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# Multi-Color MPI via Field-Free Line Projections: A Linear Mixed Inverse Approach

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## Abstract

Multi-color magnetic particle imaging (MPI) has been extensively studied for vascular intervention and tumor imaging, primarily via system matrix or relaxation-based methods. Field-free line (FFL) projection imaging avoids extensive calibration of system matrices; however, in multi-color disentanglement problems, it suffers from a lack of prior knowledge of the spectral response. We model this challenge as a linear mixed inverse problem and solve it by adapting a benchmark network from the blind source separation domain. This approach achieves effective separation of particle types on a vessel-aneurysm phantom, demonstrating promising applications.

## I. Introduction

Magnetic Particle Imaging (MPI) is a novel non-invasive modality for biomedical imaging, providing high-resolution, radiation-free visualization of superparamagnetic iron oxide nanoparticles (SPION). Multi-color MPI extends this by distinguishing particle types based on spectral signatures like frequency spectrum or relaxation times, enabling multiplexed tracking for applications in vascular imaging and tumor imaging [1].

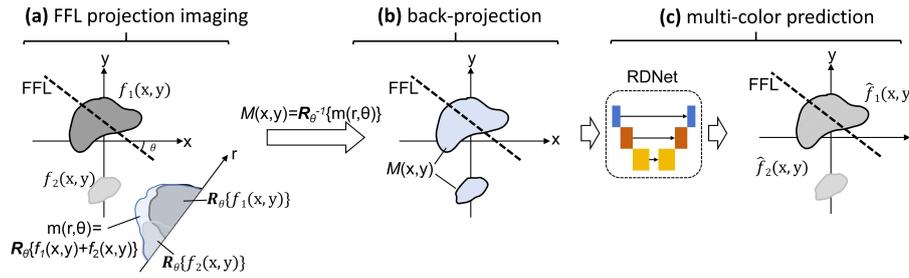
While field-free point systems allow signal localization at each scanning point, they face inherent trade-offs between sensitivity and spatial resolution. Field-free line (FFL) configurations may mitigate this dilemma, and recent years have seen multiple efforts developing human-scale imaging systems based on FFL, including human brain size designs aimed at achieving potentially higher sensitivity in projection-based tomography [2].

However, FFL projection-based multi-color imaging struggles: projections superimpose signals along the line area, nullifying relaxation-based separation [3], while

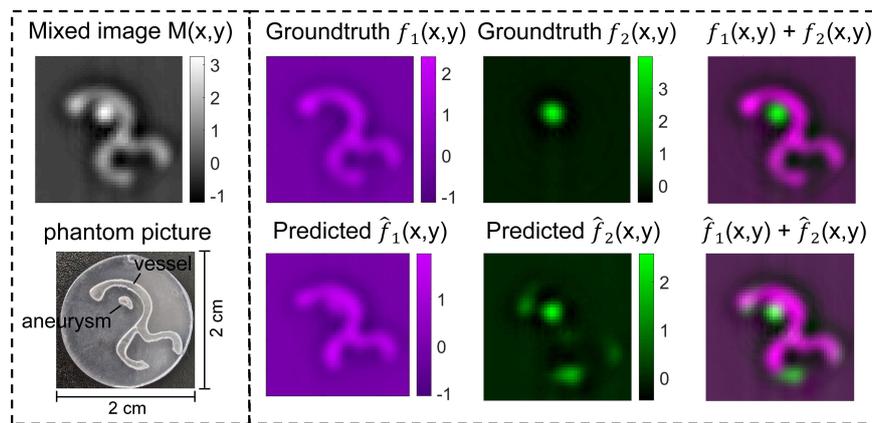
system matrix-based methods require an extensive and time-consuming calibration process for all kinds of SPIONs [4]. Here, we introduce a deep learning framework for blind source separation, inputting mixed images and outputting tracer-wise spatial distributions. The core of our approach is to leverage the trained network itself as a prior to solve the ill-posed linear mixed inverse (LMI) problem.

## II. Methods and materials

In FFL configurations, translational and rotational scanning of the line-shaped field-free region maps the SPION distribution in the  $(x, y)$  domain to the projection domain  $r$ . As illustrated in Figure 1, two types of SPION distributions  $f_1(x, y)$  and  $f_2(x, y)$  are present within the field of view. The projection operation  $\mathbf{R}_\theta\{\cdot\}$  separately maps them to  $\mathbf{R}_\theta\{f_1(x, y)\}$  and  $\mathbf{R}_\theta\{f_2(x, y)\}$ . However, the observed signal is their superposition, denoted as  $m(r, \theta)$ . Subsequent back-projection via  $\mathbf{R}_\theta^{-1}\{\cdot\}$  recon-



**Figure 1:** The FFL projections based multi-color imaging with two types of SPIONs. (a) FFL projection process; (b) back-projection process to reconstructed the mixed images; (c) prediction process to perform multi-color imaging.



**Figure 2:** Multi-color imaging results based on FFL projections obtained by solving LMI problems.

structs the mixed image  $M(x, y)$ .

The core task of multi-color imaging is to disentangle the contributions of each particle type from  $M(x, y)$ . Assuming mixed image is the linear superposition of their distributions; consequently, the multi-color imaging problem in the image domain reduces to a linear mixed inverse problem:

$$M(x, y) = f_1(x, y) + f_2(x, y) \quad (1)$$

LMI problems in image processing encompass scenarios such as reflection removal with the core objective of performing blind source separation or source separation on linearly superimposed components from mixed signals. In recent years, deep learning methods have been extensively applied to solving such LMI problems.

In this paper, we adapt the benchmark network RDNet [5] for single-image reflection removal to address the challenge in FFL projections-based multi-color MPI:

$$\text{RDNet}(M(x, y)) = \hat{f}_1(x, y) + \hat{f}_2(x, y) \quad (2)$$

Where  $\hat{f}_1(x, y)$  and  $\hat{f}_2(x, y)$  are the predicted distributions, as shown in Figure 1.

Finally, we fabricated a vessel&aneurysm phantom, injecting *Perimag* into the vessel and *Synomag* into the

aneurysm, and imaged it using our self-developed FFL-MPI scanner [6]. Furthermore, separate imaging of the *Perimag* in the vessel and *Synomag* in the aneurysm served as ground truth.

### III. Results and discussion

In Figure 2, compared to ground truth, the RDNet successfully reconstructs the primary particle distributions, including the vessel shape and aneurysm location. However, portions of vessel terminals are erroneously mapped to the aneurysm region. Given our straightforward adaptation of RDNet, these artifacts highlight that this model is not fully optimized for multi-color MPI. Specialized models for multi-color MPI are needed to further improve reconstruction accuracy.

### IV. Conclusion

In this paper, we formulate FFL projections-based multi-color MPI as a LMI problem and employ a typical network to perform multi-color imaging on an aneurysm phantom. The results disentangle the spatial concentration

distributions of the two particle types, but with residual local artifacts that require further improvement.

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## Author's statement

Conflict of interest: Authors state no conflict of interest. Xueying Liu and Guanghui Li contribute equally to this work.

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