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Super-resolving reconstruction technique for MPI

A. Güngör[1,2,*] · C. B. Top[1]

[1]Aselsan Research Center, Ankara, Turkey
[2]Department of Electrical and Electronics Engineering, Bilkent University, Ankara, Turkey
[*]Corresponding author, email: alpergungor@aselsan.com.tr

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Abstract

System matrix reconstruction of Magnetic Particle Imaging (MPI) require a time-consuming calibration process. The total number of pixels of the desired image has a direct effect on the calibration time. Although there are various techniques that can shorten the calibration process such as compressive sensing or coded calibration scenes, the increase in total number of pixels still require higher number of samples. In this study, we propose a simple super-resolution technique for MPI images without additional calibration time requirement. Using simulations on a field free line MPI scanner system with low drive field amplitude, we show that one can achieve higher resolution images by simply applying super-resolution techniques on the rows of the system matrix. We demonstrate that simple linear models can help resolve high-resolution structures when combined with non-linear reconstruction procedures.

I Introduction

Magnetic Particle Imaging is an imaging modality that allows visualization of magnetic nanoparticles (MNP) with high frame rate and resolution. However, image reconstruction requires either a time-consuming calibration procedure or a signal model that may fail to include non-ideal system response [1, 2]. For the calibration-based approach, a somewhat time-consuming calibration process is required for imaging [1, 4, 5]. The total number of pixels in the image is chosen by the operator, which has a direct effect on the calibration time. Although different techniques such as compressed sensing [4] or coded calibration scenes [5] may be used for speeding up this process, higher resolution imaging still requires more number of calibration samples, which in turn results in higher calibration time. Hence, complementary techniques that further reduces calibration time is still desired.

In this study, we propose a method for super-resolving the reconstructed image. However, instead of directly resolving the image itself, we propose a method for super-resolving the system matrix. We show that this approach improves the resolution of the image when combined with a non-linear reconstruction procedure, over conventional interpolation of the image . Moreover, the proposed method may be combined with the previously mentioned compressed sensing based methods for further reduction in the calibration process.

II Methods

The forward model of the MPI scanner can be modelled by system of linear equations:

$$\mathbf{A}\mathbf{x}+\mathbf{n}=\mathbf{y} \tag{1}$$

where $\mathbf{A}$ is the forward model matrix, $\mathbf{x}$ is the image vector, $\mathbf{n}$ is noise vector and $\mathbf{y}$ is the data vector.

In this study, we propose a super-resolution technique that relies on the physics of the system matrix for high resolution imaging, without additional calibration time. Each row of the system matrix **A** corresponds to the sensitivity of the scanner for that particular sample (either in frequency or time domain). Here, exploiting smoothness of each sensitivity map in the frequency domain, we get a super-resolved sensitivity map. Then, using the super-resolved maps, we construct the new system matrix $\hat{\mathbf{A}}$, and reconstruct the image using this super-resolved system matrix. Compared to super-resolving after image reconstruction, non-linear reconstruction better completes the missing high resolution data, because the matrix is easier to model compared to the unknown underlying image. Furthermore, this technique adds smoothness information of the sensitivity maps to the reconstruction process. In this work, we use an interpolation kernel (bicubic & nearest-neighbor interpolation) to interpolate the sensitivity map to high resolution image.

The matrix **A** is most often ill-conditioned and a regularized inverse problem has to be solved for image reconstruction. Although there are many techniques, we mainly focus on a non-linear reconstruction technique: Alternating Direction Method of Multipliers (ADMM) based imaging [3].

We compared the image reconstruction results of the same dataset with high-resolution, low-resolution, and interpolated system matrices. We simulated two system matrices with 32 x 32 (1 mm / pixel) and 8 x 8 (4 mm / pixel) resolution from a Field Free Line (FFL) scanner at 60 angles. We used 2nd to 7th harmonics of the received signal with 2 kHz bandwidth around each harmonic. The selection field gradient was 0.62 T/m. A combined drive and focus field was used to scan the 32 x 32 mm^2 field of view. Drive field was a sinusoidal signal with 26 kHz frequency and 4 mT amplitude, and focus field was a triangular wave with 14 mT amplitude. We assumed monodisperse particles with 23.5 nm core diameter, 0.55/μ_0 A/m magnetic saturation, and 300 °K temperature in the simulations. The effect of relaxation was not modelled. We acquired two system matrices using simulations: one with a low resolution using a 4 x 4 mm^2 sample, and one with a high resolution using a 1 x 1 mm^2 sample. We applied nearest neighbor and bicubic interpolation methods on the low resolution system matrix to achieve high resolution.

III Results and discussion

We first inspected the accuracy of the interpolated matrix by comparing it with the high resolution system matrix. We compared approximation error as normalized Root Mean Squared Error (nRMSE) for interpolated matrices using the following formula:

$$nRMSE = \frac{||\hat{\mathbf{A}} - \mathbf{A_{HR}}||_F}{||\mathbf{A_{HR}}||_F}, \tag{2}$$

where $\mathbf{A_{HR}}$ represents the underlying high-resolution system matrix. Bi-cubic Interpolation resulted in nRMSE of 13 %, while nearest neighbor resulted in an error of 30 %. Next, we computed the frequency response corresponding to the 7th harmonic, i.e. 182 kHz.

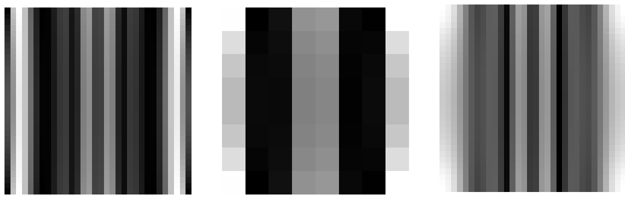

Figure 1: Frequency response corresponding to 182 kHz of the super-resolved system matrices at 0° FFL angle. Note that nearest neighbor and low-resolution responses are the same.

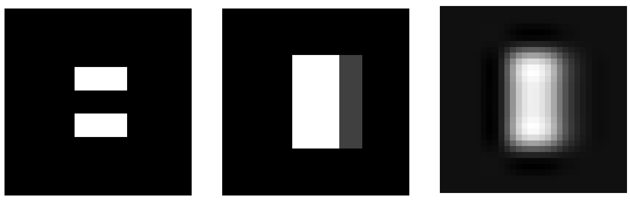

Figure 2: Used reconstruction phantom for the resolution experiment (left). The downsampled and interpolated versions of the same phantom for comparison (middle and right).

As can be seen in Fig. 1, visual inspection shows interpolation results in better performance approximating the high-resolution frequency response. Next, we show improvement of resolution. First, we constructed a simple resolution phantom having two 9 mm x 4 mm bars with 4 mm separation. The high resolution and downsampled phantom can be seen in Fig. 2. Figure 3 shows the reconstruction comparisons with various methods: High resolution reconstruction, low resolution reconstruction followed by bicubic interpolation on the reconstructed image, super-resolution reconstruction with nearest neighbor and bicubic interpolations on the system matrix. Reconstruction followed by bicubic interpolation (Fig. 3.b) resulted as good as bicubic interpolated phantom (Fig. 2.c). Nearest neighbor interpolation (Fig. 3.c) yielded an image similar to the case in "low-resolution" reconstruction (Fig. 2.b). However, reconstruction using bicubic interpolated system matrix clearly resolved two bars (Fig. 3.d). Fig. 3 (a) shows an almost perfect reconstruction with 9 mm x 3 mm bars,

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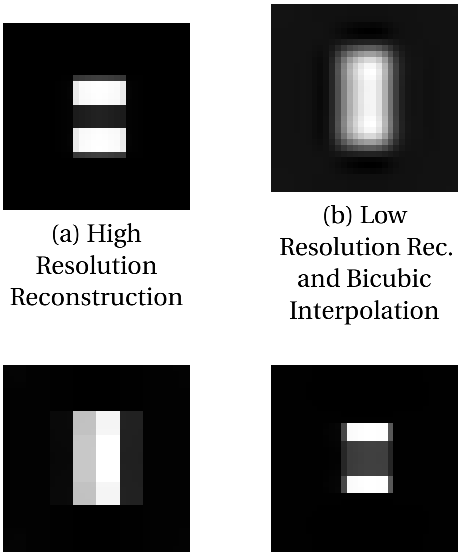

(a) High Resolution Reconstruction

(b) Low Resolution Rec. and Bicubic Interpolation

(c) Nearest Neighbor Interp. Reconstruction

(d) Bicubic Interpolated Reconstruction

Figure 3: Reconstructed images, a comparison of interpolated and non-interpolated reconstructions.

while Fig. 3 (d) shows 7 mm x 3 mm bars. This experiment shows clear advantage of system matrix interpolation.

IV Conclusions

In this study, we have dealt with the problem of reconstructing higher-resolution MPI images compared to the calibration procedure. We have demonstrated the effectiveness of interpolation of system matrix can be a powerful tool for high-resolution image reconstruction. We have shown that collecting a 64 points system matrix may be enough to approximate a system matrix of 1024 points for an FFL MPI scanning system using a relatively low drive field amplitude. Hence, we have demonstrated 16 times acceleration of system matrix calibration, which can be used jointly with compressed sensing based methods. Although we have only demonstrated linear interpolation, other single image super resolution methods may be used for super-resolved images.

Author's Statement

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References

[1] B. Gleich and J. Weizenecker. Tomographic imaging using the nonlinear response of magnetic particles. Nature, 435(7046):1217–1217, 2005. doi: 10.1038/nature03808.

[2] P. Goodwill and S. Conolly, "The x-Space Formulation of the Magnetic Particle Imaging process: One-Dimensional Signal, Resolution, Bandwidth, SNR, SAR, and Magnetostimulation," IEEE Trans. Med. Imag.,vol. 29, no. 11, pp. 1851–1859, 2010.

[3] S. Ilbey, C. B. Top, A. Güngör, T. Çukur, E. U. Saritas and H. E. Güven, "Comparison of System-Matrix-Based and Projection-Based Reconstructions for Field Free Line Magnetic Particle Imaging," Intern. J. Magnetic Particle Imaging. vol. 3, no.1, 2017.

[4] T. Knopp and A. Weber, "Sparse Reconstruction of the Magnetic Particle Imaging System Matrix," IEEE Trans. Med. Imag., vol. 32, no. 8, pp. 1473–1480, 2013.

[5] S. Ilbey, C. B. Top, A. Güngör, T. Çukur, E. U. Saritas, H. E. Güven, "Fast System Calibration with Coded Calibration Scenes for Magnetic Particle Imaging," Trans. on. Med. Imag. vol. 38, no. 9, pp. 2070-2080, Sept. 2019.

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