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MPI Transfer-Function Estimation with Receive-Coil Coupling

Marija Boberg [a,b,*] · Jacob Hunecke [b] · Florian Thieben [a,b] · Matthias Graeser [a,b,c,d] · Tobias Knopp [a,b]

[a] Section for Biomedical Imaging, University Medical Center Hamburg-Eppendorf, Hamburg, Germany
[b] Institute for Biomedical Imaging, Hamburg University of Technology, Hamburg, Germany
[c] Fraunhofer Research Institute for Individualized and Cell-based Medicine, IMTE, Lübeck, Germany
[d] Institute of Medical Engineering, University of Lübeck, Lübeck, Germany
[*] Corresponding author, email: m.boberg@uke.de

Abstract

Time- and memory-consuming calibration measurements are a major drawback in system-matrix-based reconstructions in magnetic particle imaging (MPI). Especially, exchanging the receive coils requires new system matrices and therefore new calibration measurements. To reduce the number of such measurements, the MPI transfer function can be used to transfer the system matrix of one receive coil set to another. The transfer function can be obtained by a direct measurement or by estimation using a measured system matrix of each setup. In this abstract, we extend the latter to incorporate coupling of the receive coils while using only a few voxels of the system matrices. In this way, we can transfer system matrices between two different receive setups, both of which may contain non-orthogonal coils.

I. Introduction

In magnetic particle imaging (MPI), time- and memory-consuming calibration procedures are a major drawback in system-matrix-based reconstruction methods. Each time a parameter of the system is changed, the entire calibration has to be repeated. This applies in particular to the exchange of the receive coils. Fortunately, there are already several methods to reduce the calibration time substantially so that a system matrix of one receive coil set can be reused for another one by determining and applying the transfer function of the receive path. The theoretical foundation and methods for a measurement-based calibration of the receive path were recently developed by Thieben et al. in [1]. The proposed method uses a calibration coil to measure the transfer function of the device-specific receive path and transform the measurement signal into the device-independent magnetic moment domain of the measured nanoparticles. This enables an exchange of the receive coils without new system-matrix measurements or even reusing system matrices measured with a different MPI system as it was done in [2]. Alternatively, the mapping from one system matrix to another can be obtained by solving an optimization problem as described in [3], which can also be combined with a measured transfer function [4]. While the methods [2–4] work well in practice, they have in common to determine a channel-wise transfer function assuming no coupling between the receive coils. This means that the receive coils are assumed to be perfectly orthogonal (both coils and receive paths) and that each coil picks up only the signal of one of the three principal axes. As it is challenging to produce perfectly aligned coils in particular when considering the space constraints of common MPI scanners, the assumption of orthogonal receive coils is often violated. This motivated the authors in [1] to incorporate the receive-coil coupling into the measurement of the transfer function, which, however, requires highly precise calibration coils, which are challenging to manufacture with sufficient accuracy. In this work, we estimate the transfer function between two system matrices by extending the optimization problem in [3] to account for receive path coupling. To solve the optimization problem, only a few voxels of both system matrices are required. As a first step, we neglect the spatial dependence of the transfer function and focus on the decoupling only.

II. Methods and materials

The MPI transfer function describes the mapping from a T-periodic receive signal $\hat{\boldsymbol{u}}_{\boldsymbol{r}}(k):\mathbb{Z}\to\mathbb{C}^L$ of a particle sample at position $\boldsymbol{r}\in\Omega$ measured with $L\in\mathbb{N}$ receive coils to the nanoparticles net magnetic moment $\hat{\boldsymbol{m}}:\Omega\times\mathbb{Z}\to\mathbb{C}$, where $\Omega\subseteq\mathbb{R}^3$ describes the measured field-of-view of the system matrix. As has been shown in [1], the mapping is given by

$$\hat{\boldsymbol{u}}_{\boldsymbol{r}}(k)=\underbrace{\alpha(k)\hat{\boldsymbol{A}}(k)\boldsymbol{P}(\boldsymbol{r})}_{=:\boldsymbol{G}(\boldsymbol{r},k)}\hat{\boldsymbol{m}}(\boldsymbol{r},k),$$

where $\alpha(k)=\mu_0\frac{2\pi i k}{T}$, $k\in\mathbb{Z}$ is the frequency index, μ_0 is the vacuum permeability, $\hat{\boldsymbol{A}}:\mathbb{Z}\to\mathbb{C}^{L\times L}$ describes the analog filters of the receive chains, and $\boldsymbol{P}:\Omega\to\mathbb{R}^{L\times 3}$ contains the sensitivity profiles of the receive coils.

Assuming $\boldsymbol{G}(\boldsymbol{r},k)$ to have full rank, the measurement signal of one system $\hat{\boldsymbol{u}}_{\text{approx},\boldsymbol{r}}$ can be calculated from the signal $\hat{\boldsymbol{u}}_{\text{base},\boldsymbol{r}}$ of another system by

$$\hat{\boldsymbol{u}}_{\text{approx},\boldsymbol{r}}(k)=\underbrace{\boldsymbol{G}_{\text{approx}}(\boldsymbol{r},k)\boldsymbol{G}^{+}_{\text{base}}(\boldsymbol{r},k)}_{=:\boldsymbol{T}(\boldsymbol{r},k)}\hat{\boldsymbol{u}}_{\text{base},\boldsymbol{r}}(k),$$

where $\boldsymbol{G}^{+}_{\text{base}}(\boldsymbol{r},k)$ denotes the pseudoinverse of $\boldsymbol{G}_{\text{base}}(\boldsymbol{r},k)$. Here, we restrict $\boldsymbol{T}$ to be spatially independent, i.e., we model a transfer function $\boldsymbol{T}:\mathbb{Z}\to\mathbb{C}^{L\times L}$ independent of the position $\boldsymbol{r}$.

Analogously to [3], the transfer function is then estimated by solving the minimization problem

$$\min_{\boldsymbol{T}(k)}\left\|\hat{\boldsymbol{u}}_{\text{approx}}(k)-\boldsymbol{T}(k)\hat{\boldsymbol{u}}_{\text{base}}(k)\right\|_2^2 \qquad (1)$$

with $\hat{\boldsymbol{u}}:\mathbb{Z}\to\mathbb{C}^{L\times|\Omega|}$ containing the signal at all positions $\boldsymbol{r}\in\Omega$ for all L receive coils. When the receive coil coupling can be neglected, $\boldsymbol{T}(k)$ becomes a diagonal matrix so that (1) can be solved for each l individually. But in order to account for receive channel coupling, the separate channel-wise solutions $\tilde{T}_l:\mathbb{Z}\to\mathbb{C}$ considered in [3] are not sufficient.

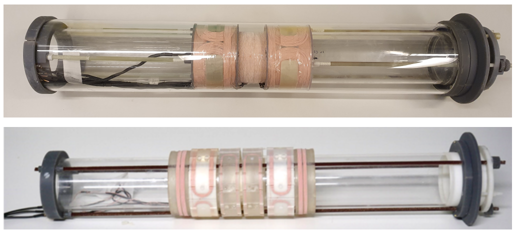

Figure 1: Receive coils used in the experiments: the 3D rat coil setup (above) and the 3D mouse coil setup (below).

Despite the generalization to non-diagonal $\boldsymbol{T}$, the minimization problem (1) can still be split into L parts

$$\min_{\boldsymbol{T}(k)}\left\|\hat{\boldsymbol{u}}_{\text{approx},l}(k)-\hat{\boldsymbol{u}}^{\intercal}_{\text{base}}(k)\boldsymbol{T}_l(k)\right\|_2^2$$

where the channel-wise solution $\boldsymbol{T}_l:\mathbb{Z}\to\mathbb{C}^L$ depends on all L receive channels. Each of the minimization problems is equivalent to the solution of the normal equation

$$\bar{\hat{\boldsymbol{u}}}_{\text{base}}(k)\hat{\boldsymbol{u}}^{\intercal}_{\text{base}}(k)\boldsymbol{T}_l(k)=\bar{\hat{\boldsymbol{u}}}_{\text{base}}(k)\hat{\boldsymbol{u}}_{\text{approx},l}(k). \qquad (2)$$

Solving (2) for an appropriate subset $\Omega_{\text{calib}}\subseteq\Omega$ of calibration points yields transfer functions for all receive channels. Thus, the measurement signal $\hat{\boldsymbol{u}}_{\text{approx},\boldsymbol{r}}$ can now be obtained at all positions $\boldsymbol{r}\in\Omega$ from a fully sampled measurement $\hat{\boldsymbol{u}}_{\text{base}}$.

III. Experiments

The proposed methods are tested on two system matrices measured in a preclinical MPI system 25/20FF (Bruker Corporation, Ettlingen, Germany) with two dedicated receive coil setups shown in Figure 1. The system matrix measured with a receive coil arrangement dedicated for rat experiments (*rat coil*) featuring a bore diameter of 72 mm is used as base measurement $\hat{\boldsymbol{u}}_{\text{base}}$ to model the system matrix of a receive coil setup for mouse experiments (*mouse coil*) [5] with a bore diameter of 40 mm. Both system matrices were measured with 12 mT drive-field amplitude in all three directions on a $26\times26\times13$ grid with a delta-sample of size $2\times2\times1\,\text{mm}^3$ filled with perimag (micromod Partikeltechnologie GmbH, Rostock, Germany) with a concentration of $152\,\text{mmol}_{\text{Fe}}\,\text{L}^{-1}$. The system matrix of the rat coil was measured on a field-of-view of size $34.6\times34.6\times17.3\,\text{mm}^3$ with gradient strengths of $(-0.75,-0.75,1.5)\,\text{T}\,\text{m}^{-1}$. For the mouse coil, gradient strengths of $(-1,-1,2)\,\text{T}\,\text{m}^{-1}$ and a field-of-view of $26\times26\times13\,\text{mm}^3$ were used because of its smaller bore diameter, but they result in the same offset field in each voxel as in the voxels of the rat coil's system matrix. For both coil setups, a coil-coupling omitting channel-wise transfer function was measured, which are used as baseline method for comparison. The measured transfer functions are applied to the base system matrix in order to generate a system matrix for the mouse coil.

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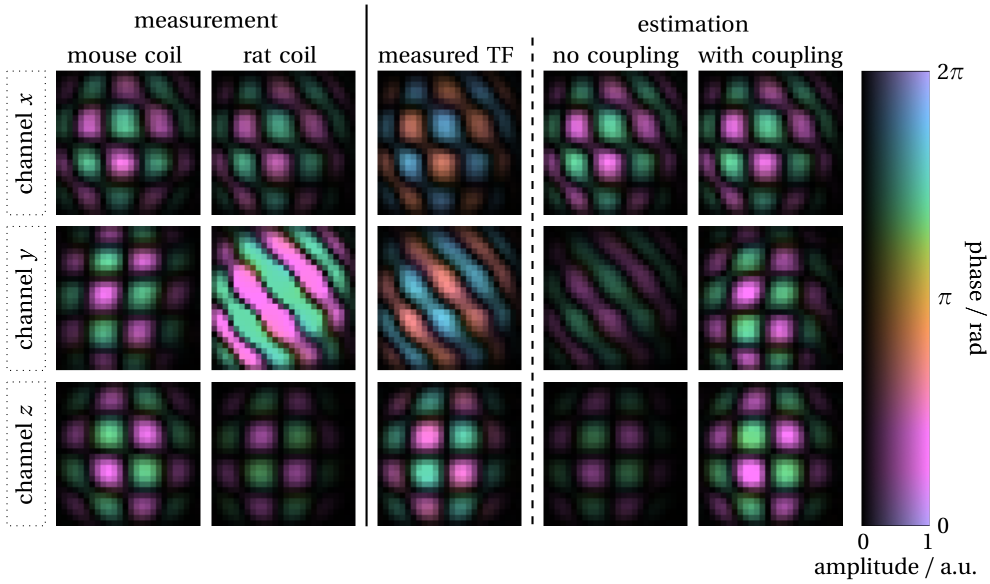

Figure 2: Representative row of system matrices resulting from measurements (left) and of the different transfer function (TF) estimation approaches (right). Shown is the xy-plane of mixing order (5,5,5). The colormap is adjusted to the maxima of the first column. For the third column, the maxima of the colormap are scaled by 2, 20, and 2 %, respectively.

The estimated transfer functions are calculated by solving (2) using Ω_{calib} with 15 voxels around the center of the measured grid. For comparison, also the transfer function $\tilde{T}_l$ without coupling is calculated as proposed in [3] using the same subset of voxels.

IV. Results

In Figure 2, results of the application of the different measured and estimated transfer functions are compared to the explicitly measured system matrices. Shown is the central xy-plane of mixing order (5,5,5) [6]. The estimated transfer function considering the receive coil coupling provides system matrices that are most similar to the measured system matrices. Especially the system matrix measured with the y-receive channel of the rat coil has significant coupling artifacts, which can only be handled by our proposed model yielding decoupled system matrices for the mouse coils.

Additionally, Figure 3 shows the normalized root-mean-square error (NRMSE) comparing the central xy-plane of the system matrices of each method with the measured ones in the mouse coil for mixing orders $m_x, m_y \in \{0,9\}$ and $m_z = 5$. Taking into account the coupling during transfer function estimation decreases the NRMSE especially for the y-receive channel significantly, but also for the other channels a decrease is visible.

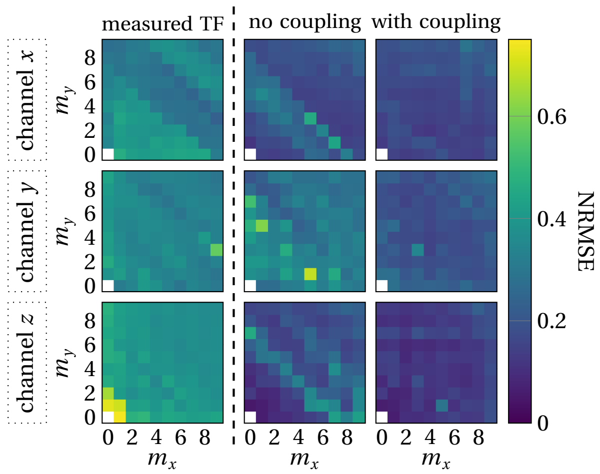

Figure 3: Mixing-order-dependent NRMSE comparing the different approaches to the system matrix of the mouse coil.

V. Discussion and conclusion

In conclusion, a proper handling of the coupling of receive coils is important to reuse system matrices measured with another receive coil setup. It can be incorporated into the measurement process as done in [1] or in the system-matrix-based estimation as proposed in this work. The latter can be easily applied, if the desired system matrix is given at some calibration positions. It corrects both coupling of the receive coils and capacitive coupling of the receive paths. Afterwards, with the estimated transfer function every system matrix obtained with the base receive coil setup (measured with any scan-

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ner parameter or particles) can be reused in the second setup. To ensure high accuracy of the estimated transfer function, the system matrices used for the estimation should provide high signal-to-noise ratios.

Author's statement

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