

Design of Self-Shielding Gradient Coils Based on a Modified Pigeon-inspired Optimization Algorithm

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This paper presents an optimization method based on the pigeon-inspired optimization (PIO) algorithm to determine the optimal dimensions of self-shielding gradient coils suitable for a magnetically shielded cylinder (MSC). The coil set comprises inner and outer layers, with the internal region configured to generate a gradient magnetic field while the external region is maintained at near-zero field strength by applying opposing currents. In the design of the coil using the target field method (TFM), the challenge of solving closed-form equations is transformed into a constrained nonlinear objective optimization problem. Consequently, a modified pigeon-inspired optimization algorithm is introduced to derive optimal parameters for coil size. This approach incorporates a collaborative and competitive mechanism between global and local populations, enabling the algorithm to effectively balance exploration and exploitation capabilities. As a result, it can swiftly identify global optimal solutions without converging to local optima. The final results demonstrate that the coil we designed can achieve a high linear gradient with a maximum spatial gradient magnetic field deviation below 2.36%, and it exhibits a significant self-shielding effect in the external region.

Index Terms—Magnetic shielding, Coils, Algorithm design and analysis, Structural parameter, Electromagnetic field theory.

I. INTRODUCTION

HIGH precision Magnetocardiogram (MCG) imaging technology [1] provides a new perspective for exploring the electrophysiological mechanisms of the heart, and the magnetically shielding cylinder (MSC) is a key device for MCG measurements. In practical applications, one side of the MSC must remain open, which leads to a significant gradient magnetic field in the MSC. Consequently, the design and research of gradient coils are necessary.

The coupling effect between the active coil and the magnetic shielding material may degrade the quality of the measured biological signals. Self-shielding [2] is an effective method to solve the coupling effect problem, with its main principle being the mutual cancellation of the far field through nested inner and outer coils, thus mitigating the influence of the external environment. In the process of designing self-shielding coils, the coil design problem is usually transformed into a constrained optimization problem, with intelligent algorithms used to find the optimal solution. Duan [3] proposed the pigeon-inspired optimization (PIO) algorithm in 2014.

In this paper, the TFM[4] is employed to design self-shielding gradient coils for the MSC, aiming to provide a low-noise, zero-magnetic environment for cardiac magnetic field measurement. In the coil optimization stage, an enhanced PIO algorithm is proposed by introducing a speed correction mechanism and parallel search strategy to enhance the algorithm's exploration capability. Finally, the convergence of the algorithm is analyzed and the final parameters of the coils are determined.

II. BRIEF EXPLANATION OF THE COIL DESIGN PROBLEM

The structure of self-shielding coils is depicted in Fig.1. The detailed process of designing the coil using the TFM can be found in [5], from which the current density expression of the coil in cylindrical coordinates was derived. In practical applications, the size of the coil must remain within the physical dimensions of the magnetic shielding cylinder. Based on these limitations, a target function was constructed as follows:

$$\begin{cases} \min F = \max f_1 + \max f_2 & s.t. r_{min} \leq a \leq b \leq r_{max} \\ f_1 = \frac{G_{in}(x, y, z) - G_0(0, 0, 0)}{G_0(0, 0, 0)} \\ f_2 = \frac{B_{out}(x, y, z) - B_{in}(0, 0, l_{target}/2)}{B_{in}(0, 0, l_{target}/2)} \end{cases} \quad (1)$$

where G and B represent the field and field gradient produced by the corresponding coil, respectively.

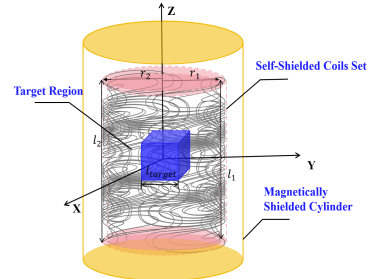


Fig. 1. Schematic diagram of self-shielding coils design based on the TFM.

TABLE I
TEST RESULTS

Testing function	Statistic function value	PSO	AW-PSO	PIO	Mod-PIO
Sphere	Minimum	0.027	0.0201	0.0262	0.0204
	Maximum	0.0535	0.0211	0.1490	0.0234
	Average	0.0412	0.0205	0.0740	0.0216
	Std.dev	0.0085	0.0003	0.0456	0.0010
Rosenbrock	Minimum	0.9417	0.8070	0.8072	0.8092
	Maximum	1.6052	0.9431	2.8898	0.8540
	Average	1.1459	0.8384	1.3755	0.8179
	Std.dev	0.2027	0.0538	0.7343	0.0131
Rastrigin	Minimum	4.7220	3.8665	3.8203	3.8473
	Maximum	7.2726	4.1407	7.2093	4.3716
	Average	5.9746	3.9538	5.3032	4.0468
	Std.dev	0.7985	0.1088	1.0589	0.1447

III. THE IMPROVEMENT OF THE PIGEON-INSPIRED OPTIMIZATION ALGORITHM

The important process of the Mod-PIO algorithm is given by following steps:

Step 4: Update the global pigeon population according to Eq.(2), and enable the speed correction mechanism to constrain the dispersion of update velocity values. Meanwhile, record the best solution X_1 and the corresponding fitness $best_1$.

$$\begin{cases} V_i^t = V_i^{t-1} \cdot e^{-R_1 \cdot t} + rand \cdot (X_1 - X_i^{t-1}) \\ X_{center}^{t-1} = \frac{\sum_{i=1}^{M_1} X_i^{t-1} \cdot F(X_i^{t-1})}{\sum_{i=1}^{M_1} F(X_i^{t-1})} \\ X_i^t = X_i^{t-1} + V_i^t + rand \cdot (X_{center}^{t-1} - X_i^{t-1}) \end{cases} \quad (2)$$

Step 5: Update the local population of pigeons according to Eq.(3), and also limit the updated velocity values. Record the best solution X_{1m} ($m = 1, 2, \dots, M$) and the corresponding fitness $best_{1m}$. Meanwhile, introduce a dynamic adjustment mechanism for the local population: 1) If a single pigeon in the local population is too close to others and X_{1m} has no significant update, replace the local population with the global best solution X_1 to reset it; 2). If the global best solution X_1 is updated, reset the pigeon with the worst fitness in the local population to make it closer to the new global best solution; 3). If X_{1m} is better than X_1 , replace X_{1m} with the pigeon with the worst fitness in the global population.

$$\begin{cases} V_i^t = V_i^{t-1} \cdot e^{-R_2 \cdot t} + rand \cdot (X_{1m} - X_i^{t-1}) \\ X_i^t = X_i^{t-1} + V_i^t + rand \cdot d \quad (m = 1, 2, \dots, M) \end{cases} \quad (3)$$

IV. OPTIMIZATION RESULTS

In this section, the results obtained from benchmark functions and from the coil design problem are exposed and discussed, as well as the respective parameter settings.

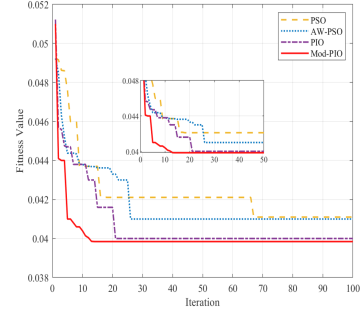


Fig. 2. Optimization of the Self-shielding Coils

A. Convergence Comparison

Optimization experiments were performed on three benchmark functions: Sphere, Griewank, and Rastrigin, to assess the convergence and effectiveness of the proposed Mod-PIO algorithm. The PIO, PSO [5] and its variant AW-PSO are also introduced here for comparison to make the analysis more universal and convincing. The result is shown in Table I.

B. Design Results

In the previous section, we verified the convergence and effectiveness of the Mod-PIO algorithm. In this section, based on the proposed optimization algorithm, we obtained optimal parameters for the self-shielding coils in the MSC. According to the final iterative results, $f_1 = 0.0236$, $f_2 = 0.0162$, $F = 0.0398$, the corresponding inner and outer coil radius are $r_1 = 0.2482$ and $r_2 = 0.2962$. Figure 2 shows the optimization iteration curve.

V. CONCLUSION

This paper presents an improved pigeon-inspired optimization algorithm designed to address the parameter design problem of self-shielding gradient coils applied in MSC. The proposed algorithm incorporates a speed correction mechanism and a competitive cooperative mechanism, building upon the original PIO algorithm to enhance performance and accelerate convergence rates. Furthermore, we validate the effectiveness of modified algorithm through comparative analyses with various intelligent algorithms. The final results demonstrate that our approach provides significant advantages in addressing multi-parameter coil design challenges.

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