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Design and Simulation of a Multi-Receiver Coil Array–Based Magnetic Particle Imaging System without Selection Field Generation

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Abstract

Conventional magnetic particle imaging (MPI) relies on high-gradient selection fields to create field-free point (FFP) or field-free line (FFL) for spatial encoding; however, these fields require high power and limit scalability. We present a field free region-less (FFR-less), fully stationary MPI configuration that achieves 3-D spatial encoding without mechanical motion. The system integrates a single excitation field with a multi-receiver coil array, providing coverage of a $100 \times 100 \times 50$ mm^3 (extendable) field of view. Simulation results confirm nanoparticle localization without selection fields or motion, demonstrating a compact, power-efficient, and scalable path toward human-scale MPI.

I. Introduction

Magnetic particle imaging (MPI) visualizes the distribution of superparamagnetic iron oxide nanoparticles (SPIONs) through their nonlinear magnetization response under oscillating magnetic fields [1]. Several MPI geometries have been developed, including closed-bore, open-sided, and single-sided configurations [2-4], along with various reconstruction approaches [5], with increasing focus on and research is now progressing toward human-scale MPI systems [6].

Conventional MPI relies on strong magnetic field gradients to define field-free regions (FFP or FFL) for spatial encoding [5]. Although effective at small scale, such designs are power-intensive and mechanically complex, limiting scalability to clinical applications. In addition, high magnetic field amplitudes and frequencies are limited by peripheral nerve stimulation (PNS) and specific absorption rate (SAR) constraints [7]. To overcome these challenges, a breakthrough alternative is required to advance MPI toward human-scale applications. Recently, several studies have explored gradient-free or FFR-less concepts [8], [9], [10], however, these approaches still rely on mechanical motion, provide partial (1D/2D) spatial encoding, or restricted field of view (FOV), complicating reconstruction and scaling. In this work, we present a multi-receiver coil array–based MPI configuration that achieves spatial encoding using a single cylindrical excitation coil. The inherent decay of the excitation field amplitude with depth combined with amplitude modulation and a gradiometric pancake receiver array enables 3D localization based on multi-channel magnetic nanoparticles (MNPs) signal profiles effectively removing the need for a selection field or mechanical motion. The proposed system was modeled and simulated to validate the feasibility and performance.

II. Methods and materials

The proposed system consists of a single cylindrical excitation coil generating an oscillating magnetic field along

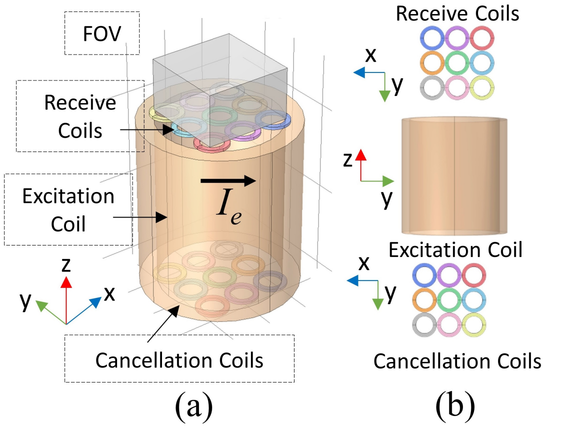

Figure 1: Schematic of the proposed multi-receiver coil array–based MPI system showing excitation, receive and cancellation coils with the defined FOV.

Table 1: Design parameters of the proposed multi-receive coil-based MPI system.

Parameter /coil	Receive coil	Cancellation coil	Excitation coil
Inner Radius	13 mm	13 mm	70 mm
Outer Radius	19 mm	19 mm	90 mm
Height	2 mm	2 mm	150 mm
Turns	50	50	120
Layers	1	1	3
Resistance (Average)	3.2 Ω	3.19 Ω	1.96 Ω

the z-axis and an array of planar receiver coils arranged in the horizontal plane. Each receiver coil is paired with a cancellation coil to form a differential gradiometer that minimizes feed-through interference and ambient noise, a topology successfully validated in our prior hardware prototypes [11]. The overall configuration is shown in Figure 1. The receiver array covers a 100 × 100 × 50 mm^3 FOV. The excitation coil operates at 25 kHz with a 20 Hz amplitude modulation, and key system parameters are summarized in Table 1.

Magnetic field distributions and receiver sensitivity profiles were simulated using COMSOL Multiphysics (COMSOL, AB, Stockholm, Sweden) using AC/DC Module with steady-state and frequency-domain studies. The simulated data were exported to MATLAB (MathWorks, Inc., Natick, MA, USA) for signal generation and spatial encoding. SPION magnetization was modeled using the Langevin function, with parameters consistent with Synomag-D nanoparticles (micromod Partikeltechnologie GmbH, Germany; PEG 25,000–OME, 50 nm; c(Fe) = 30 mg/mL). Spatial encoding in the x–y plane was achieved by combining multi-channel receive signals into a system matrix, reconstructed using a regularized Kaczmarz algorithm. Z-axis encoding was realized through excitation-field decay and amplitude modulation, generating depth-dependent harmonic signatures. Practical effects such as mutual coupling and coil misalignment will be addressed via time-multiplexed readout and calibration-based system matrix measurement. High-moment, fast-relaxing MNPs with rich harmonic spectra, with optimized size distribution can further improve SNR and spatial encoding accuracy [12].

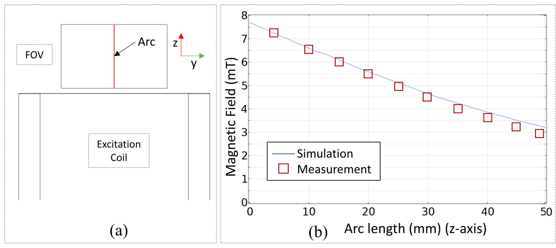

Figure 2: (a) Arc length along the z axis within the FOV; (b) simulated (blue line) and measured (red boxes) magnetic field magnitude along the arc length.

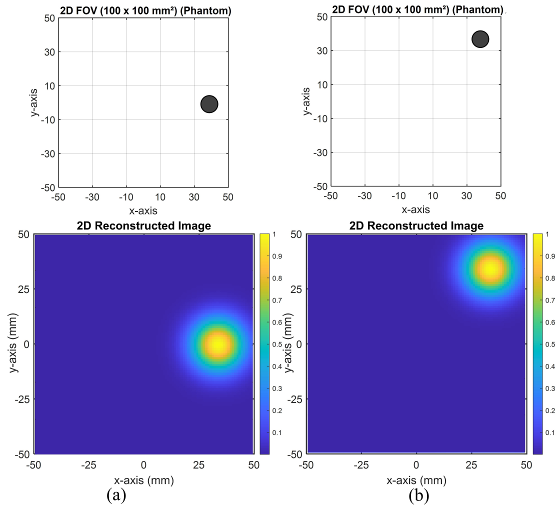

Figure 3: Simulated 2D phantoms and normalized reconstructed images in a 100 × 100 mm^2 FOV: (a) MNPs sample at mid-right and (b) MNPs sample at upper-right positions.

III. Results

The reconstruction algorithm was evaluated by localize MNPs at various positions within the FOV. The 2D spatial encoding results for the x–y plane are shown in Figure 3. The excitation magnetic field naturally decays with depth as illustrated in Figure 2, was combined with amplitude modulation to generate distinct harmonic responses in the received signals.

For varying z-axis positions, depth-dependent harmonic spectra were generated using the 1st–5th harmon-

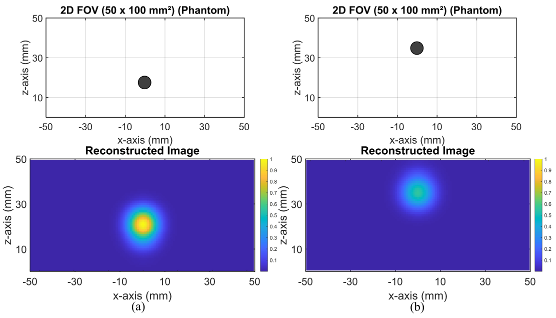

Figure 4: Simulated phantoms and reconstructed images in a 50 × 100 mm^2 FOV, varying z-axis position: MNPs sample at (a) x = 0 mm, z = 18 mm and (b) x = 0 mm, z = 35 mm.

ics during calibration and reconstruction. Reconstructed images of two phantoms at different depths are shown in Figure 4, demonstrating volumetric imaging capability.

The results confirm that receiver sensitivity patterns across the 3×3 coil array, enabling precise x–y spatial encoding, while the amplitude-modulated excitation field provides harmonic-based z-axis encoding.

Compared with conventional gradient-based FFR MPI, proposed configuration achieves fully stationary 3D spatial encoding without selection fields or mechanical motion, significantly simplifying the hardware architecture while maintaining localization accuracy.

IV. Conclusion

A multi-receiver coil array–based MPI configuration without selection field was designed and evaluated through simulations. By combining receiver-array sensitivity with amplitude-modulated excitation, the proposed approach enables fully stationary 3D localization of MNPs without FFRs or mechanical motion. The results validate the feasibility of this FFR-free approach, indicating a compact, energy-efficient, and scalable path toward human-scale MPI. Future work will involve prototype development and experimental verification.

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Author's statement

Authors state no conflict of interest.

References

[1] B. Gleich, J. W.- Nature, and undefined 2005, "Tomographic imaging using the nonlinear response of magnetic particles," *Nature*, doi: 10.1038/nature03808.

[2] T. M. Buzug et al., "Magnetic Particle Imaging: Introduction to imaging and hardware realization," *Z Med Phys*, vol. 22, no. 4, pp. 323–334, Dec. 2012, doi: 10.1016/j.zemedi.2012.07.004.

[3] T. -A. Le, M. Umar Tahir, T. -L. Cao and J. Yoon, "Development of an Open-Sided Magnetic Particle Imaging System With Amplitude Modulation-Based Reconstruction," *IEEE Transactions on Instrumentation and Measurement*, vol. 74, pp. 1-12, 2025, Art no. 4509712, doi: 10.1109/TIM.2025.3568946.

[4] T. -L. Cao et al., "Development of a Rabbit-Scale Amplitude-Modulated Single-Sided MPI With Flattened FFL Trajectory-Based Reconstruction," in *IEEE Transactions on Instrumentation and Measurement*, vol. 74, pp. 1-11, 2025, Art no. 4020011, doi: 10.1109/TIM.2025.3628415.

[5] L. Zhang et al., "Current reconstruction approaches of magnetic particle imaging: A review," *J Magn Magn Mater*, vol. 594, p. 171894, Mar. 2024, doi: 10.1016/J.JMMM.2024.171894.

[6] Cao, T.L., Oh, S., Le, T.A., Bui, M.P., Tahir, M.U., Ahmad, H.A. and Yoon, J., 2024. Design of a magnetic particle imaging integrated with magnetic hyperthermia by aiming at pediatric cancer treatment. *International Journal on Magnetic Particle Imaging IJMPI*, 10(1 Suppl 1). doi: 10.18416/IJMPI.2024.2403039

[7] E. U. Saritas, P. W. Goodwill, G. Z. Zhang, and S. M. Conolly, "Magnetostimulation limits in magnetic particle imaging.," *IEEE Trans Med Imaging*, vol. 32, no. 9, pp. 1600–1610, Apr. 2013, doi: 10.1109/TMI.2013.2260764.

[8] Q. Wang et al., "Single-Sided Magnetic Particle Imaging Device with Offset Field Based Spatial Encoding," *IEEE Trans Med Imaging*, vol. 44, no. 4, pp. 1878–1889, 2025, doi: 10.1109/TMI.2024.3522979.

[9] C. Kim, J. Nan, K. T. Nguyen, J. O. Park, E. Choi, and J. Kim, "Non-FFP-Based Magnetic Particle Imaging (NFMPI) with an Open-Type RF Coil System: A Feasibility Study," *Sensors 2025*, Vol. 25, Page 665, vol. 25, no. 3, p. 665, Jan. 2025, doi: 10.3390/S25030665.

[10] B. Zhang, H. Zhang, P. Gao, H. Hui, Y. An, and J. Tian, "Magnetic Field Strength Encoded Handheld Magnetic Particle Imaging System with Multiwaveform Excitation," *IEEE Trans Instrum Meas*, vol. 73, 2024, doi: 10.1109/TIM.2024.3450917.

[11] M. U. Tahir, T.-A. Le, T.-L. Cao, J. Yoon, "Development of Pancake-type Gradiometer Receive Coil for Amplitude Modulated Open-sided Magnetic Particle Imaging", *IEEE International Magnetics Conference (INTERMAG)*, Sendai, Japan, May 2023, pp. 1-2, doi: 10.5281/zenodo.18098896.

[12] Harvell-Smith, S. and Thanh, N.T.K., 2022. Magnetic particle imaging: tracer development and the biomedical applications of a radiation-free, sensitive, and quantitative imaging modality. *Nanoscale*, 14(10), pp.3658-3697.