Supplementary Information (SI) for Lab on a Chip.

Supplemental material

Z-direction magnetic field strength between energized coil elements

Table S1. Z-direction magnetic field values at points $P_1(0, 0, 1)$ and $P_2(0, 0.25, 1)$ for two parallel circular coils with different plane distances, both having a radius of 1 mm and current values of 50 mA and −50 mA, respectively.

Distance (mm)	$B_{P_1}\,(T\times 10^{-7})$	$B_{P_2}\,(T\times 10^{-7})$
3	49.92	54.99
4	24.40	26.31
5	12.99	13.80
6	7.42	7.81
7	4.48	4.69

Calculation algorithm for current value of MCs coil element

The process of optimizing the size of microelements in MCs coils was implemented in MATLAB (The MathWorks, Inc., Natick, MA). Nonlinear least-squares fitting was performed to fit the set of currents required for the first 15 orders of SH fields by using the "lsqcurvefit" function. The genetic algorithm and simulated annealing (GASA) were performed to find the optimal size of the MCs, as shown in figure S1.

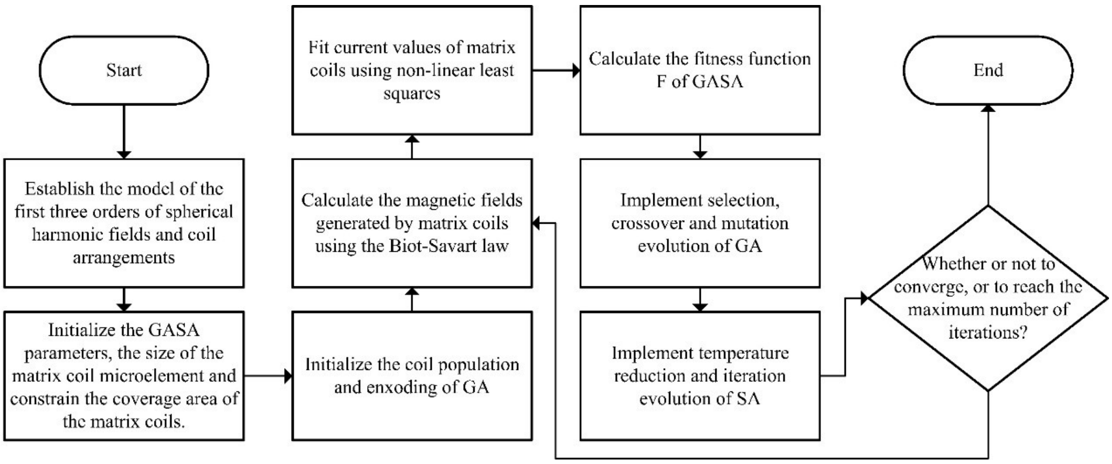

Fig. S1 Flowchart of the whole algorithm.

Throughout the process, the average of the standard deviations of the fitting degrees of 15 groups of spherical harmonic fields was used as the cost function, and the fitness function F was used as the discriminant criterion, namely.

$$F(n) = \frac{1}{|cost(n) - cost(n-1)|} \qquad (S1)$$

where n is the number of iterations, $cost(n)$ is the average of the standard deviations of the fitting degrees of 15 groups of spherical harmonic fields after the n^{th} iteration, and δ is the threshold value. If $|cost(n) - cost(n-1)| < \delta$, and this condition holds for a given number of iterations, the calculation is ended and the optimal coil size is returned

The cost function for optimization was defined as

$$cost(x) = \frac{1}{m}\sum_{i=1}^{m}\sqrt{\frac{1}{n-1}\sum_{j=1}^{p}(\Delta B_{zij}|_{\Delta V} - \Delta\bar{B}_{zi}|_{\Delta V})^2} \qquad (S2)$$

where x is the coil radius in the current iteration, m is 15, denoting the total number of target SH fields within the first three orders, ΔV is the target region, p is the total number of sampling points in the target region, $\Delta B_{zij}|_{\Delta V} = (\sum_{k=1}^{q} I_{ijk}B_{zijk}^{MCs} - B_{zij}^{tg})|_{\Delta V}$, $\Delta\bar{B}_{zi}|_{\Delta V} = \frac{1}{n}\sum_{j=1}^{n}(\sum_{k=1}^{q} I_{ijk}B_{zijk}^{MCs} - B_{zij}^{tg})|_{\Delta V}$, B_{zij}^{tg} is the z-direction magnetic field value at the j^{th} spatial point of the i^{th} target SH field, B_{zijk}^{MCs} is the base mapping of the k^{th} coil fitting the j^{th} spatial point of the i^{th} target SH field, q is 19 × 4, representing the numbers of the two pairs of double-plane circular coils in the model, and I_{ijk} is the current value of the k^{th} coil of the i^{th} target SH field calculated by the nonlinear least squares method.

Automatic shimming

How to improve magnetic field homogeneity has always been one of the important issues in NMR technology. With the emergence of active shimming methods and coils based on spherical harmonic compensation, experimenters can flexibly manually adjust the magnetic field homogeneity according to the experimental sample and experimental state.[S1] Due to the complexity of orthogonal design of shim coils and spatial magnetic field distribution, manual shimming adjustment requires manual and repeated adjustment of the current in each group of shim coils. The tedious operation and a large amount of experimental time consumption are not conducive to the smooth progress of experiments, especially in modern nuclear magnetic resonance experiments that often require the collection and processing of large quantities of experimental samples. Therefore, automatic shimming technology has emerged. At present, the main automatic shimming methods include search automatic shimming and gradient automatic smoothing. Although the search automatic shimming method is prone to getting stuck in local optima and needs a longer search time. However, searching for a homogeneous field always shows a trend of improving magnetic field homogeneity, which is beneficial for achieving homogeneous field in situations where the initial magnetic field is poor, such as during the initial installation, debugging, and probe replacement of instruments. On the other hand, the search automatic shimming method based on the improved Simplex algorithm greatly reduces these issues of local optimal solution and time consumption in the search automatic shimming. Gradient echo pulse sequences are used in gradient automatic shimming to measure and fit the spatial distribution of static magnetic field inhomogeneity and achieve fast and accurate automatic shimming. Gradient shimming is considered the most direct and effective automatic shimming method in nuclear magnetic resonance technology.[S2-S5] For achieving gradient shimming technology a good initial field and additional hardware, such as gradient coils and driving units, are required. Therefore, existing commercial nuclear magnetic resonance spectrometers are equipped with two types of automatic shimming techniques: search-based and gradient-based.

Automatic search was the earliest automatic shimming method.[S6] The basic idea is to let computer to replace humans in the process of manual homogenization. In this process, the current values of the shimming coils are adjusted, the shimming indices (including the value of deuterium lock level, FID area, etc.) are recorded, the shimming indices are compared, and optimization is carried out. This is a multivariate optimization problem, where the independent variable is a set of set current values of the shim coils, and the dependent variable is the corresponding shimming indices. The biggest difficulty of this problem lies in the inability to establish a suitable equation between the independent and dependent variables. The search algorithm proposes a possibility for finding the solution to the problem. All search algorithms are established based on initial conditions and expansion rules to find nodes that meet the target value. In terms of algorithm implementation, the way in which the search extension nodes are controlled is important. The common algorithms for automatic search in shimming are mainly divided into two types: one-dimensional linear search tuning algorithm for adjusting fields with a single shim coil, and multi-dimensional spatial search simplex algorithm based on combining fields with multiple shim coils.[S7]

In the search-based automatic shimming method, the step length, search path, and convergence conditions are important guarantees for the rationality of the iteration space range setting and the accuracy of the final result. The step length usually refers to the increment of current in the shim coil. The search path refers to the adjustment sequence of each harmonic coil. The convergence condition is the condition for terminating the search. The search step are generally set to the change in magnetic field homogeneity sensitivity (such as the value of deuterium lock level or FID area), while the convergence condition is generally set to the change in search step. This set of parameters is not fixed. The setting of initial conditions for searching is a complex and tedious task that must be manually set. This places high demands on the operational skills of NMR experimenters and their understanding of the principles of shimming.

The space occupied by the MCs boards, RF boards, and microfluidic chip in the microfluidic NMR probe designed in this paper makes it impossible to assemble commercial gradient coils. The gradient function based on the designed probe is still under research. At the same time, the distortion field caused by the susceptibility results in poor initial field homogeneity in the detection region of microfluidic chips. So we have adopted a search-based method for automatic shimming. By utilizing the adaptive simplex algorithm that we had previously researched,[S8] we combined automatic shimming with MCs systems, enabling the outer MCs coils to perform search-based automatic shimming. The convergence condition was based on FID area. Step length was variable with large steps for coarse adjustment and small steps for fine adjustment. Multiple search paths were used. The convergence condition was that the difference in FID area between two adjacent searches was less than the threshold.

The search-based automatic shimming process is as follows:

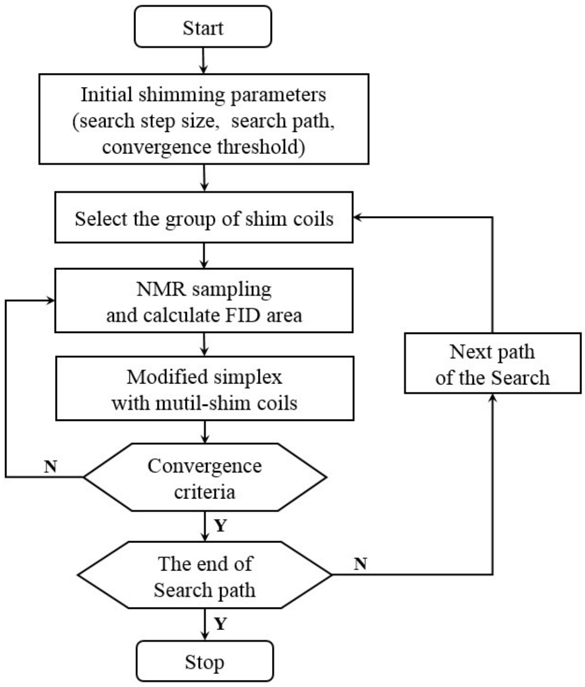

Fig. S2 Flowchart of the automatic shimming algorithm.

The search path set is as follows:

Table S2. The search paths used in the automatic shimming

Path Number	Path order	Iteration
1st	Z1\Z2\Z3\Z4	50
2nd	Z1\Z2\X1\Y1\ZX\ZY\X2-Y2\XY	50
3rd	X1\Y1\ZX\ZY\Z2X\Z2Y\Z3X\Z3Y	50
4th	X2-Y2\XY\Z(X2-Y2)\ZXY\Z2(X2-Y2)	50
5th	Z1\X3\Y3\ZX3\ZY3	50
6th	Z1\Z2\X1\Y1\ZX\ZY	50
7th	Z1\Z2\Z3\Z4	50
8th	Z1\Z2\X1\Y1\ZX\ZY\X2-Y2\XY	50
9th	ZX\ZY\Z2X\Z2Y\Z3X\Z3Y	50
10th	Z1\X2-Y2\XY\Z(X2-Y2)\ZXY\X3\Y3	50

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