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ORIGINAL RESEARCH ARTICLE

APPLICATION OF FIREFLY OPTIMIZATION ALGORITHM TO THE DESIGN AND CHARACTERIZATION OF HELMHOLTZ COILS FOR MAGNETIC FIELD SENSOR CALIBRATION

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ABSTRACT

This paper presents the application of Firefly Optimization Algorithm (FOA) to the design and characterization of Helmholtz coils to create homogenous magnetic field needed for calibrating magnetic field sensors and used for other experiments. Magnetometer is used to monitor and record the earth's magnetic field data at the geomagnetic observatory. Earth's magnetic field data from ground-based magnetometer observatories are important for studying geomagnetic storm. The absence of earth's magnetic field data observatories results in a complex mysterious phenomenon of geomagnetic storm and remains as unexplained one. Fluxgate magnetometer is contributing to the ongoing extensive research work dedicated to the explanation of some of the complex phenomena related to geomagnetic storm and solar terrestrial system. In order to examine magnetic field sensing of a fluxgate sensor, a large area with uniform magnetic field is required. The advantage of having a large area is to allow easy access of the sensor during magnetic field measurements. A laboratory design and characterization of high quality Helmholtz coils is a better choice when Helmholtz coil with larger areas that are available in the market are very expensive

1.0 Introduction

Helmholtz coil is a parallel pair of two similar circular or square shaped coils, spaced one radius apart with coils wound in series such that the current passes in the same direction in each coil (Abbott, 2015; Alao et al., 2018). Helmholtz coils are used for Earth's magnetic field nullification, magnetic field sensors calibration and other experiments where a controllable amount of uniform magnetic field is required (Abbott, 2015). The basic principle of Helmholtz coils is that the coils produces uniform magnetic field at the center (Abbott, 2015; Daron et al., 2015) of the coils, which is equivalent to the radius of the coil. This arrangement of coil was invented by German physicist, Hermann von Helmholtz, over a century ago (Bhatt et al., 2010). The intensity of magnetic field is directly proportional to the number of turns, radius of the coil and the excitation current through the coils (Abbott, 2015). According to the definition of Helmholtz coil, there are some uncertainties even if the mean radius of the coils is equals to the separation distance between the coils (Yang et al., 2018). An ideal Helmholtz coil with ampere-turn (Ni) can be realized with the number of layers, number of turns per layer, coil excitation current and radius of the coil (Yang et al., 2018). Biot-Savart law is employed for the magnetic field calculation, while the coil turns of each Helmholtz coil are concentric rings as shown in Figure 1. Thus, the magnetic field strength at the center of Helmholtz coils due to current-carrying element is as follows (Bhatt et al., 2010):

$$B = N \,.\, \frac{\mu_0 . I_C}{R} \,.\, \left(\frac{4}{5}\right)^{3/2} \tag{1}$$

Where: R is the radius of each turn of a coil, IC is the coil current, and μ0 is the permeability of air. When calculating the diameter of wire for the design of Helmholtz coils, the power supply for driving the coils must be taken into consideration as this provides the current needed to generate the required magnetic field (Bhatt et al., 2010; Yang et al., 2018). The schematic describing the configuration of Helmholtz coils is shown in Figure 1.

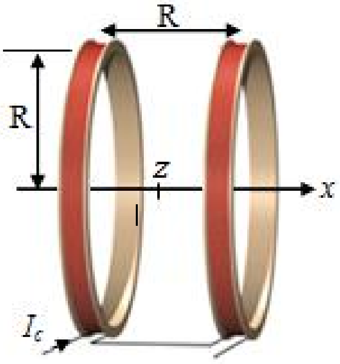

Figure 1: The Schematic Diagram of Helmholtz Coils (Bhatt et al, 2010)

As shown in Figure 1, each Helmholtz coil produces equal amount of magnetic field parallel to the axis of the coils (Bhatt et al., 2010), while the two coils produce uniform magnetic field, which is accomplished by a controllable amount of excitation current (Abbott, 2015). The uniform field within the coils is due to the summation of fields parallel to the axis and the difference of vertical component fields (Abbott, 2015; Yang et al., 2018). Helmholtz coil design is simple and there are many commercially available designs for all kinds of applications (Yang et al., 2018). In order to examine the magnetic field sensing of a fluxgate sensor, a large area with uniform magnetic field is required (Butta et al., 2010). Helmholtz coils with large area will allow easy access of the sensor during measurements (Butta et al., 2010; Alao et al., 2018). A laboratory design and characterization of Helmholtz coils is of great advantage when large area Helmholtz coil is desired and the commercial Helmholtz coils are very expensive (Alao et al., 2018).

Moreover, in order to calibrate magnetic field sensors, a high magnetic field with low rise in temperature and power consumption are required. When total power consumption and magnetic field of the Helmholtz coils are the objectives function, Helmholtz coils design needs to satisfy the design limits and geometric constraints. In order to find the optimal performance of Helmholtz coils in this study, a systematic design approach is employed, where the modified multi-objective Firefly Optimization Algorithm (FOA) is used to simultaneously obtain the parameters and predicts the magnetic field inside the Helmholtz coils. Such a multi-objective optimization approach is powerful in dealing with design problems in electro-magnetic with a

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large number of design variables and multiple objectives under complex nonlinear constraints (Yang, 2013).

2.0 Methodology

In order to implement the design of Helmholtz coils, the FOA was written in Matlab environment and the results were obtained by running the developed program on a 1.50 GHz Intel® core™ Duo CPU Windows 7 Ultimate 32-bit personal computer (Alao et al., 2018). In this study, the primary aim of the Helmholtz coils design was to create uniform magnetic field in the test area. The characterization was carried out by using a MatLab program for plotting the magnetic field inside the Helmholtz coils.

2.1 Helmholtz Coils Design Approach Using FOA

The aim of systematic design approach applied to Helmholtz coils design in this study is to simultaneously find the optimal number of coil turns per layer, number of coil layers, wire size, coil radius, and the excitation current requires for creating uniform magnetic field at the center of the Helmholtz coils. This is achieved by using Helmholtz coils equation to modify firefly optimization algorithm. The algorithm starts by placing the fireflies in random locations. The location of a firefly corresponds to the values of the parameters (number of coil turns per layer, number of coil layers, wire size, coil radius, and the excitation current) for the objective function (magnetic field) to be solved.

Initialize the number of fireflies, n, biggest attraction β0, absorption coefficient of light intensity γ, step size factor α, and maximum number of iterations or generations tmax.

Initialize the positions of fireflies randomly, namely initializing design variables of the Helmholtz coils parameters (number of coil turns per layer, number of coil layers, wire size, coil radius, and the excitation current), the values of objective function (magnetic field) of fireflies are set as their maximum brightness of fluorescence I0.

Calculate relative brightness and attractiveness of fireflies, which belong to the population. The direction of movement depends on the relative brightness of fireflies. Here (Yang, 2013):

$$\mathrm{I} = \mathrm{I}_0 \times \mathrm{e}^{-\gamma \mathrm{rij}} \tag{2}$$

$$\beta = \beta_0 \times \mathrm{e}^{-\gamma \mathrm{rij}} \tag{3}$$

Where: I_0 is the maximum fluorescence brightness of the firefly, namely the fluorescence brightness itself (r = 0), which depends on the value of the objective function. β0 is the maximum attractiveness, namely the attractiveness of the light source (r = 0). γ is the absorption coefficient of the light intensity. The fluorescence will gradually weaken according to the increasing distance and the absorption of media. The absorption coefficient of light intensity is set to reflect this feature. r_{ij} is the spatial distance between firefly i and j.

Update the spatial positions of fireflies. Random perturbations are injected to the firefly with the best position. The updated equation is:

$$\mathrm{x_i} = \mathrm{x_i} + \beta \times (\mathrm{x_j} - \mathrm{x_i}) + \alpha \times (\mathrm{rand} - 0.5) \tag{4}$$

where x_i, x_j represent the spatial positions of firefly i and j, respectively. α is the step size factor. rand is random factor distributed uniformly in [0,1].

Recalculate the brightness of fireflies according to the updated positions.

Return to Step 3 until the search precision is met or the maximum number of generations is achieved.

The optimization of Helmholtz coils design problem is formulated as non-linear programming problem, expressing the objective function and constraint function in terms of the specified independent variable.

2.2 Design Variables

In the design optimization of Helmholtz coils in this study, if large number of variables is selected, the problem will become complicated. The following quantities are chosen as Helmholtz coils design variables for optimization.

Number of turns per layer (x_1)

Number of coil layers in the winding (x_2)

Wire diameter (x_3), mm

Radius of coil winding (x_4), m

Coil excitation current (x_5), A

The problem can be stated in mathematical terms as follows:

$$X = [x_1, x_2, \dots x_5] = \begin{bmatrix} \text{Number of turns per layer} \\ \text{Number of layers} \\ \text{Wire diameter} \\ \text{Coil radius} \\ \text{Coil current} \end{bmatrix}^T \quad (5)$$

Where x_1, x_2, x_3, x_4, and x_5 are the set of independent design variables with their lower and upper bounds as x_{min} and x_{max}. The design variables are presented in Table 1.

Table 1: Helmholtz Coils Design Variables and Ranges

Variables	Range	Unit
Number of turns per layer	8 – 60	-
Number of layers	6 – 65	-
Wire diameter	0.135 – 1.5	mm
Coil radius	0.01 – 0.35	m
Coil current	5 – 250	mA

2.3 Constraints

g(x) is the set of constraints imposed on the design to make it feasible and practically acceptable, the constraints that have been used in this study are:

Total number of winding turns

Total magnetic field

The geometric constraints and operating limits are represented in Equation (6) and the geometry constraints and operating limits are shown in Table 2.

$$g(x) \leq 0 \;\Leftrightarrow \begin{Bmatrix} \text{Total winding turns} \\ \text{Total magnetic field} \end{Bmatrix} \quad (6)$$

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Table 2: Helmholtz Coils Design Constraints

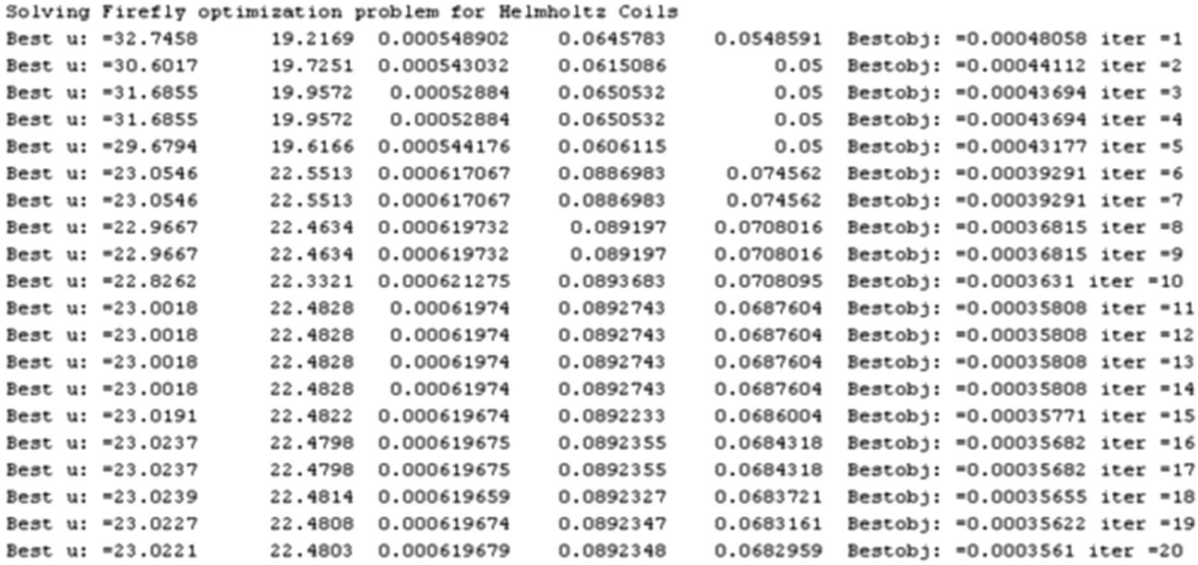
Constraints	Range	Unit
Total winding turns	≤ 1600	-
Magnetic field	≤ 750	µT

The objective function optimization problem is to optimize the magnetic field. In the computation of F(x) and g(x) as well as calculating the optimal performance of the Helmholtz coils, the optimization design problem of the Helmholtz coils is formulated by defining the magnetic field at the center of the Helmholtz coils as the objective function:

$$\text{Maximize } B(z) = \frac{\mu_0 . I_c . R^2}{2} . \left(\begin{array}{c} \left(\left(z + \frac{R}{2}\right)^2 + R^2\right)^{-\frac{3}{2}} \\ + \left(\left(z - \frac{R}{2}\right)^2 + R^2\right)^{-3/2} \end{array} \right) \quad (7)$$

3.0 Results and Discussion

To verify the effectiveness of the proposed FOA for optimizing the Helmholtz coils design problem, the optimization procedure starts with the design variables. In the design optimization problem, five independent variables are chosen, such as number of coil turns per layer, number of coil layers, wire size, coil radius, and the excitation current during the iteration. The modified FOA was written in Matlab environment and the results were obtained by running the developed program on a 1.50 GHz Intel® core™ Duo CPU Windows 7 Ultimate 32-bit personal computer. Equation (7) is used in the firefly optimization algorithm to calculate the optimum magnetic field inside the Helmholtz coils and to find the coils parameters. The algorithm predicts the total number of windings needed to produce a magnetic field of 356.1µT. The number of windings is a function of the radius of the raw coil form. The results obtained by the proposed FOA method are presented in Figure 2.



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Solving Firefly optimization problem for Helmholtz Coils
Best u: =32.7458       19.2169  0.000548902     0.0645783     0.0548591  Bestobj: =0.00048058 iter =1
Best u: =30.6017       19.7251  0.000543032     0.0615086          0.05  Bestobj: =0.00044112 iter =2
Best u: =31.6855       19.9572   0.00052884     0.0650532          0.05  Bestobj: =0.00043694 iter =3
Best u: =31.6855       19.9572   0.00052884     0.0650532          0.05  Bestobj: =0.00043694 iter =4
Best u: =29.6794       19.6166  0.000544176     0.0606115          0.05  Bestobj: =0.00043177 iter =5
Best u: =23.0546       22.5513  0.000617067     0.0886983      0.074562  Bestobj: =0.00039291 iter =6
Best u: =23.0546       22.5513  0.000617067     0.0886983      0.074562  Bestobj: =0.00039291 iter =7
Best u: =22.9667       22.4634  0.000619732      0.089197     0.0708016  Bestobj: =0.00036815 iter =8
Best u: =22.9667       22.4634  0.000619732      0.089197     0.0708016  Bestobj: =0.00036815 iter =9
Best u: =22.8262       22.3321  0.000621275     0.0893683     0.0708095  Bestobj: =0.0003631 iter =10
Best u: =23.0018       22.4828   0.00061974     0.0892743     0.0687604  Bestobj: =0.00035808 iter =11
Best u: =23.0018       22.4828   0.00061974     0.0892743     0.0687604  Bestobj: =0.00035808 iter =12
Best u: =23.0018       22.4828   0.00061974     0.0892743     0.0687604  Bestobj: =0.00035808 iter =13
Best u: =23.0018       22.4828   0.00061974     0.0892743     0.0687604  Bestobj: =0.00035808 iter =14
Best u: =23.0191       22.4822  0.000619674     0.0892233     0.0686004  Bestobj: =0.00035771 iter =15
Best u: =23.0237       22.4798  0.000619675     0.0892355     0.0684318  Bestobj: =0.00035682 iter =16
Best u: =23.0237       22.4798  0.000619675     0.0892355     0.0684318  Bestobj: =0.00035682 iter =17
Best u: =23.0239       22.4814  0.000619659     0.0892327     0.0683721  Bestobj: =0.00035655 iter =18
Best u: =23.0227       22.4808  0.000619674     0.0892347     0.0683161  Bestobj: =0.00035622 iter =19
Best u: =23.0221       22.4803  0.000619679     0.0892348     0.0682959  Bestobj: =0.0003561 iter =20
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Figure 2: Optimization Results obtained from MATLAM Program

As shown in Figure 2, magnetic field of 356.1µT will be generated with an excitation current of 68.30 mA by each of the Helmholtz coils when wound with 23 turns per layer and 22 layers of coil. As obtained from the modified FOA result, each coil had a diameter of 8.9 cm with 506 turns each of copper wire and copper wire size of 0.62 mm diameter. Table 3 shows the optimal design variables for the proposed Helmholtz coils design.

Table 3: FOA Results for the Helmholtz Coils Simulations.

	Input variables					Output variable
Helmholtz Coils	Coil turns per layer	Number of layers	Wire diameter (mm)	Coil radius (mm)	Coil current (mA)	Magnetic field (µT)
FOA Design	23	22	0.62	89.23	68.30	356.1

As shown in Table 3, the width of each coil is 14.26 mm while the height of each coil is 13.64 mm. Moreove, the mean radius of each coil is 96.05mm with inner radius of 89.23 mm and outer radius of 102.87 mm, respectively. The designed ampere-turn is Ni = 68.3 mA * 506, where number of layers is 22 and number of turns per layer is 23. In order to characterize the designed Helmholtz coils, these parameters were put in MatLab-program. Magnetic field plot arising from the contributions of the modified FOA designed coils is shown in Figure 3.

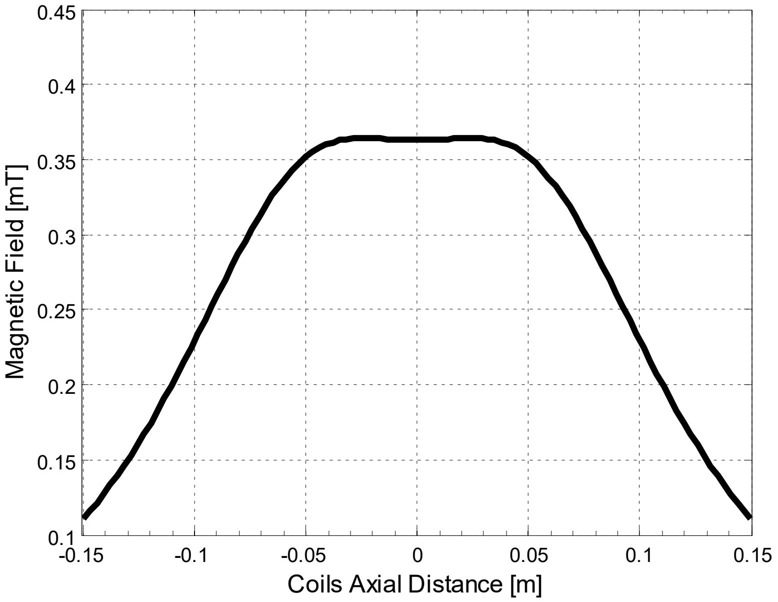

Figure 3: Magnetic Field as a function of Distance obtained from FOA Design.

From this plot, good agreement between the predicted and simulated magnetic fields can be found in the Helmholtz coils. It is observed that the total magnetic field at the center point of the Helmholtz coils is eventually the vector summation of the two coil winding pairs. The field distribution is homogenous, especially at the center of the coils where the axial distance is equivalent to the radius of the coil. Beyond this distance, the field uniformity tends to be deteriorated. This result indicates that one can increase the axial distance to improve the field uniformity by increasing the coil radius.

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Moreover, the magnetic field in the negative axis on the graph represents the contribution of the left coil while the magnetic field in the positive axis on the graph represents the contribution of the right coil. The magnetic field inside the Helmholtz coils is homogenous within 0.08 m axial distance. This is close to the 0.089 m coil radius predicted by firefly algorithm. Therefore, any deviation from the optimum coil configuration would cause the graph to be in different form.

4.0 Conclusion

The optimization algorithm and MatLab program have enabled the predictions of the Helmholtz coils design parameters and the visualization of the magnetic field coverage inside the chosen design. This is done by using Equation (7) to modify the firefly optimization algorithm and also using MatLab program to plot Equation (7) as a function of distance along the axial length of the Helmholtz coils. It is observed that there is 10% difference between the radius of the coil and the magnetic field coverage along the axial distance of the Helmholtz coils (Figure 3). This validates the Helmholtz coils principle; the separation distance between the Helmholtz coils equals the radius of each coil. This therefore shows the effectiveness of firefly optimization algorithm for Helmholtz coils design.

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