

Proceedings Article

Theoretical Verification of Coil-Array-Based 3D Magnetic Particle Imaging Technology

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Abstract

To enable real-time three-dimensional (3D) magnetic particle imaging (MPI) based on the field-free line (FFL), we propose a novel 3D MPI strategy that employs tomographic encoding by utilizing the spatially specific sensitivities of a receive coil array. Based on the spatially specific sensitivity encoding (SSSE) algorithm of multi-channel receive coil arrays, 3D reconstruction can be achieved with only a 2D translational scan of the FFL. Compared with conventional parallel-beam tomography, this approach reduces the scanning dimensionality by one, offering a new paradigm for rapid, real-time 3D imaging. During reconstruction, the multi-channel projection data transform the 3D inverse problem into a series of 1D inverse problems, significantly reducing the computational complexity. Finally, the feasibility of sensitivity-based spatial encoding was validated in simulation experiments, demonstrating its broad application prospects and innovative value for 3D MPI.

I. Introduction

Field-Free Line (FFL) Magnetic Particle Imaging (MPI) scanners have attracted considerable attention for their high sensitivity[1]. However, the conventional parallel-beam tomography mode compromises the temporal resolution of three-dimensional (3D) imaging.

To achieve real-time 3D MPI based on an FFL, we propose a novel method that employs tomographic encoding utilizing the spatial specificity of the sensitivities of an array of receive coils. Multiple receive coils are arranged along the FFL long axis, and the spatial specificity of each coil's sensitivity encodes positions along the FFL. With this encoding strategy, the FFL requires only 2D translation to complete 3D reconstruction, reducing the

scan dimensionality by one relative to conventional rotational parallel beam scanning and thereby significantly improving 3D temporal resolution.

II. Sensitivity-based spatial FFL encoding

II.I. Architecture of the SSSE MPI system

The system architecture of the SSSE MPI is illustrated in Figure 1(a), with the FFL oriented along the Y-axis. Helmholtz coil pairs are used in the X- and Z-axes to generate drive fields in their respective axis, driving the FFL

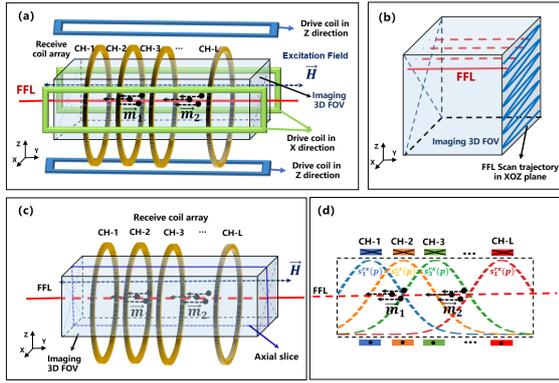


Figure 1: Structural diagram of SSSE MPI system. (a) Architecture of the SSSE MPI system, \vec{m}_1 and \vec{m}_2 denote the magnetization of the magnetic particles at different locations. (b) Scanning trajectory of FFL. (c) Configuration of the multi-channel receive coil array relative to the 3D imaging FOV. (d) 1D sensitivity distribution along the Y-axis for the multi-channel receive coil array.

to perform translational scanning perpendicular to the XOZ plane. The scanning trajectory of the FFL is shown in Figure 1(b). In this configuration, high-resolution imaging in the X- and Z-axes is achieved through the spatial encoding capability of the gradient magnetic fields. To accomplish high-resolution imaging in the Y-axis, a multi-channel receive coil array is arranged along this axis. The spatial distribution of magnetic nanoparticle concentration in the Y-axis is solved by leveraging the spatially specific sensitivity of the multi-channel receive coils along the Y-axis. The structural relationship between the multi-channel receives coil array, the FFL, and the 3D imaging FOV is depicted in Figure 1(c). An axial cross-section is extracted from Figure 1(c), and the one-dimensional spatial sensitivity distribution of the multi-channel receive coils along the Y-axis within this cross-section is plotted in Figure 1(d). The SSSE imaging system enables comprehensive coverage of the entire 3D field of view (FOV) with only a 2D translation of the FFL along the X- and Z-axes. 3D imaging is achieved through the combined use of gradient encoding and spatially specific sensitivity encoding. This characteristic of obtaining 3D imaging from 2D scanning provides a novel approach for real-time volumetric imaging.

II.II. Physical Model

In an MPI tomographic-encoding system with an array of L receive coils, the physical model of the induced voltage $u_{sp}^{rx}(t)$ is, the physical model of the l -th receive coil's induced voltage as shown,

$$u_{l,sp}^{rx}(t) = - \int_{\Omega} \mu_0 s_l^{rx}(p) \frac{\partial \mathbf{M}(p, t)}{\partial t} d^3 p, \quad (1)$$

here, $s_l^{rx}(p)$ is the sensitivity of the l -th receive coil array, $\mathbf{M}(p, t)$ is the magnetized component of the magnetic particle in the FOV, $\mathbf{M}(p, t) = c(p)\mathbf{m}(p, t)$, $c(p)$ is the magnetic particle concentration distribution.

The X-space reconstructed image for the l -th receive coil is expressed as,

$$IMG_l = c_s(p(x, z)) \star K(p(x, z))|_{p(x, z)=p_{FFL}(t)}, \quad (2)$$

where, IMG_l denotes the X-space projection reconstruction image of receive coil l in the XOZ plane. The term $c_s(p)$ denotes the 3D sensitivity distribution of the magnetic particle concentration, $c_s(p) = s_l^{rx}(p)c(p)$. The term $K(p(x, z))$ denotes the point spread kernel function in the XOZ plane perpendicular to the FFL. The term $c_s(p)$ and $K(p(x, z))$ can be expressed as,

$$c_s(p) = \begin{bmatrix} s_1^{rx} c(x, y_1, z) \\ s_l^{rx} c(x, y_2, z) \\ \vdots \\ s_l^{rx} c(x, y_N, z) \end{bmatrix}, \quad K(p(x, z)) = \begin{bmatrix} K(x, y_1, z) \\ K(x, y_2, z) \\ \vdots \\ K(x, y_N, z) \end{bmatrix}. \quad (3)$$

In multi-channel FFL projection X-space imaging, the 3D magnetic particle distribution is projected onto the X-space images of multiple channels. If the X-space image of the l -th channel shows a signal at pixel $P_{l,1,1}$, this indicates the presence of particles along the FFL passing through point $P_{l,1,1}$. To determine the particle distribution along that FFL, a system of linear equations based on the multi-channel sensitivities is constructed as follows,

$$\begin{aligned} P_{1,1,1} &= [s_1^{rx} c(y_1) + s_1^{rx} c(y_2) + \dots + s_1^{rx} c(y_N)] K(p(x_1, z_1)) \\ P_{2,1,1} &= [s_2^{rx} c(y_1) + s_2^{rx} c(y_2) + \dots + s_2^{rx} c(y_N)] K(p(x_1, z_1)) \\ &\vdots \\ P_{L,1,1} &= [s_L^{rx} c(y_1) + s_L^{rx} c(y_2) + \dots + s_L^{rx} c(y_N)] K(p(x_1, z_1)) \end{aligned} \quad (4)$$

where, $c(y)$ denote the concentration distribution of magnetic nanoparticles along the FFL passing through point $P_{1,1}$, which can be obtained as shown,

$$c(y) = s^{rx}(y)^{-1} P_{1,1} / K(p(x_1, z_1)). \quad (5)$$

Thus, multi-channel FFL projection X-space imaging can guide the reconstruction of the magnetic particle concentration distribution along the FFL. This approach transforms the complex 3D matrix inversion problem into a series of 1D problems, reducing computational complexity.

III. Results

The feasibility of sensitivity-based FFL encoding was evaluated through simulations. In the simulation, the following parameters were configured: a magnetic field gradient of 2 T/m along the X-axis and -2 T/m along the Z-axis; a 3D imaging field of view (FOV) of 40 mm × 44 mm × 40

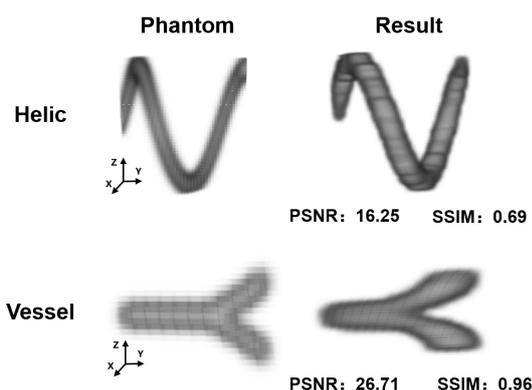


Figure 2: Reconstruction and Quantitative Evaluation of a 3D Phantom.

mm; an excitation frequency of 25 kHz, and an excitation magnetic field amplitude of 5 mT. Magnetic nanoparticles with a diameter of 50 nm were used. A 7-channel receive coil array was modeled, with each coil element having a length of 4 mm and an inter-coil spacing of 3 mm. The spatial selectivity of the receive coils is characterized by the measured sensitivity profile, with the full width at half maximum (FWHM) of the single-coil sensitivity profile along the Y-axis measured as 15 mm. Our reconstruction approach integrated 2D spatial projections derived from the X-space method with 1D encoding provided by multi-channel coil sensitivity profiles. The results of this 3D reconstruction were then quantitatively analyzed, as shown in Figure 2.

IV. Conclusion

In conclusion, we propose a novel SSSE-based 3D MPI strategy that reduces the scanning dimensionality to a 2D

FFL translation and transforms the 3D reconstruction into a series of 1D inversions. This framework significantly lowers the computational burden and provides a feasible path toward real-time 3D MPI, as preliminarily validated by simulations. Future work will involve constructing an experimental MPI system based on this theoretical model to validate the method's feasibility and performance in practice, with assessment focusing on key imaging metrics such as resolution, sensitivity, and temporal dynamics.

Acknowledgments

This work was supported by the National Key Research and Development Program of China under Grant No. 2022YFB3203803, the National Natural Science Foundation of China under Grant Nos. 62027901, 62471372, 62071362.

Author's statement

Conflict of interest: Authors state no conflict of interest.

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