Infinite Science
Publishing

Proceedings Article

Advances in Frequency-Mixing MPI: Block-ADMM Multi-Contrast Reconstruction for Drug-Release Thermometry and Monitoring

T. Viereck[a,*] · K. Luenne[a] · M. Schilling[a]

[a] Institut für Elektrische Messtechnik und Grundlagen der Elektrotechnik (EMG), TU Braunschweig, Braunschweig, Germany
*Corresponding author, email: t.viereck@tu-braunschweig.de

Abstract

Magnetic particle imaging (MPI) provides quantitative maps of magnetic nanoparticle concentration and is well suited for monitoring magnetically induced hyperthermia and drug release. Building on the frequency-mixing, narrowband MPI platform previously presented at IWMPI 2024, we now focus on a reconstruction framework based on a block Alternating Direction Method of Multipliers (block-ADMM) operator formulation for efficient multi-contrast image recovery. The system employs dual-frequency excitation around 280 kHz and < 1 kHz, allowing simultaneous heating and imaging with excellent spectral separation and sensitivity. The proposed algorithm jointly inverts multiple spectral components centered at $2 \cdot f_{HF} \pm N \cdot f_{LF}$ that share a common nanoparticle distribution while exploiting their complementary spatial responses. This operator-based formulation enables near real-time reconstruction with improved resolution and noise robustness. First experimental results demonstrate temperature-dependent contrast formation, establishing a foundation for potentially quantitative MPI thermometry and feedback-controlled drug release.

I. Introduction and motivation

Magnetic particle imaging (MPI) directly measures the nonlinear magnetization of superparamagnetic nanoparticles, providing quantitative maps of tracer concentration. Its ability to selectively image only the magnetic tracer makes it particularly attractive for functional and therapeutic applications such as magnetically induced drug release. In these applications, magnetic nanoparticles serve simultaneously as heating agents and imaging probes. Achieving localized heating of the nanoparticles – without affecting the surrounding tissue – requires a system capable of simultaneous heating, imaging, and temperature quantification. To address this need, we employ a frequency-mixing, narrowband MPI system that combines magnetic particle heating (MPH) with image-based thermometry. While the underlying hardware was presented previously at IWMPI, this work focuses on the reconstruction framework and its first experimental validation. Using a block-ADMM operator formulation, we demonstrate initial multi-contrast reconstructions that jointly exploit multiple spectral components for improved spatial resolution, noise robustness, and temperature-sensitive contrast.
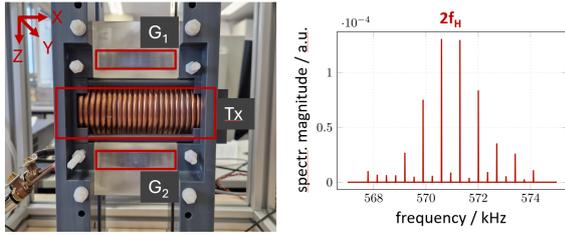
Figure 1: Left: Shared transmit coil for heating and imaging constructed from hollow copper tubing with NdFeB gradient generator. Right: Receive spectrum (linear scale) near $2 \cdot f_{HF}$ with distinct intermodulation frequencies.
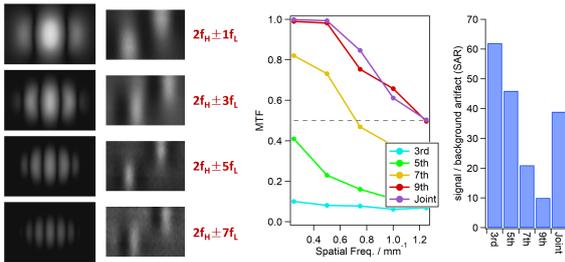

Figure 2: Left: Point spread function (PSF) and raw images of a 2-dot phantom at 3f-9f, with visibly increased noise at 9f. Right: Modulation transfer function (MTF) and signal-to-artifact ratio (SAR) for individual 3f-9f versus joint reconstruction. Joint reconstruction achieves 9f-level resolution with fewer artifacts.

II. Hardware concept

The hybrid MPI–hyperthermia system employs a dual-frequency excitation scheme sharing a single transmit coil. A high-frequency (≈ 280 kHz) drive provides both imaging excitation and magnetic heating, while a low-frequency (< 1 kHz) component enables field-free-point (FFP) displacement and scan modulation. The excitation paths are combined through passive filters and coupled to a resonant coil system for efficient operation. A pair of NdFeB permanent magnets generate gradients of about 2 T/m in-plane and 4 T/m axially. The receive chain uses a high-Q resonant circuit tuned to the second harmonic (≈ 560 kHz), achieving roughly 45 dB passive amplification and sub-nanovolt noise performance. This configuration provides high sensitivity and clean spectral separation between heating and imaging bands, forming the basis of the frequency-mixing, narrowband MPI approach used here.

III. Reconstruction with Block–ADMM Operator

To reconstruct the multi-contrast MPI data, we employ a block Alternating Direction Method of Multipliers (block-ADMM) framework that jointly processes several spec-

tral components centered at $2 \cdot f_{HF} \pm N \cdot f_{LF}$. Each component provides a different point-spread-function, and their combined inversion yields a more accurate and noise-robust estimate of the underlying nanoparticle distribution. The reconstruction is formulated as a regularized least-squares problem

$$\min_x \sum_c \lambda_c \|A_c x - b_c\|_2^2 + \|D x\|_{1,w}$$

where A_c represents the forward operator for the c-th spectral band, b_c is the corresponding complex measurement, and D is a finite-difference operator imposing total-variation (TV) regularization. In the block-ADMM scheme, all contrasts are updated within a coupled optimization cycle. The x-update solves the joint normal equation

$$\left(\sum_c \lambda_c A_c^* A_c + \rho D^T D \right) x = \sum_c \lambda_c A_c^* b_c + \rho D^T \left(z^k - u^k \right)$$

while the z- and u-updates apply soft-thresholding and dual accumulation, respectively. Because the operators A_c and D are convolutional, the x-update can be computed efficiently in the Fourier domain as element-wise multiplication and division, avoiding large matrix inversions. This enables near real-time reconstruction even for multi-contrast datasets. The block structure allows the algorithm to exploit correlations between frequency channels: high-SNR components stabilize the inversion of weaker ones, effectively fusing spatial and spectral information. This joint reconstruction improves spatial resolution, suppresses noise, and preserves temperature-dependent spectral contrast that would otherwise be lost in single-component reconstructions.

IV. Initial results

Narrowband 2D data were acquired using the frequency-mixing MPI scanner, recording the full complex spectrum around $2 \cdot f_{HF} \pm N \cdot f_{LF}$ at each FFP position. The multi-contrast datasets were jointly reconstructed using the block-ADMM operator framework, yielding sharper images and higher noise robustness than single-component reconstructions. Amplitude and phase variations across spectral components correlated with local temperature changes, confirming the system's sensitivity to relaxation-based effects. In heating experiments, temperature peaks coincided with the FFP and decayed rapidly with distance, validating localized magnetic particle heating. These results represent the first experimental demonstration of multi-contrast block-ADMM reconstruction in a frequency-mixing MPI system, enabling the foundation for quantitative thermometry and drug-release monitoring.

Acknowledgments

Author's statement

Conflict of interest: Authors state no conflict of interest.

References

[1] K. J. Janssen et al., *Quantitative temperature visualization with single harmonic-based magnetic particle imaging.* J. Magn. Magn. Mater. 563, 2022, pp. 169915 (DOI: 10.1016/j.jmmm.2022.169915).

[2] S. Boyd et al., *Distributed Optimization and Statistical Learning via the Alternating Directions Method of Multipliers.* Found. Trends ML 3(1), 2011, pp. 1-122 (DOI: 10.1561/2200000016).