International Journal on Magnetic Particle Imaging
Vol 8, No 1, Suppl 1, Article ID 2203029, 4 Pages

Infinite Science Publishing

Proceedings Article

Algorithmic Channel Decoupling for Misaligned Receive Coils in Magnetic Particle Imaging

Florian Thieben [1,2,*] · Fynn Foerger [1,2] · Marija Boberg [1,2] · Tom Liebing [2] · Matthias Graeser [1,2,3,4] · Martin Möddel [1,2] · Tobias Knopp [1,2]

[1]Section for Biomedical Imaging, University Medical Center Hamburg-Eppendorf, Hamburg, Germany
[2]Institute for Biomedical Imaging, Hamburg University of Technology, Hamburg, Germany
[3]Fraunhofer Research Institute for Individualized and Cell-based Medicine, Lübeck, Germany
[4]Institute of Medical Engineering, University of Lübeck, Lübeck, Germany
[*]Corresponding author, email: f.thieben@uke.de

Abstract

Magnetic particle imaging (MPI) uses orthogonal receive coils aligned with the directions of the drive-field coils for signal detection. In case of misaligned receive coils, the particle magnetization couples differently into the receive coils such that a re-calibration involving the measurement of a new system function would be necessary. In this work, we propose a method for decoupling the channels algorithmically into the drive-field coil directions using an MPI transfer function matrix. In that way, system functions for different receive coil units can be reused.

I. Introduction

Magnetic particle imaging (MPI) is an emerging tomographic technology, which encodes the spatial distribution of the magnetic nanoparticle (MNP) concentration in a unique magnetization response. These magnetization responses are detected via inductive receive coils, filtered and then digitized. For reconstruction, a calibration measurement is performed and the spatially dependent signal responses are stored in a system function (SF) [1]. Approaches to minimize the calibration time include the use of a system calibration unit [2] or a 3D magnetic particle spectrometer [3]. The underlying methods allow SFs to be reused within other measurement setups. Generally, the generating magnetic fields (drive field, DF) are perpendicularly arranged, such that the MNP signal response, more precisely the magnetic moment spans an orthogonal space. However, if the receive coils are not perfectly orthogonal and are not aligned with the directions of the DF coils, the receive signal contains superimposed information from multiple directions.

In this work we focus on decoupling the receive channels in the DF coil directions. Our method requires spatially dependent MPI transfer functions, but no prior information about the orientation of the receive coils. In this way, the SFs measured with different receive coil units can be transformed into the same signal space and thus SFs can be reused.

II. Methods and Materials

In MPI the aim is to obtain the particle concentration $c : \Omega \to \mathbb{R}^+$ inside a field of view $\Omega \subseteq \mathbb{R}^3$. For receive channel $l \in \{1, \ldots, L\}$ and frequency index $k \in I_{\text{freq}} \subseteq \mathbb{N}$ of a T-periodic excitation the relation between particle concentration and system specific signal response $\hat{u}_l : I_{\text{freq}} \to \mathbb{C}$ can be expressed in Fourier domain using the SF $\hat{S}_l : \Omega \times I_{\text{freq}} \to \mathbb{C}$ as

$$\hat{u}_l(k) = \int_{\Omega} \hat{S}_l(\boldsymbol{r},k)c(\boldsymbol{r})\mathrm{d}\boldsymbol{r}\,. \tag{1}$$

In practice, the SF is sampled by measuring the system specific signal response of a small MNP δ-sample for a discrete number of positions $\boldsymbol{r} \in \Omega$: $\hat{S}_l(\boldsymbol{r},k) = \hat{u}_{l,\boldsymbol{r}}(k)$.

Here, the system specific alternations, called the MPI transfer functions $\hat{\boldsymbol{g}}_l : \Omega \times I_{\mathrm{freq}} \to \mathbb{C}^3$ link the MNP signal response in form of the net magnetic moment $\hat{\boldsymbol{m}} : \Omega \times I_{\mathrm{freq}} \to \mathbb{C}^3$ with the system specific signal response:

$$\hat{u}_{l,\boldsymbol{r}}(k) = \underbrace{-\hat{a}_l(k)\mu_0 2\pi i k T^{-1} \boldsymbol{p}_l(\boldsymbol{r})^{\mathsf{T}}}_{=:\hat{\boldsymbol{g}}_l(\boldsymbol{r},k)} \hat{\boldsymbol{m}}(\boldsymbol{r},k), \tag{2}$$

where $\hat{a}_l : I_{\mathrm{freq}} \to \mathbb{C}$ is the signal alternation due to filters and amplifiers in the receive channel, μ_0 is the vacuum permeability and $\boldsymbol{p}_l : \Omega \to \mathbb{R}^3$ is the receive coil sensitivity [4].

The SFs acquired with different receive units are system specific and not compatible with other setups. Therefore the aim in [3] was to store the SFs in form of MNP signal responses, assuming that the receive coils are orthogonal and aligned with the DF coil directions, i.e $\langle \boldsymbol{p}_l(\boldsymbol{r}), \boldsymbol{p}_{l'}(\boldsymbol{r}) \rangle = 0$ if $l \neq l'$. Then, the receive channels can be considered as decoupled or independent and we have $\hat{\boldsymbol{g}}_l(\boldsymbol{r},k) = \hat{g}_l(\boldsymbol{r},k)\boldsymbol{e}_l$. For $k \neq 0$ the SFs can thus be transformed into the magnetic moment domain using

$$\hat{m}(\boldsymbol{r},k)\boldsymbol{e}_l = g_l(\boldsymbol{r},k)^{-1}\hat{S}_l(\boldsymbol{r},k). \tag{3}$$

In practice, receive coils are neither perfectly orthogonal nor perfectly aligned with the DF coil directions. Hence, the receive signal contains superimposed information of multiple directions. In this work, we propose a method to decouple the receive channels in the DF coil directions and transform the received signals into the MNP signal response, even if the receive channels are coupled and contain a spatially dependent coil sensitivity. The following more general form of (3) relates the spatially dependent MNP signal response and the system functions

$$\hat{\boldsymbol{S}}(\boldsymbol{r},k) = \hat{\boldsymbol{G}}(\boldsymbol{r},k)\hat{\boldsymbol{m}}(\boldsymbol{r},k), \tag{4}$$

where

$$\hat{\boldsymbol{S}}(\boldsymbol{r},k) = (\hat{S}_l(\boldsymbol{r},k))_{l=1,\dots,L}\,,$$
$$\hat{\boldsymbol{m}}(\boldsymbol{r},k) = (\hat{m}_x(\boldsymbol{r},k), \hat{m}_y(\boldsymbol{r},k), \hat{m}_z(\boldsymbol{r},k))^{\mathsf{T}}$$

and

$$\hat{\boldsymbol{G}}(\boldsymbol{r},k) = \begin{pmatrix} \hat{g}_{1,x}(\boldsymbol{r},k) & \hat{g}_{1,y}(\boldsymbol{r},k) & \hat{g}_{1,z}(\boldsymbol{r},k) \\ \vdots & \vdots & \vdots \\ \hat{g}_{L,x}(\boldsymbol{r},k) & \hat{g}_{L,y}(\boldsymbol{r},k) & \hat{g}_{L,z}(\boldsymbol{r},k) \end{pmatrix} \tag{5}$$

defines the MPI transfer function matrix for L receive channels. It consists of spatially dependent MPI transfer functions $\hat{g}_{l,j}(\boldsymbol{r},k)$, $j \in \{x,y,z\}$ mapping the spatial dependent MNP signal response in j-direction to the system specific signal response of the lth-receive channel [3].

For $k \neq 0$ and misaligned receive coils $\boldsymbol{G}(\boldsymbol{r},k)$ is invertible, such that the system specific changes to the measurement signal can be reverted via transformation into the net magnetic moment

$$\hat{\boldsymbol{m}}(\boldsymbol{r},k) = \hat{\boldsymbol{G}}(\boldsymbol{r},k)^{-1}\hat{\boldsymbol{S}}(\boldsymbol{r},k). \tag{6}$$

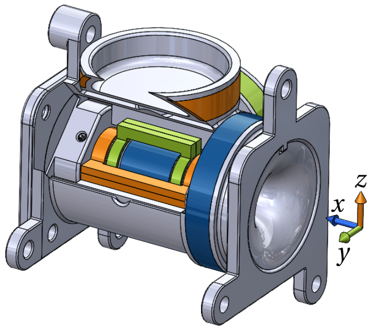

Figure 1: CAD rendering of the 3D receive coil insert with a cut-out on the inner receive coils. In x-direction a solenoid (blue) is build, for the y- (green) and z-directions (orange) saddle-coils are used for signal detection. Corresponding cancellation coils in form of solenoids are placed on the outside.

III. Experiments

The developed method is used to decouple two SFs acquired with different receive coil orientations. All measurements are performed with a preclinical MPI system (Bruker, Ettlingen), a custom 3D receive coil insert (Fig. 1) and custom receive chains [5]. The receive coil insert is developed as a system calibration unit, where a field based approach is used to gain spatial information [2].

The first SF is measured when the coils are *aligned* with the DF coils and the other when the insert is *rotated* by 45° in the yz-plane. The SFs are measured in 2D in the yz-plane with a DF strength of 12 mT and a gradient strength of 2 Tm^{-1} in the z-direction. Using focus fields, the SFs are sampled on a 25×13 grid, corresponding to a FOV of $25 \times 13\,\mathrm{mm}^2$ when considering unit gradient strength. A 1 mm^3 δ-sample filled with perimag (micromod Partikeltechnologie GmbH, Rostock) with a concentration of $8.5\,\mathrm{mg_{Fe}ml^{-1}}$ is used. Prior to the SF measurements, the MPI transfer function matrix $\hat{\boldsymbol{G}}(\boldsymbol{r},k)$ for the y- and z-receive channel is measured for both orientations of the insert. Due to the field based approach, this only needs to be done for the center position $\boldsymbol{r}_0$, hence $\hat{\boldsymbol{G}}_0(k) := \hat{\boldsymbol{G}}(\boldsymbol{r}_0,k)$.

With (6), the SF of the aligned setup is transformed into the magnetic moment domain:

$$\hat{\boldsymbol{m}}_{\mathrm{aligned}}(\boldsymbol{r},k) = \hat{\boldsymbol{G}}_{\mathrm{aligned},0}(k)^{-1}\hat{\boldsymbol{S}}_{\mathrm{aligned}}(\boldsymbol{r},k).$$

For comparison, a receive channel independent transformation into the magnetic moment is performed for the rotated setup:

$$\hat{\boldsymbol{m}}_{\mathrm{rot,diag}}(\boldsymbol{r},k) = \begin{pmatrix} \hat{g}_{1,y,0}(k)^{-1} & 0 \\ 0 & \hat{g}_{2,z,0}(k)^{-1} \end{pmatrix} \hat{\boldsymbol{S}}_{\mathrm{rot}}(\boldsymbol{r},k).$$

To decouple the receive channels of the rotated setup and transforming the signals into an orthogonal magnetic moment vector the inverse of the MPI transfer function matrix is utilized:

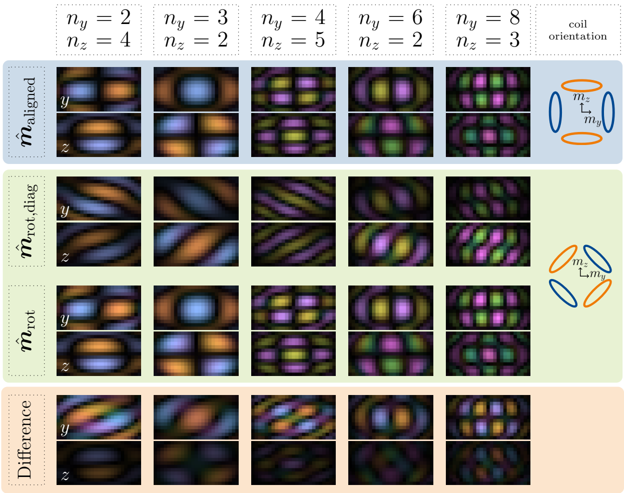

Figure 2: 2D color-coded, complex-valued SF patterns in magnetic moment domain $\hat{\boldsymbol{m}}$ for different mixing factors n_y and n_z. The first two rows with blue background show results from the orientation aligned with the excitation direction. The next rows with green background result from a 45 ° rotated coil orientation. In the right column the set coil orientation is depicted. For the bottom two rows, the differences between $\hat{\boldsymbol{m}}_{\mathrm{aligned}}$ and $\hat{\boldsymbol{m}}_{\mathrm{rot}}$ are depicted. Here the maximum value is normalized to 15 % of the maximum of the first row.

$$\hat{\boldsymbol{m}}_{\mathrm{rot}}(\boldsymbol{r},k) = \hat{\boldsymbol{G}}_{\mathrm{rot},0}(k)^{-1}\hat{\boldsymbol{S}}_{\mathrm{rot}}(\boldsymbol{r},k).$$

The resulting SFs in the magnetic moment domain are compared in terms of their difference and structural similarity.

IV. Results and Discussion

In Fig. 2 several magnetic moment patterns of the y- and z-channels for both orientations are shown for an exemplary set of mixing factors. It can be observed that the patterns of $\hat{\boldsymbol{m}}_{\mathrm{rot,diag}}$ result from a superposition of both receive channels from $\hat{\boldsymbol{m}}_{\mathrm{aligned}}$. Applying the inverse of the MPI transfer function matrix $\hat{\boldsymbol{G}}_{\mathrm{rot},0}(k)$, the pattern of $\hat{\boldsymbol{m}}_{\mathrm{rot}}$ become very similar to the ones of $\hat{\boldsymbol{m}}_{\mathrm{aligned}}$. The channel-wise difference between them is shown in the two bottom rows, where the maximum value is normalized to 15 % of the maximum of the first row. For quantitative comparison the structural similarity (SSIM) index between $\hat{\boldsymbol{m}}_{\mathrm{rot}}$ and $\hat{\boldsymbol{m}}_{\mathrm{aligned}}$ is shown in Fig. 3 for the mixing factors $n_y \in \{0,1,...9\}$ and $n_z \in \{0,1,...9\}$. The mean SSIM index over y, z, and all mixing factors is 0.642 for $\hat{\boldsymbol{m}}_{\mathrm{rot,diag}}$ compared to $\hat{\boldsymbol{m}}_{\mathrm{aligned}}$ and 0.973 for $\hat{\boldsymbol{m}}_{\mathrm{rot}}$ compared to $\hat{\boldsymbol{m}}_{\mathrm{aligned}}$. The method still has some imperfections in the vicinity of the receiver's resonance frequency, which is around $(n_y, n_z) = (8,8)$. For all mixing factors, the presented method using the MPI transfer function matrix shows an improvement compared to a channel independent approach.

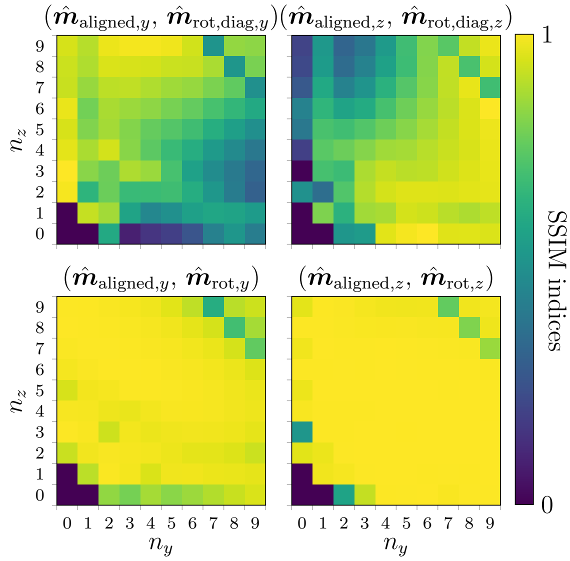

Figure 3: SSIM indices of the y- and z-channel. The upper row shows the channel independent comparison between $\hat{\boldsymbol{m}}_{\mathrm{aligned}}$ and $\hat{\boldsymbol{m}}_{\mathrm{rot,diag}}$ for different mixing factors n_y and n_z. In the lower row $\hat{\boldsymbol{m}}_{\mathrm{aligned}}$ and $\hat{\boldsymbol{m}}_{\mathrm{rot}}$ are compared. Mixing factors $(n_y, n_z) \in \{(0,0),(0,1),(1,0)\}$ are omitted and set to zero, since they are filtered out by the analog receive filter.

V. Conclusion

Numerous SF comparison experiments [2, 3] have shown that a channel independent consideration is sufficient, if the receive coils are perpendicular and aligned with the DF coils. However, with the proposed method a new degree of freedom for the receive coil design, e.g. the orientation is possible. Most importantly, our method allows to reuse the same SF for different receive units, which can drastically reduces the calibration effort for MPI scanners with exchangeable receive coils. In the future, the robustness of the method regarding the spatial dependency needs to be evaluated.

Author's statement

Research funding: The authors thankfully acknowledge the financial support by the German Research Foundation (DFG, grant number KN 1108/7-1 and GR 5287/2-1). Conflict of interest: Authors state no conflict of interest.

References

[1] B. Gleich and J. Weizenecker. Tomographic imaging using the nonlinear response of magnetic particles. *Nature*, 435(7046):1214–1217, 2005, doi:10.1038/nature03808.

[2] A. Halkola, J. Rahmer, B. Gleich, J. Borgert, and T. Buzug, System calibration unit for magnetic particle imaging: System matrix, in *2013 International Workshop on Magnetic Particle Imaging (IWMPI)*, IEEE, 1–1, 2013.

[3] A. von Gladiss, M. Graeser, A. Cordes, A. C. Bakenecker, A. Behrends, X. Chen, and T. M. Buzug. Investigating spatial resolution, field sequences and image reconstruction strategies using hybrid phantoms in MPI. *International Journal on Magnetic Particle Imaging*, 6(1), 2020.

[4] T. Kluth. Mathematical models for magnetic particle imaging. *Inverse Problems*, 34(8):083001, 2018, doi:10.1088/1361-6420/aac535.

[5] M. Graeser, T. Knopp, P. Szwargulski, T. Friedrich, A. von Gladiss, M. Kaul, K. M. Krishnan, H. Ittrich, G. Adam, and T. M. Buzug. Towards picogram detection of superparamagnetic iron-oxide particles using a gradiometric receive coil. *Scientific reports*, 7(1):1–13, 2017.

