A straightforward direct optimization method for designing biplanar gradient coils using artificial bee colony algorithm

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INTRODUCTION: Winding patterns of gradient coils are often designed using target-field (TF) methods. However, the TF methods need time-consuming parameter tuning and trial-and-error approach to obtain a desired performance. Moreover, the TF methods ignore the dimensions of winding wires and sometimes lead to unrealizable coils for construction. Here we proposed a simple and straightforward method for designing planar gradient coils with discrete windings, which does not require parameter tuning. In the proposed scheme, the coil geometric parameters were optimized by an artificial bee colony (ABC) algorithm [1]. The use of ABC greatly accelerates the design speed, compared with other discrete-wire based methods [2], and can also provide coil performances comparable with the TF method. The proposed method was used to design gradient coils for a vertical wide-bore superconducting MRI system (4.74 T), and the validity of the method was experimentally confirmed.

METHODS: The geometry of a transverse gradient (G_x) coil was expressed as a set of a Bezier curve and an arc with the ends connected with each other, and that of a longitudinal (G_z) coil was expressed as a set of concentric circles (Fig. 1). The procedure for optimizing the geometric parameters was formulated as a constraint optimization problem where the power efficiency was substituted into an objective function to be maximized and the other specifications were regarded as constraints. The optimization iteration was repeated until the number of the cycles reached to a predetermined value or until the best solution remained unchanged within predetermined successive iteration cycles.

The ABC algorithm was compared with the other multi-point search algorithms, genetic algorithm with a minimal generation gap model (GA/MGG) and particle swarm optimization (PSO), in terms of the computational time and the best coil performances. Two typical types of constraints (A and B) for G_x were considered (Table 1), and the power efficiency was chosen as a coil performance which should be maximized in the optimization process. Two tests were conducted using ABC, GA, and PSO. First, to evaluate the efficiency of the algorithms, the minimum number of iteration cycles for discovering a solution which requires the given constraints was measured for the constraints A and B. Second, to evaluate the best coil performance, the highest power efficiency obtained after a sufficiently large iteration cycles (10000 cycles) was measured for the constraint A. Each test was repeated 20 times and the measured values were averaged.

To compare with the TF method, the coils under the constraint C (suitable for an 89 mm wide bore magnet) were designed by the TF and ABC. The TF method used was the same as that proposed by Zhang et al [3]. The total number of basis functions, Q, varied from 4 to 6, and the penalty factor for the dissipated power, λ, varied from 2×10^{-6} to 3.3×10^{-5}. After the optimal current density was obtained, the winding pattern was determined by discretizing the current density using a stream function. In the discretization process, the number of coil turns was chosen as many as possible within a range where the adjacent coils were not overlapping with each other. The optimal winding patterns designed by the ABC were fabricated and used for validation experiments.

RESULTS AND DISCUSSION: Tables 2 and 3 show the optimization results by ABC, GA, and PSO under the constraints A and B. The minimum iteration cycles for discovering a suitable solution were the smallest for ABC; the iteration cycles for ABC were five times smaller than those for the other two algorithms. The optimal values after the sufficiently large number of iteration cycles were almost the same between ABC, GA, and PSO. These results indicate that ABC can provide suitable solutions with an accelerated computational speed. Figure 2 compares the coil performances designed under the constraint C between the ABC and TF. At a given nonlinearity, the ABC can provide a coil with the high efficiency, which is comparable with the TF. One of the designed coils (the nonlinearity = 10 %) was constructed (Fig. 3). Figure 4 shows the MR images of the lattice phantom, in which a regular lattice pattern was imaged with less distortion. The measured efficiency and nonlinearity were almost the same as the designed values. Figure 5 shows a cross section selected from a 3D image dataset of blueberry, in which fine structures were visualized. In conclusion, we proposed the simple and fast method using the ABC which can design planar gradient coils with the high performances.

REFERENCES: [1] D. Karaboga et al., Appl. Math. Comput. 2009;214:108-132. [2] B. J. Fisher et al., Magn. Reson. Imaging 997:15:369-376. [3] R. Zhang et al., Meas. Sci. Technol. 2011:22:125505.

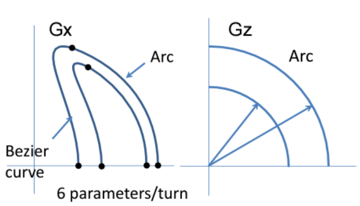

Fig. 1: Parameterized geometry for Gx and Gz coils

	Constraint A	Constraint B	Constraint C
Coil gap	76 mm	105 mm	25.7 mm
Coil radius	90 mm	160 mm	27.5 mm
Wire width	0.6 mm	1 mm	0.4 mm
Nonlinearity	< 5 %	< 8%	-
Efficiency	> 11.5 mT/m/A	> 2 mT/m/A	-
ROI width	60 mm	220 mm	15 mm
ROI height	50 mm	70 mm	10 mm

Table 1 Constraints used for comparison test.

	Iteration cycles ($\times 10^3$ cycles)					
	ABC		GA		PSO	
	Average	SD	Average	SD	Average	SD
Constraint A	106.2	54.8	518.4	63.7	636	477.6
Constraint B	67.1	20.6	504.4	68.6	3792	2221.5

Table 2 Result of iteration cycles required for discovering a solution.

	Current efficiency [mT/m/A]					
	ABC		GA		PSO	
	Average	SD	Average	SD	Average	SD
Constraint A	8.06	0.056	7.87	0.128	7.86	0.203

Table 3 Result of optimal values after sufficient iteration cycles for constraint A.

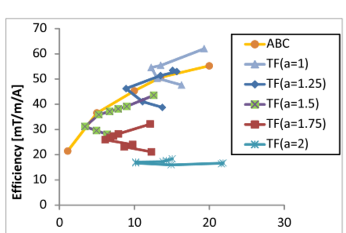

Fig. 2: Comparison in coil performances between ABC and TF under constraint C. In the TF method, the target ROI was set to be larger than the desired ROI at the ratio, *a*.

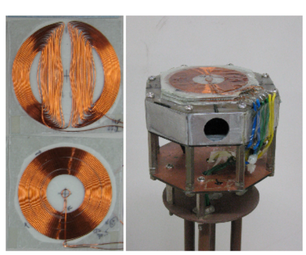

Fig. 3: Gradient coils designed by ABC under constraint C and a gradient probe with a solenoid RF coil.

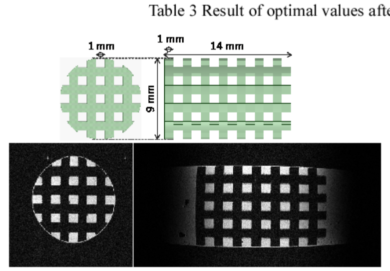

Fig. 4: Cross sections of a baby-oil phantom. FOV = 12.8mm x 12.8mm x 25.6mm, 3D spin echo, TR/TE = 200ms/8ms, matrix = 256 x 256 x 512.

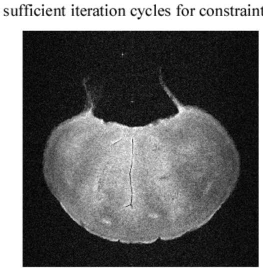

Fig. 5: Cross section of a blueberry. FOV = $(12.8\text{mm})^3$, 3D spin echo, TR/TE = 400ms/8ms, matrix = 512 x 512 x 32.