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Simulation verification of dimensionality extension reconstruction based on field free line coding

Jiawei Hu[a,b] · Ning He[a,b] · Yuzhou Wang[a,b] · Yao Tong[a,b] · Dong Liang[a,b] · Yihan Wang[a,b,*] · Shouping Zhu[a,b,*]

[a]School of Life Science and Technology, Xidian University Engineering Research Center of Molecular and Neuro Imaging, Ministry of Education, Xi'an, Shaanxi 710126, China
[b]Xi'an Key Laboratory of Intelligent Sensing and Regulation of trans-Scale Life Information International Joint Research Center for Advanced Medical Imaging and Intelligent Diagnosis and Treatment, School of Life Science and Technology, Xidian University, Xi'an, Shaanxi 710126, China
*Corresponding author, email: spzhu@xidian.edu.cn;wangyihan@xidian.edu.cn

Abstract

Magnetic Particle Imaging (MPI) is an emerging imaging technology. Traditional scanning methods often use field free point (FFP) to traverse the entire imaging field of view (FOV), or use field free line (FFL) to reconstruct images through parallel beam projection. In this study, we propose a dimensionality extension reconstruction method based on FFL line coding, this method extends the FFP along the vertical direction of its motion to form the FFL, enabling the FFR to traverse a 3D field of view during 2D scanning. This scheme enables low-dimensional scanning with high-dimensional reconstruction, which can enhance sensitivity and MPI scanning speed. This study verified the feasibility of the method through simulation experiments.

I. Introduction

MPI is an emerging imaging modality that utilizes the nonlinear magnetization response of superparamagnetic iron-oxide nanoparticles (SPIONs) for imaging. Since its proposal in 2005, it has garnered widespread attention due to its significant advantages in sensitivity, imaging depth, resolution, and many other aspects. Free field point (FFP) scanning is a common spatial encoding method in MPI, which has the advantages of simple principle and easy implementation. However, FFP schemes are usually only used for tomographic imaging, and layer by layer scanning is required to achieve projection reconstruction or 3D reconstruction. When the scanning speed of the device is slow, layer by layer scanning will result in very long scanning times. And FFP is often designed to be as small as possible, which results in a relatively small number of responsive particles, making the particle signal more easily overwhelmed by noise and not conducive to improving sensitivity. To address this issue, we propose a dimensionality extension reconstruction method based on FFL line encoding. This method uses FFL instead of FFP, and the direction of FFL is parallel to its motion direction. Apply a bias field with varying magnetic field strength in the FFL direction, and then use the system matrix method to reconstruct the particle distribution on the FFL, thereby achieving low dimensional scanning and high-dimensional reconstruction.
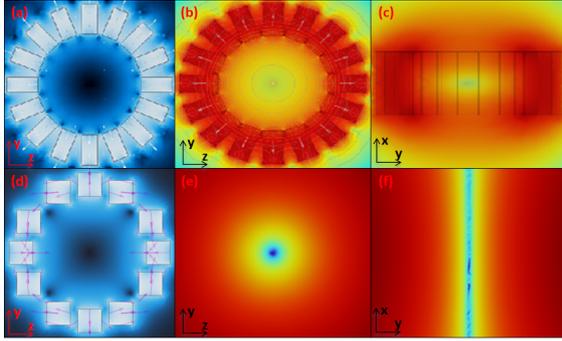
Figure 1: Two types of Halbach magnetic arrays. (a) - (c) is the magnetic array reported in [1] forms an FFP selection field within the FOV. (d) - (f) is the FFL selection field proposed in this study, with the FFL direction along the x-direction.
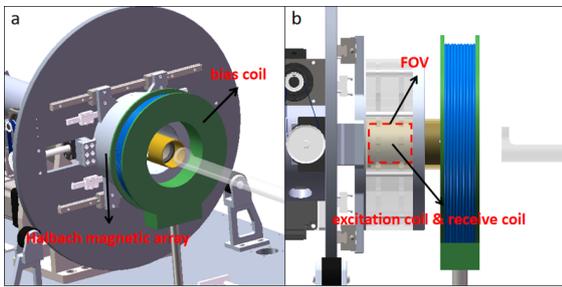

Figure 2: The scanning structure designed in this study is shown in the figure. The bias coil is placed on one side of the FOV to generate a bias field that varies with distance within the FOV. The color change from red to blue within the FOV indicates a gradual weakening of the bias field.

II. Methods and materials

II.I. Structural design

This study validated the scheme using the device structure proposed in [1]. The original device utilizes a Halbach magnetic array to generate an FFP selection field (Figure 1a-c). Then, the FFP is driven to traverse the YOZ plane by mechanically moving the permanent magnet array, achieving tomographic scanning. To perform 3D imaging, the sample needs to be moved along the X-direction and scanned layer by layer. This study replaces the original magnetic array with a permanent magnet array for generating FFL, which will form an FFL selection field perpendicular to YOZ (Figure 1d-f).

The structure designed in this study is shown in Figure 2. Driven by the mechanical structure, the FFL generated by the magnetic array is allowed to move in its vertical direction, thereby scanning the entire field of view. To obtain the particle concentration distribution on the FFL, we installed a bias coil on one side of the field of view (FOV) (Figure 1b).

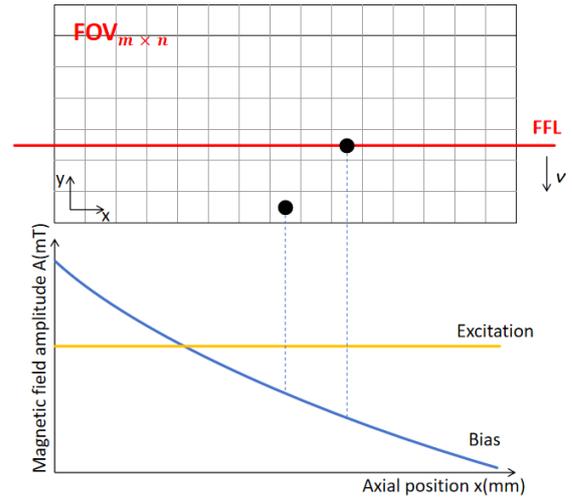The bias field is designed as an alternating field, and

Figure 3: Dimensional expansion and reconstruction diagram. The red line represents FFL, which is parallel to the x direction. During the scanning process, FFL moves along the y-axis, and only a one-dimensional projection on the y-axis can be obtained. By applying a bias magnetic field that varies along the x-direction, particles at different positions on the FFL will generate different magnetization response signals.

the axial magnetic field strength H can be expressed as:

$$H(r, t) = A_E cos(2\pi f_E t) + A_B(r)cos(2\pi f_B t). \quad (1)$$

Among them, A_E and A_B are the strengths of the excitation field and bias field, respectively, and f_E and f_B are the frequencies. The magnetic field frequency should satisfy $f_E \gg f_B$, the spectral composition of the particle signal under this condition should be $m f_E + n f_B$[2].

II.II. Reconstruction method

As shown in Figure 3, the area to be reconstructed *img* is a 2D plane. The direction of the excitation field and bias field is parallel to the x-direction. Within the field of view, the amplitude of the excitation field remains constant, while the amplitude of the bias field gradually decreases along the x-direction. Discretize the space into $m \times m$ pixels. FFL sweeps across the plane in the y-direction, and during this process, the voltage signal received by the receiving coil is u. Segment the signal by time, represented as:

$$u = \begin{bmatrix} u_1 & u_2 & u_3 & \cdots & u_m \end{bmatrix}, \quad (2)$$

where m is the number of rows in the discrete space. Under ideal conditions, particles outside of FFL do not generate response signals, and the signal u_i for each time period is entirely contributed by the particles in the i-th row when FFL passes through it. The discrete space *img* can be partitioned by rows:

$$img = \begin{bmatrix} c_1 & c_2 & c_3 & \cdots & c_m \end{bmatrix}^T. \quad (3)$$
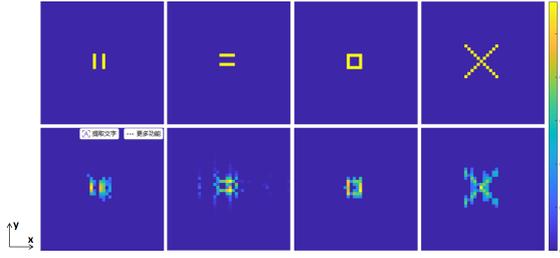
Figure 4: Presented the results of 2D simulation reconstruction. The original image is shown above, and the reconstruction result is shown below.

$c_i \in \mathbb{C}^{1\times n}$ represents the particle distribution on the i-th row. Perform Fourier transform on u_i to obtain $\tilde{u}_i$, and obtain the system matrix for each row:

$$\begin{bmatrix} S_1 c_1 & S_2 c_2 & \cdots & S_m c_m \end{bmatrix}^T = \begin{bmatrix} \tilde{u}_1 & \tilde{u}_2 & \cdots & \tilde{u}_3 \end{bmatrix}^T, \quad (4)$$

where $S_i \in \mathbb{C}^{k\times n}, \tilde{u}_i \in \mathbb{C}^{k\times 1}$. k is the number of selected frequency components. If the bias field amplitude on each column is the same for the jth row, then the particles on this row will have the same response. Therefore, it can be considered that $S_i = S$, and only one row of the system matrix needs to be measured to reconstruct the entire 2D image, significantly reducing the time required to measure the system matrix.

III. Results and discussion

The simulation experiment results are shown in Figure 3. The FFL gradient set for simulation is 2T/m, the bias magnetic field gradient is 0.6T/m, and the pixel size is set to 1mm. The simulation results indicate, both directions have a spatial resolution better than 2mm.

IV. Conclusion

In this study, we propose a dimensionality extension reconstruction method based on FFL line coding. Com-pared with the FFP scheme, this scheme does not require layer by layer acquisition of tomographic images, which will significantly improve scanning speed. In the process of obtaining the system matrix, this study assumes that the space perpendicular to the FFL direction has the same magnetic field environment, causing particles to produce the same magnetization response. However, for practical systems, it is difficult to obtain a sufficiently uniform magnetic field. Therefore, how to simplify the acquisition of system matrices using the same magnetic field environment as in simulation schemes is still a difficult problem that needs to be studied.

Acknowledgments

Author's statement

Conflict of interest: Authors state no conflict of interest.

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