motion capture system is usually 28 cm $\times$ 28 cm $\times$ 28 cm, the corresponding 3D spaces, satisfying $\theta_t < 1^\circ$, for evenly distributed and edge-concentrated cases are 55.1% and 88.6%, respectively.

D. DESIGN ISSUES FOR GEOMAGNETIC FIELD CANCELLATION

In practice, one of the DC magnetic field distortion factors of the UFG is the geomagnetic field generated from Earth.

To mitigate the geomagnetic disturbance, the thickness of the core-bars and core-plates is an important parameter because the geomagnetic flux penetrates the core-cage and distorts the uniform DC magnetic field in the $y$-axis. To ensure neglecting the geomagnetic field inside the UFG, the worst case scenario that the geomagnetic flux $\phi_g$ only penetrates the UFG in the $x$-axis or $z$-axis; hence, the thickness of the core-bars and the core plates should be carefully considered, as shown in Fig. 6. If the geomagnetic flux $\phi_g$ only penetrates $y$-axis direction to the UFG, geomagnetic flux effect becomes highly reduced because $\phi_g = \phi_s$ and core plate is more effective than core bar.

According to the Fig. 8(a), the magnetic tilted angle $\theta_t$ defined in the first requirement distorted by the geomagnetic flux can be expressed as follows:

\[ \tan \theta_t \equiv \frac{B_g}{B_y} = \frac{\phi_o}{B_s I_o} = \frac{\phi_g}{B_s I_o} \left( \frac{\mathcal{M}_c}{\mathcal{M}_o} \right) \approx \frac{\phi_g \mathcal{M}_c/2}{B_s^2 \mathcal{M}_o} \beta_b \approx \frac{\mathcal{M}_c}{\mathcal{M}_o} \approx \theta_t, \] (10a)

\[ \beta_b \equiv \frac{A_{\text{eff}}}{A_b} \approx \frac{I_{\text{eff}}^2}{I_b^2}, \quad \mathcal{M}_c = \mathcal{M}_p + \mathcal{M}_b, \] (10b)
where $B_y$ and $B_g$ are the target and Earth magnetic field: $B_y = 300 \mu T$ and $B_g = 45 \mu T$, respectively, in this paper. $\mathcal{N}_c$ is the summation of $\mathcal{N}_p$ and $\mathcal{N}_b$ ($\mathcal{N}_c = \mathcal{N}_p + \mathcal{N}_b$).

From (10), $\beta_b$ is an effective area ratio, defined as the magnetic concentration due to the core-cage from Earth magnetic flux to the case magnetic field. Because $\beta_b$ cannot be analytically obtained in general due to non-linear magnetic distortion by the core, 3D FEM simulation analysis has been performed, as shown in Fig. 9. From the simulation result of Fig. 9, the value of $\beta_b$ was obtained as 2.4. On the other hands, the equivalent reluctance $\mathcal{N}_c$ (10) and the core-inside reluctance $\mathcal{N}_o$ in (8b) can be approximately calculated based on the geometrical information as follows:

\[
\mathcal{N}_c = \frac{l_b}{\mu \alpha_b w_p l_b a_b} + \frac{w_p}{\mu_0 \mu_b h_p l_p} \lesssim \frac{l_b}{\mu_0 \mu_b h_p l_p} + \frac{l_b}{\mu_0 \mu_b l_p} \lesssim \frac{\alpha_b + 1}{\mu_0 \mu_b l_b a_b} \quad (11a)
\]

\[
\mathcal{N}_o \lesssim \frac{l_b}{\mu_0 l_pl_b} - \frac{1}{\mu_0 \mu_b} \Rightarrow \mathcal{N}_o = \frac{\mathcal{N}_c}{(1 + \alpha_b)l_b} \quad (11b)
\]

where $t_b = t_p$, $w_p = h_p = l_b$ for this motion capture measurement applications.

From (10)-(11), the thickness of the core-bars and the core-plates can be found to be 2 mm by following equations.

\[
t_b = \frac{\beta_b B_g (1 + \alpha_b)l_b}{2 \zeta_B B_y \mu_m a_b}. \quad (12)
\]

From (12), The solution of $t_b = t_p = 2$ mm guarantees the system requirements, which leads to $\theta_i < 1^\circ$ for the magnetic field distortion minimization.

E. DESIGN CONSIDERATIONS FOR MECHANICAL FABRICATION

Considering commercializing the proposed UFG, there are two main design considerations for its mechanical fabrication. One is to adopt a mechanical frame for the UFG, which not only supports the core-bars and core-plates, but also resistant to external impacts. The other is the material selections for the core-bars, core-plates, and the mechanical frame because the material selections can influence the DC magnetic field uniformity, geomagnetic cancellation, cost effectiveness, workability, and weight. To meet the above design issues, aluminum having almost the same relative permeability as air is selected for the frame so as not to distort the DC magnetic field, as shown in Fig. 10(a). On the other hands, iron having a high relative permeability of 4,000 is adopted in the core-bars and the core-plates, as shown in Fig. 10(b). Easy fabrication of the UFG is one of the important considerations to maximize its productivity. For this reason, the core-cage is separated into four parts for an easy assembly with the frame, as shown in Figs. 10(b) and (c). By multiple winding coils to each separated core-cage, the coil winding process can be further relieved and easily finished before assembling the core-cage with a frame, which results in significant cost and time reductions for its fabrication. However, it should be noted that additional leakage flux passing out of the core occurs because multiple coils are wound around the core-cage for the separated core-cages. For this reason, it is important to provide a strong connection between core-bars and core-plates because a weak connection between them leads to asymmetric magnetic reluctances, which result in non-uniform DC magnetic field in the UFG. For strong connections between them, aluminum hinges are used at the corners, as shown in Fig. 10(d).

F. DESIGN EXAMPLE FOR THE PROTOTYPE UFG

For a patient’s hand motion capture measurement, a prototype UFG of 27,000 cm$^3$ (30 cm $\times$ 30 cm $\times$ 30 cm) has
been fabricated based on the proposed design procedures in this section. As shown in Fig. 5, all the design parameters of the proposed UFG are included, and selected values are summarized in Table 1. \( w_b \) and \( h_p \) are selected as 27 cm and 30 cm, respectively, to make a distance of 30 cm between the core-plates as well as the sets of the core-bars so that the target uniform DC magnetic field volume of at least 21,600 cm\(^3\) can be achieved, considering about 85% of the total volume. After that, \( w_p \) and \( h_p \) are all determined as 34 cm to perfectly cover the frame while \( l_{bb} \) is selected as 2 cm, which is the same as \( t_f \). As mentioned in the previous section, at least one third of the area of the core-bars should have a cut-away shape for the high penetrability inside the UFG, and then \( w_{bs} \) and \( d_{bs} \) are selected as 1.8 cm and 1 cm, respectively. The number of windings turns \( N_1 \) is selected as 37 turns, and the ampere-turn \( N_I \) is 148 AT by \( I_s = 4.0 \) A. This ampere-turn value is optimally determined by simulations and experiments to meet the system requirements as well as a uniform DC magnetic field of 300 \( \mu \)T in the y-direction, considering the measurement range of the terrestrial magnetism sensor of the IMU.

### TABLE 1. Designed parameters of the proposed UFG.

| Parameter | Value |
|-----------|-------|
| \( w_p \) | 34 cm |
| \( h_p \) | 34 cm |
| \( w_f \) | 34 cm |
| \( h_f \) | 34 cm |
| \( w_{bs} \) | 27 cm |
| \( h_{bs} \) | 30 cm |
| \( t_f \) | 2.0 cm |
| \( l_{bs} \) | 30 cm |
| \( t_f \) | 2.0 cm |
| \( d_{bs} \) | 1.0 cm |
| \( l_s \) | 2.0 cm |
| \( N_1 \) | 37 turns |

**FIGURE 11.** Experimental results of non-uniform DC magnetic fields due to the residual magnetic field in core-bars and core-plates.

G. DESIGN OF THE POWER SUPPLY FOR BOTH MAGNETIZING AND DEMAGNETIZING THE UFG

Since iron is adopted for the core-cage, the residual magnetic field, which is an inherent characteristic of ferromagnetic materials, is inevitably left in the iron after magnetizing the UFG, and the residual magnetic field significantly distorts the uniform DC magnetic field, as shown in Fig. 11. Therefore, residual magnetic field mitigation method is proposed in this section.

As a remedy for this problem, a power supply is newly proposed in this paper, which can supply not only a DC current to generate a uniform DC magnetic field in normal conditions but also an AC current to demagnetize residual magnetic field in the core-cage before operation, as shown in Fig. 12. Here, the power supply consists of an isolation transformer, a utility rectifier, a buck converter, a full bridge inverter, and a load selector. Coil 1 to 4 are an upper coil, a lower coil, front coil, and a right coil, respectively. As shown in Fig. 13, the control sequence of a micro controller unit (MCU) for the power supply can be classified into four modes: a ready mode, a degauss (=demagnetizing) mode, a normal operation mode, and a turn-off mode.

In the ready mode, the duty cycle of the buck converter goes up to increase the DC capacitor voltage \( V_c \) while the select switch for load is at the normal state. At the end of the ready mode, the connection between the two coil sets (Coils 1~2 & Coils 3~4), where a coil set consists of face-to-face coils, as shown in Figs. 12, changes from a series connection to an anti-series connection by the selective switch. Because large magnetic reluctance inside the UFG \( R_o \) can be ignored by the anti-series connection, as shown in Fig. 14, strong magnetic flux can be generated through the core, as follows:

\[
\Phi_{c,AS} \approx \frac{N_s I_s}{R_c} \text{ for } R_o \gg R_c, \tag{13}
\]

From (13), because demagnetizing flux directions of two face-to-face coils are opposite, as shown in Fig. 14, the strong magnetic flux can pass through only the core, not inside the air, by this anti-series connection. On the other hands, in the case of series connection, as shown in Fig. 15, magnetic flux can be calculated as follows:

\[
\Phi_{c,S} = \frac{N_s I_s}{4R_o + \frac{1}{R_c}} \approx \frac{N_s I_s}{4R_o} \text{ for } R_o \gg R_c, \tag{14}
\]

From (14), because the magnetic flux directions are the same for four coils, the uniformed magnetic field is generated to inside the air for this series connection. Therefore, by virtue of the proposed complimentary connection method, the required source current in anti-series connection for degauss mode can decrease by about 70 times compared to the series connection.

In the degauss mode, the switches \( S_1, S_3 \) and \( S_2, S_4 \) complementarily operate to supply AC currents while the duty cycle of the buck converter steadily decreases so that AC currents flowing into the coil sets decrease from the saturation currents to 0 for demagnetizing the coil sets. When the AC currents reach to zero, the selection switch moves to its original state to recover the polarity of the coil sets. The switching frequency \( f_s \) for the degauss operation can be determined by a time
constant of the coil sets in the UFG to closely reach the designed saturation current as follows:

$$\frac{T_s}{2} = \frac{1}{2f_s} \geq 6\tau_c \rightarrow f_s \leq \frac{1}{12\tau_c} \quad \therefore \tau_c = \frac{L_c}{R_c}, \quad (15)$$

where $R_c$ and $L_c$ are the inductance and resistance of a coil set, respectively, and $\tau_c$ is selected to allow enough time to reach the maximum current.

In the normal operation mode, $S_1$, $S_4$ are turned on while $S_2$, $S_3$ are turned off to supply the target DC current of 4 A.

### III. EXPERIMENTAL VERIFICATIONS

To verify the proposed design in the previous sections, the proposed prototype UFG of 27,000 cm$^3$ (30 cm $\times$ 30 cm $\times$ 30 cm) was fabricated, as shown in Fig. 16. All the parameters are the same, as listed in Table 1, and all the material selections of the UFG are fabricated based on the proposed design procedure. To measure a functional progression of the hands of the elderly or patients, a motion capture glove having 11 EA IMUs is adopted, as shown in Fig. 17(a). The magnetic flux density inside the core-cage was measured with a terrestrial magnetism sensor of the IMU, as shown in Fig. 17(b). The IMU consists of a 3-axis linear acceleration sensor, a 3-axis gyro sensor, and a 3-axis terrestrial magnetism sensor, having the measurement range from $-400$ µT to $+400$ µT; hence, considering the commercialized product performance of the IMU sensors, target DC magnetic field was set to 300 µT in the y-axis. Enamel-coated coil, having a diameter of 1.45 mm of AWG 15, was selected to obtain the uniform DC magnetic field density of 300 µT, where $I_s$ and $N_s$ were 4 A and 37 turns, respectively. According to the coil design selection for uniform magnetic field generation, the edge-concentrated coil structure was applied to the experimental prototype: 37 total turns are distributed as (6, 2, 3, 3, 3, 3, 3, 2, 6), and the distance $d$ between coils is 30 mm in this case. To measure angular error $\theta_t$ for the y-axis, following equation can be used from the measurement results of the
3-axes magnetic flux densities.

\[
\theta_t = \frac{180}{\pi} \cos^{-1} \left( \frac{|B_y|}{\sqrt{|B_x|^2 + |B_y|^2 + |B_z|^2}} \right) \tag{16}
\]

**A. MEASUREMENTS OF GEOMAGNETIC FLUX**

To verify the geomagnetic field cancellation design, the geomagnetic field in the UFG was measured during the ready mode while all the residual magnetic field in the UFG was demagnetized by the proposed power supply before the measurement. If the proposed degauss process is not included for the proposed UFG system, the DC magnetic field uniformity may be too low, whose values are arbitrarily determined, depending on the magnetizing conditions of the core and the other surrounding environment, as identified from Fig. 11.

Because \( \theta_t < 1^\circ \) for system design requirement by the geomagnetic field cancellation, the geomagnetic flux density should be under 5.3 \( \mu \)T (=53 mG) from (10a). As shown in Fig. 18, all the measured geomagnetic flux density is under 3.6 \( \mu \)T (=36 mG), where the uncompensated geomagnetic field of 45 \( \mu \)T (=450 mG) inside the UFG had been significantly attenuated by 22 dB. Therefore, the magnetic distortion from the geomagnetic field can be ignored because it is 1.1% smaller enough, compared to \( B_y = 300 \mu \)T in the y-axis.

**B. DEMAGNETIZATION PROCESS**

To demagnetize the residual magnetic field as well as to magnetize the core-cage, a prototype power supply for the UFG was fabricated from fabricated prototype. \( L_{coil} \) and \( R_{coil} \) are measured as 823 \( \mu \)H and 1.34 \( \Omega \), respectively; hence, \( f_s \) was determined as 130 Hz from (15). As shown in Fig. 19, AC current of 8 A flows into the coils to generate the saturation magnetic field density of 2 T for the iron core-cage and then steadily decreases to zero current to demagnetize the core-cage.

**C. MEASUREMENTS OF DC MAGNETIC FIELD DISTRIBUTION**

After the geomagnetic field cancellation as well as the core-cage demagnetization, which significantly mitigate the uniform magnetic field distortion, the experiments were made to show the uniform DC magnetic field distribution inside the UFG, as shown in Fig. 20. To calculate angular error \( \theta_t \), the IMU made by Mintosys has been used based on the measured
3-axes magnetic field data. From the experimental results, it is found that the magnetic field in the UFG is under the target y-axis angle of 5°, as identified from Fig. 8, over 85% of the 3D volume, except the region near the coils. In the same manner, ϑ₁ < 3° and ϑ₂ < 10° for 68% and 89% of the 3D volume range, respectively, whose values can be obtained by the proposed geomagnetic field de gauss process. Throughout the experiments, there were discrepancy between design calculations and experiments and small unexpected asymmetric magnetic field distortions, as shown in Fig. 20, although the geomagnetic field and residual magnetic field are small enough. These major discrepancies may come from assembly tolerances as well as fabrication errors, which will be improved by sophisticated manufacture process.

IV. CONCLUSION

A widely uniform and highly ambient robust UFG for precise motion sensors using IMUs has been successfully evaluated and experimentally verified. By the proposed optimal design process of the UFG, geomagnetic field effect and surrounding environment changes can be highly mitigated. The proposed active residual magnetic cancellation methods can significantly suppress 22 dB of the geomagnetic field inside the UFG; thus, this result is so small enough for practical use, compared to the conventional cases that used several possible coils [16], [17], [18], [19], [20], [21] and active compensation feedback control methods [22], [23]. From the results of the high DC magnetic field uniformity (<5°) from 85% of the total volume 27,000 cm³, this achievement has the highest DC magnetic uniformity to generate 3D uniformly distributed magnetic field; hence, it is expected that motion capture measurement can be highly reliable to various applications by the proposed DC magnetic generators.

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