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# Time Domain System Matrix (TD-SM) for Isotropic Resolution and Artifact Removal image reconstruction in X-space MPI

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**Abstract**

Magnetic Particle Imaging (MPI) is an emerging medical imaging modality based on the non-linear response of superparamagnetic iron oxide nanoparticles (SPIONs), and imaging the concentration of the SPIONs. At present, MPI reconstruction mainly includes x-space and system matrix methods. The x-space method has an extremely fast reconstruction speed and the final reconstructed image can be seen as the result of convolution of particle distribution with point spread function (PSF), but it causes anisotropic resolution and artifacts due to the effect of anisotropic PSF. In this work, we propose a hybrid approach that combines the x-space and model-based system matrix methods to remove the PSF blur and reconstruct the isotropic resolution and artifact removal MPI images. We first build the system matrix in the time domain transformed by the ideal MPI scan model in the time domain. Then, we convert the x-space reconstruction process into a matrix operation, and subsequently combine several matrices into a system matrix (forward model). The input of this forward model is particle distribution and the output is the x-space reconstructed image, which is affected by the PSF blurring. The PSF blur removal is then converted to an inverse problem solving, which we implement using the Kaczmarz method to obtain isotropic resolution and artifact removal images. The results of simulation and phantom experiments demonstrate that our method could achieve the best isotropic resolution and image quality comparing with the standard x-space method and other PSF removal methods.

## I. Introduction

Magnetic particle imaging (MPI) is a novel molecular imaging modality based on the non-linear response of superparamagnetic iron oxide nanoparticles (SPIONs) [1]. By measuring the magnetization response, one can use the reconstruction methods to image the concentration distribution of SPIONs. MPI reconstruction aims at transforming the measured voltage signal into SPIONs distributions, the reconstruction methods of MPI are mainly divided into two categories, x-space and system matrix methods.

There are two major strengths of the x-space method: fast reconstruction and low memory requirements. The x-space method requires two steps to reconstruct the image from the voltage signal in the time domain, velocity compensation and gridding the normalized signal onto the FFP trajectory [2]. However, the x-space reconstructed images show that the distribution of SPIONs is blurred by an anisotropic resolution point spread func-

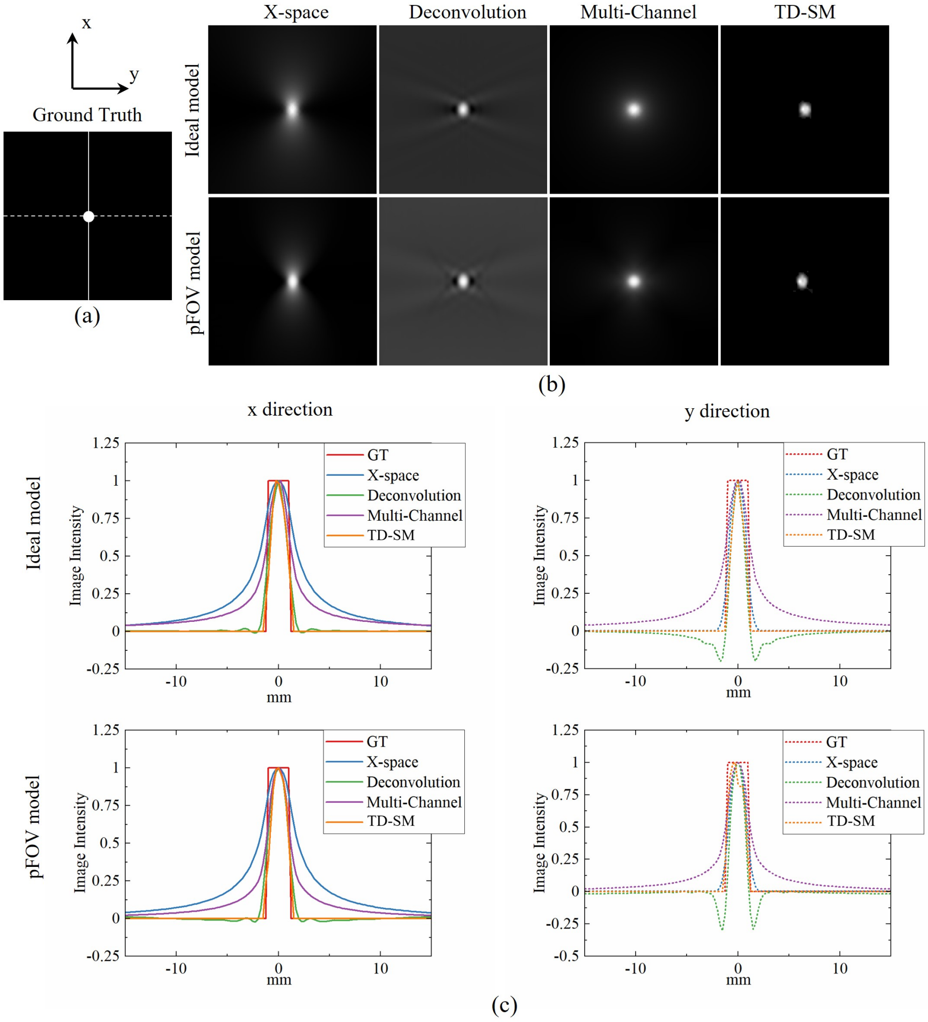


**Figure 1:** Simulation results of different reconstruction methods for a circle phantom with a diameter of 2mm with an ideal model and a pFOV scanning model. (a) A 2mm diameter circle phantom in a 3x3 $cm^2$ FOV. Solid line: 1D cross-section along the x direction. Dashed line: 1D cross-section along the y direction. (b) shows the reconstruction results using the standard x-space method, Wiener deconvolution method, multi-channel acquisition method, and TD-SM method of two different simulation models, respectively. (c) the 1D cross-section normalized image intensity of all the reconstructed images, different color lines mean different reconstruction methods.

tion (PSF), which leads to the x-space reconstructed images exhibiting anisotropic resolution and consequent artifacts [3]. There are some solutions to improve the x-space image quality, image deconvolution by PSF kernel was proposed at first, later, a multi-channel acquisition method was proposed for achieving isotropic resolution x-space MPI [4], which requires scanning twice in two mutually perpendicular directions and collecting the colinear signals from both scans, reconstructing them using standard x-space methods, and finally merging the two anisotropic images into one isotropic image. In [5], the method of using the system matrix is first proposed to improve the accuracy of the compensation speed in the x-space reconstruction process, thereby improving the image quality.

## II. Material and methods

We consider that MPI is, after recovery of the fundamental frequency signal, a linearity and shift-invariant(LSI) process [6], and that x-space reconstruction of particle images involves convolution of particle distribution and the PSF kernel [3]. Within the Cartesian trajectory applied, the magnetic field slowly changes perpendicularly to the excitation, which makes the PSF anisotropic [7].

If we construct a forward model to describe the relationship between the particle distribution and the image reconstructed using x-space, which also involves convolution of the PSF kernel, then we can use an inverse problem solver to obtain an image without relying on the PSF.

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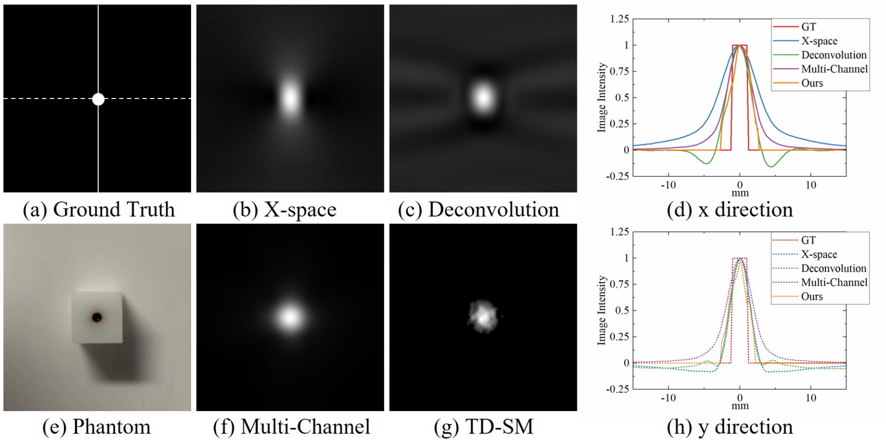


**Figure 2:** Experiment results of different reconstruction methods for a circle phantom with a diameter of 2mm.

The forward model should describe the scanning operation and subsequent x-space reconstruction. The linear relationship between the particle concentration and the x-space reconstructed raw image could be represented by simplifying the MPI imaging equation to the following form:

$$I = Tc, \tag{1}$$

here, $T$ represents the forward model covering the entire imaging process from the deblurred image to the PSF-blurred image, $I$ denotes the x-space reconstructed image, $c$ denotes the particle concentration, $T \in \mathscr{R}^{m\times n}$, $I \in \mathscr{R}^{m}$, we choose to keep the number of pixels of the output image the same as the raw image reconstructed by x-space, then $T$ will become a square matrix, then its least squares solution exists and is unique:

$$\arg\min_{c\geq 0} \|Tc - I\|_2^2, \tag{2}$$

the inverse problem will be a fitness problem, which means that the convergence of the iterative results can be achieved without adding the regularization constraint term, and the iteration results converged quickly.

The reconstruction method we proposed could be divided into three steps: A. Using the traditional x-space method to reconstruct the raw image from the voltage signal. B. According to the MPI scanning and x-space reconstruction procession, construct the forward model and transfer it to a matrix: TD-SM, to describe the PSF blur in the raw images. C. Reconstructing the image from the x-space reconstructed image in the last step based on the TD-SM by the Kaczmarz method.

We consider two different simulation models for MPI imaging. The first model is a scan of the entire FOV without fundamental frequency signal loss, represents the ideal case. The second model is constructed considering the filtering of the excitation frequency signal and pFOV scan, and the DC recovery method in [6] was used. The imaging experiments are performed on 2D scanning mode of the MPI scanner (MOMENTUM, Magnetic Insight Inc., Alameda, CA, USA).

The circular phantom is used to verify the ability of improving the anisotropic resolution and PSF artifacts of the x-space reconstructed images, with a FOV size of 30 mm x 30 mm and a circular magnetic nanoparticle mimic of 2 mm diameter placed in the center of the FOV, where the particle concentration is chosen to be 1 mg/ml and the particle diameter is 30 nm, which is similar to the Synomag-D, the particle we choose in the mimic experiment, remained consistent. The “Default” and “Isotropic” mode of the MPI device are used to get the x-space and multi-channel images. The Wiener deconvolution and TD-SM method are based on the output images of the “default” mode, the 2D PSF kernel, and the TD-SM forward model are both obtained by the ideal simulation.

We imaged physical phantoms similar to the simulated ones: a circle phantom with 2 mm diameter, filled with superparamagnetic iron oxide nanoparticles of 30 nm diameter (Sinomag-D, Micromod, Rostock, Germany) at a concentration of 1 mg/ml. The volume of the particle is about 12.57$\mu$l.

## III. Results and discussion

Fig. 1 shows the simulation results of the TD-SM and the previous x-space reconstructed methods regarding circular phantom under the ideal situation and pFOV scanning situation. It can be seen that all x-space improvement methods seem to weaken the resolution anisotropy caused by PSF blurring, but the images reconstructed by Wiener deconvolution introduce new negative artifacts along the excitation direction on both sides of the phantom. The images reconstructed by the multichannel acquisition method have a reduced resolution in the x-direction, but the original smaller resolution along the y-direction is increased, with the result that an isotropic resolution is achieved while causing a slight blurring blur.

In Fig. 1b, it can be seen that the x-space reconstructed image of the simulated model with pFOV scanning has a slight difference compared with that of the ideal model, and we believe that the DC recovery algorithm used may not have fully recovered the fundamental frequency component of the received signal. The circular particle distribution reconstructed by the Wiener deconvolution method still presents an elliptical shape (Fig. 1b, Fig.2c), while this cannot be solved by adding non-negative constraints or iterative deconvolution methods, which also means that deconvolution methods still cannot fully achieve resolution isotropic reconstruction. The quality of the image reconstructed by the remaining methods will be degraded compared to the image of the ideal model, but the results still show that our proposed method has the best reconstruction.

Fig. 2 shows the experimental results of a circular phantom with a diameter of 2 mm. The experimental results show the presence of some noise, while the resolution of the actual device experiment is lower than that of the simulated model, which can also be seen in the one-dimensional cross section. The Wiener deconvolution method eliminates the blurring of the PSF, but induces new artifacts around the particles. Both the multichannel method and our proposed method reconstruct the results well, reconstructing the affine shape as a circle, but the resolution of the multichannel method is slightly worse compared to our method. For our method, the resolution is the best in both directions, although the smoothed area is less, which may be caused by the noise of the MPI device.

## IV. Conclusions

In this work, we have proposed a reconstruction method achieving isotropic resolution and artifact removal of standard x-space reconstructed images. Simulation and experiment results demonstrate that the method could remove the PSF blur and not induce new artifacts. The quantitative results also prove that the hybrid method improved image quality. Besides, by this method, the anisotropic resolution of the Cartesian trajectory has been improved, the normal direction resolution could improve to the same as the one in the tangential direction.

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## Author's statement

Authors state no conflict of interest.

## References

[1] B. Gleich and J. Weizenecker, "Tomographic imaging using the non-linear response of magnetic particles," Nature, vol. 435, no. 7046, pp. 1214-7, Jun 30 2005.

[2] P. W. Goodwill and S. M. Conolly, "The X-space formulation of the magnetic particle imaging process: 1-D signal, resolution, bandwidth, SNR, SAR, and magnetostimulation," IEEE Trans Med Imaging, vol. 29, no. 11, pp. 1851-9, Nov 2010.

[3] P. W. Goodwill and S. M. Conolly, "Multidimensional x-space magnetic particle imaging," IEEE Trans Med Imaging, vol. 30, no. 9, pp. 1581-90, Sep 2011.

[4] K. Lu, P. Goodwill, B. Zheng, and S. Conolly, "Multi-Channel Acquisition for Isotropic Resolution in Magnetic Particle Imaging," IEEE Trans Med Imaging, vol. 37, no. 9, pp. 1989-1998, Sep 2018.

[5] A. Tateo et al., "Hybrid x-space: a new approach for MPI reconstruction," Physics in Medicine & Biology, vol. 61, no. 11, p. 4061, 2016/05/10 2016.

[6] K. Lu, P. W. Goodwill, E. U. Saritas, B. Zheng, and S. M. Conolly, "Linearity and shift invariance for quantitative magnetic particle imaging," IEEE Trans Med Imaging, vol. 32, no. 9, pp. 1565-75, Sep 2013.

[7] T. Knopp et al., "Trajectory analysis for magnetic particle imaging," Phys Med Biol, vol. 54, no. 2, pp. 385-97, Jan 21 2009.