

Multi-Objective Optimization Algorithm Based Geometry Optimization of Calibration Coils for OPM Array

Changxu Zhu¹, Xu Zhang¹, Chunyu Qu¹, and Jianli Li¹, *Member, IEEE*

¹Ultra-Weak Magnetic Field Measurement Technology, Ministry of Education, School of Instrumentation and Optoelectronic Engineering, Beihang University, Beijing, 100191 China, zhang_xu@buaa.edu.cn

Calibration methods based on electromagnetic coils are of great significance for the application of optically pumped magnetometer (OPM) arrays, as accurate calibration ensures the reliability of magnetic source analysis. However, analyzing the influence of the coil structure on the calibration results is always a challenging issue. In this paper, we investigate the design of coil arrays that consider the coupling effect between the magnetic shield and coil for the spatial position calibration of OPM sensors in a magnetocardiography measurement system. The basic frame of the coil was designed based on the structure of the cylindrical magnetic shield barrel, and the key geometric parameters affecting the calibration accuracy are also determined. We employed a multi-objective grey wolf optimization (MOGWO) algorithm to refine the cost function associated with position uncertainty, yielding satisfactory results.

Index Terms—Calibration, Finite element method, Pareto optimization, Error analysis

I. INTRODUCTION

BIOLOGICAL magnetic field measurement is a promising noninvasive electrophysiological measurement method. Electrical activities and functional information of neurons or muscles are reconstructed using magnetic source analysis obtained through the OPM sensor array, offering valuable medical insights [1]. To ensure accurate biomagnetic source analysis and superimposition, the position of each magnetic sensor relative to the subject must be precisely determined [2]. The OPM array calibration methods based on electromagnetic coils directly measures the sensitive positions of magnetic sensors and is not constrained by the array structure, making it an important calibration technique. Nevertheless, the design of OPM array calibration coils often confronts the issue of coupling effects between the magnetic shield and the coils [3]. Furthermore, the impact of the coil structure on the calibration accuracy in the context of ferromagnetic boundary coupling is seldom addressed.

Consequently, this article focuses on optimizing OPM array calibration coils under ferromagnetic boundary coupling and taking into account contribution of each coil to the calibration result by means of finite element method (FEM) simulations. Unlike classical design methods, we employ a multi-objective grey wolf optimization algorithm (MOGWO) to minimize position uncertainty under proportional and fixed errors. In addition, an objective function for positioning accuracy is proposed.

II. CALIBRATION COIL ARRAY DESIGN

The proposed calibration coil array design and cylindrical coil plane development diagram is depicted in Fig. 1. The coil is modeled as a perfect conductor and is tightly attached to the inner wall of the magnetic shield barrel with a radius of 0.5 m. Theoretically, only three independent coils are required to estimate positions of OPM sensors. Despite that, to achieve acceptable calibration uncertainty, the coil count must be augmented, although the higher coil count associated with a

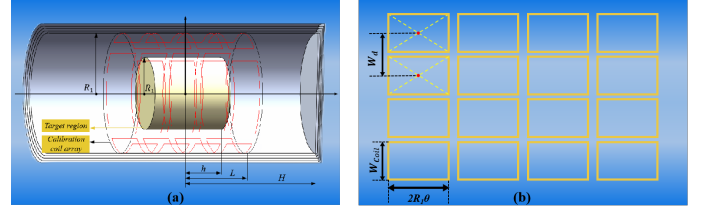


Fig. 1. (a) Magnetic shield and coil structure diagram and (b) cylindrical coil plane expansion diagram. The number of coils is set to 16 to obtain reasonable calibration uncertainty, and the dimensions are optimized using MOGWO algorithm.

increased fabrication and measurement demands [4]. In this study, considering the reliability and symmetry of the design, the saddle-shaped coil array is designed to obtain a group of 16 coils.

The spatial resolution of the calibration coilarray depends on the magnetic field gradient and magnetic field error [5]. Considering the actual error type in the calibration system of uniaxial OPM sensor, we model the magnetic field error as fixed error and proportional error.

$$\delta x_i = \frac{\delta B_i}{G_{xxi}}, \delta y_i = \frac{\delta B_i}{G_{xyi}}, \delta z_i = \frac{\delta B_i}{G_{xzi}}, \quad (1)$$

$$\delta B_i = \delta B_{Pi} + \delta B_{Ri} \quad (2)$$

$$\delta d_i = \sqrt{\delta x_i^2 + \delta y_i^2 + \delta z_i^2} \quad (3)$$

where δx_i , δy_i , δz_i represent the uncertainty of x, y, and z axis coordinates under the influence of error δB_i of the i-th coil, which consists of proportional error δB_{Pi} and random error δB_{Ri} . G_{xxi} , G_{xyi} , G_{xzi} are the gradients of the B_x of i-the coil in three directions. δd_i represents the position uncertainty generated by the i-th coil.

The proposed coil array design involves three key design parameters: the coil coverage angle θ , coil width W_{Coil} , and distance between coils W_d . In order to determine the optimal coil array structure, numerous parameter combinations are

TABLE I
GEOMETRIC PARAMETER LIMITS FOR OPTIMIZATIONS

Parameter	Lower Limit	Upper Limit	Original design
θ	40°	180°	85°
W_{Coil}	0.05 m	0.5 m	0.2 m
W_d	0 m	0.3 m	0.25 m

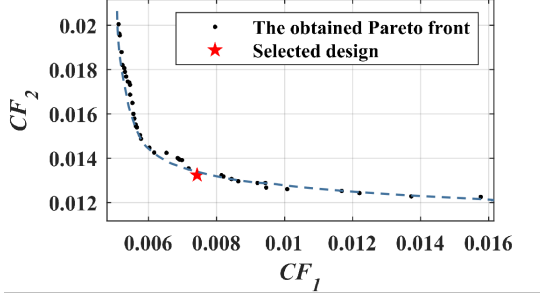


Fig. 2. The obtained Pareto front design and selected design of design objectives.

required to achieve the best calibration performance. Therefore, we use the evolutionary process to optimize the design parameters of the calibration coil array.

III. OPTIMIZATION OF CALIBRATION COIL ARRAY WITH MOGWO

The optimization of coils geometry parameters is carried out by employing a MOGWO algorithm in MATLAB Livelink, and simulations with COMSOL software are used for the electromagnetic solver part in this optimization procedure. The lower and upper limits, and the Original design of the geometric parameters are specified as in Table. I. The selected sampling point set Ω is uniformly distributed within the central target area of the coil array. The cost function is a crucial parameter for optimizing the calibration of the coil array using the multi-objective grey wolf algorithm [6]. To assess the calibration effect of the coil array on the uniaxial magnetometer, the cost functions used in this study are as follows:

$$CF_1 = \frac{\sum_{m=1}^M \delta d_R(s_m)}{M}, \text{ for } s_m \in \Omega \quad (4)$$

$$CF_2 = \frac{\sum_{m=1}^M \delta d_P(s_m)}{M}, \text{ for } s_m \in \Omega \quad (5)$$

where δd_R and δd_P are the weighted position uncertainties under the influence of random error and proportional error, respectively. s_m represents the m-th element in the target sampling point set Ω . During the calibration procedure, the gradient data serve as ancillary information to refine the alignment of the uniaxial magnetometers within the designated area. The δd_R and δd_P are defined as:

$$w_i = \frac{1}{1/G_{xxi} + 1/G_{xyi} + 1/G_{xzi}} \quad (6)$$

$$\delta d_P = \sqrt{\frac{\sum_{i=1}^{16} w_i^2 \cdot \delta d_{Pi}^2}{\left(\sum_{i=1}^{16} w_i\right)^2}}, \delta d_R = \sqrt{\frac{\sum_{i=1}^{16} w_i^2 \cdot \delta d_{Ri}^2}{\left(\sum_{i=1}^{16} w_i\right)^2}} \quad (7)$$

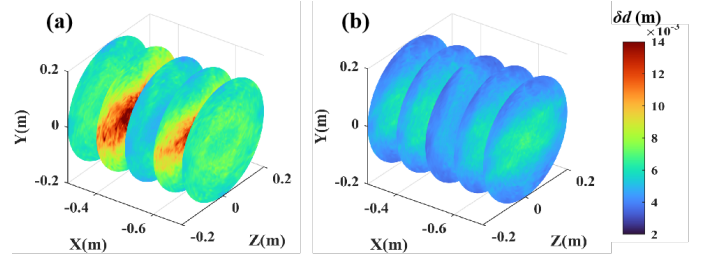


Fig. 3. The weighted position uncertainty of Original structure (a) and optimized structure (b) under the same magnetic field error with the same standard deviation. ($\delta B_P = 0.01 B_x$ and $\delta B_R = 20 pT$)

where w_i represents the weight of the i-the calibration coil at each position determined by the triaxial gradients of B_x . The larger the triaxial gradient of the i-th coil, the smaller the position uncertainty of the coil under the same error and the greater the weight.

The MOGWO population consists of 30 individuals, undergoing 30 iterations. The Pareto front design, along with the CF_1 and CF_2 for selected design ($\theta = 1.439$, $W_{Coil} = 0.255$, $W_d = 0.0914$) is shown in Fig. 2. Fig. 3 shows the distribution of weighted position uncertainty before and after optimization, considering the same errors. For visualization, the target area is divided into five layers. Under the influence of same magnetic field error, the selected design demonstrates a 34.18% reduction in mean weighted position uncertainty within the target area, from 0.0079 m to 0.0052 m, compared to the original design. These results indicate the effectiveness of the proposed cost function.

IV. CONCLUSION

In this paper, we investigate the optimization of the calibration coil with ferromagnetic boundary coupling to enhance its calibration accuracy under both proportional and random error. Future work can involve optimizing coil arrays with intricate structures to extend the range of the effective calibration space. Additionally, the calibration algorithm can be refined to achieve higher accuracy.

REFERENCES

- [1] O. Feys, P. Corvilain, A. Aeby, C. Sculier, N. Holmes, M. Brookes, S. Goldman, V. Wens, X. De Tiege, and F. Christiaens. On-scalp optically pumped magnetometers versus cryogenic magnetoencephalography for diagnostic evaluation of epilepsy in school-aged children. *Radiology*, 304(2):429–434, Aug 2022.
- [2] R. Zetter, J. Iivanainen, M. Stenroos, and L. Parkkonen. Requirements for coregistration accuracy in on-scalp meg. *Brain Topogr.*, 31(6):931–948, Nov 2018.
- [3] J. Iivanainen, A. Borna, R. Zetter, T. R. Carter, J. M. Stephen, J. McKay, L. Parkkonen, S. Taulu, and P. D. D. Schwindt. Calibration and localization of optically pumped magnetometers using electromagnetic coils. *Sensors*, 22(8), Apr 2022.
- [4] Y. Adachi, D. Oyama, M. Higuchi, and G. Uehara. A spherical coil array for the calibration of whole-head magnetoencephalograph systems. *IEEE Trans. Instrum. Meas.*, 72, 2023.
- [5] N. Gudino and S. Littin. Advancements in gradient system performance for clinical and research mri. *J. Magn. Reson. Imaging.*, 57(1):57–70, Jan 2023.
- [6] S. Mirjalili, S. Saremi, S. M. Mirjalili, and L. Coelho. Multi-objective grey wolf optimizer: A novel algorithm for multi-criterion optimization. *Expert Syst. Appl.*, 47:106–119, Apr 2016.