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# Modular Simulation Framework for Magnetic Particle Imaging

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**Abstract**

Simulations are of high interest in all areas of scientific research, especially for finding novel approaches or optimizing existing methods. For the young field of Magnetic Particle Imaging (MPI) only few quite specific simulation frameworks exist, which cover the entire process from hardware simulation and signal generation to data reconstruction and final visualization. With the presented modular simulation framework consisting of three cooperating packages, all important steps can be provided. Each package is a tool for a specific purpose: Magnetic Field Simulator for signal generation, Reconstruction Framework for data reconstruction and 3D Visualization Tool for data visualization, which can be used as framework, stand-alone or in combination with third party software packages.

## I. Introduction

Magnetic Particle Imaging (MPI) is a novel tomographic technology [1], which has shown significant improvements in hardware design and development as well as reconstruction methods [2] in the last decade. Several different hardware approaches, such as field-free point (FFP) or field-free line (FFL) scanner types are available using quite different hardware setups in the background. Furthermore, multiple different methods are usable for data processing and reconstruction.

One major step in the designing and optimization process of (novel) hardware and reconstruction methods is the simulation, emulation and visualization of specific hardware components and magnetic fields as well as the signal behavior of realistic tracers. For that, multiple different software solutions have been presented [3-9] offering appropriate simulation and emulation results for the specific application.

However, a major drawback of existing modular solutions is the restriction and inflexibility of software for self-contained use. The combined use often requires complex interfaces between the different software packages, e.g., when generating a coil setup in tool 1, calculating the signal with tool 2 and visualize the results in tool 3.

In this abstract, a modular simulation framework for MPI consisting of three cooperative modules is presented covering the entire process from hardware simulation of complex scanner designs via the signal generation with sophisticated particle models and signal processing to reconstruction and final 3D visualization.

## II. Material and Methods

The MPI simulation framework consists of three different software modules:

1. Magnetic Field Simulator (MFS)
2. Reconstruction Framework (RiFe)
3. 3D Visualization Tool (3DVT)

Every software module is programmed in Delphi® (Embarcadero RAD Studio 11.1, USA), which provides cross-platform support.

For data transfer between the software modules, either specific data (time data, frequency data, image data, system matrix data, etc.) can be used or a fast data exchange through Memory Mapped File technology (MMF) is available.

All modules are user-friendly designed (3D graphical user interface, etc.) and optimized for fast data processing (Magnetic Field Simulator), for interactive use and handling and for near real-time visualization with low latency (Reconstruction Framework and 3D Visualization Tool). The latter feature in combination with specific data transfer protocols, e.g., for data transfer of digital oscilloscopes or Analog Digital Converter (ADC) cards, allows the near real-time reconstruction and visualization of data streams coming directly from real MPI scanners [8, 10, 11, 12].

## II.I. Magnetic Field Simulator – MFS

The MFS tool is a versatile and flexible simulation environment for magnetic fields in 4D [6, 20]. A 3D-GUI with intuitive controlling (mouse and/or multi-touch) provides a fast and easy navigation around the designed structures. Standard features known from versatile 3D software are available, e.g., specific lighting or different rendering settings.

The MFS software is structured in different types of helper-containers with different assignments. This allows a standardization and thus optimization of data processing.

### II.I.1. Conductor-container

For the simulation of quasi-static and dynamic magnetic fields with frequencies below 10 MHz, the law of Biot-Savart is valid, which is sufficient for common MPI experiments [13]. Based on this concept, arbitrary coil designs consisting of multiple elements can be used for magnetic field calculations. For that, parameterized function-based templates as well as a user-defined tool are available for the generation of complex coils and conductor structures. Each conductor can be used as transmit (tx-mode) or receive coil (rx-mode). In tx-mode, the conductor-container is used for magnetic field calculation, in rx-mode the induced signal is calculated using a point-cloud array (see MFA-container) connecting transmit and receive site with desired magnetization functions (Magnetic Nanoparticle (MNP)-container).

### II.I.2. MFA-container

MFA stands for magnetic field array and represents an ensemble of $N$ dedicated points in 3D space. This container calculates the magnetic fields at these points. Specific modes allow the visualization of the magnetic fields, magnetic field gradients and many more parameters. This container is optimized providing a highly responsive environment for fast investigation via different features, such as FFP or FFL surface rendering and 3D tracking.

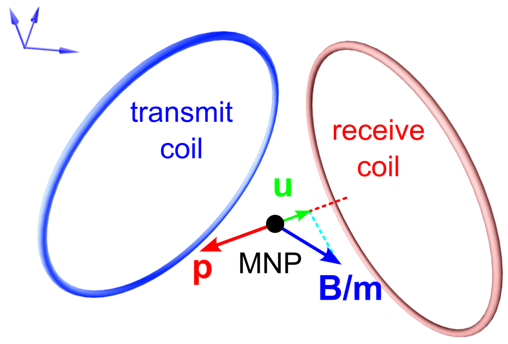


Figure 1: Projection calculation to obtain the induced voltage $u$ within a receive coil.

### II.I.3. MNP-container

The MNP-container provides the point cloud for simulating the MNP distribution in space. Furthermore, the magnetization response of magnetic particle ensembles as well as macroscopic spin ensembles (isochromates in Magnetic Resonance Imaging) in dynamic magnetic fields can be calculated utilizing different theories and models (Langevin-theory [14], modified mean-field-theory [15] for particle-particle interaction or solving phenomenological Bloch equations [16]).

### II.I.4. Receive coil-container (rx-mode)

The calculation of induced signals in a virtual receive chain, can be performed by employing Faraday's Law and volume-based sensitivity areas. These areas are defined and connected by the selected MNP-containers. Figure 1 shows the projection calculation for a single point defined in the MNP-container. The magnetic field $\boldsymbol{B}$ generated by the transmit coil is used to calculate the magnetization $\boldsymbol{m}$ at this point following the selected magnetization model (MNP-container). The induced voltage $u$ is the change of the projected magnetization $\boldsymbol{m}$ on the sensitivity map $\boldsymbol{p}$ defined by the receive coil.

The generated data sets can either be manipulated and visualized inside the MFS tool or directly provided to the reconstruction framework (Sec. II.II.) via MMF.

A built-in scripting tool (similar to Matlab) allows to run customizable scripts for automatization within the software, which can be used for optimization, visualization and demonstration of magnetic fields and MPI or MRI signals.

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## II.II. Reconstruction Framework – RiFe

The reconstruction framework is a software package, which provides fast processing of data sets either coming directly from an analog-digital converter (e.g., MPI scanner) or a simulation tool (e.g., MFS, Sec. II.I.) via MMF (Figure 1 d). It allows fast data correction and filtering (i.e. required for receive-chain correction of real MPI scanners) as preparation step for multiple reconstruction methods, such as image-based (re-gridding, direct deconvolution, image-based system matrix) and Fourier-based peak picking system matrix reconstruction. Different algorithms are available for reconstruction: Wiener filter, Kaczmarz algorithm, singular-value decomposition, etc., all optimized for near real-time calculation. The system matrix data can be generated directly within the MFS environment for multiple scanner and reconstruction types [8, 20].

A built-in graphic tool allows the direct visualization of time-signals, spectra, 2D raw-images and 2D reconstructed images. For 3D visualization, the data can be transferred via MMF to the 3D visualization tool (Sec. II.III).

## II.III. 3D Visualization Tool

The 3D visualization tool is a fast OpenGL volume renderer for the direct visualization of 3D data sets using shader technology [21]. With adjustable contrast, brightness and opacity parameters, the visualization of 3D data can be adapted. As data pipelines, the open-source data format NiFTI [17] or direct data transfer via MMF from, e.g., the reconstruction framework (Sec. II.II.), are provided.

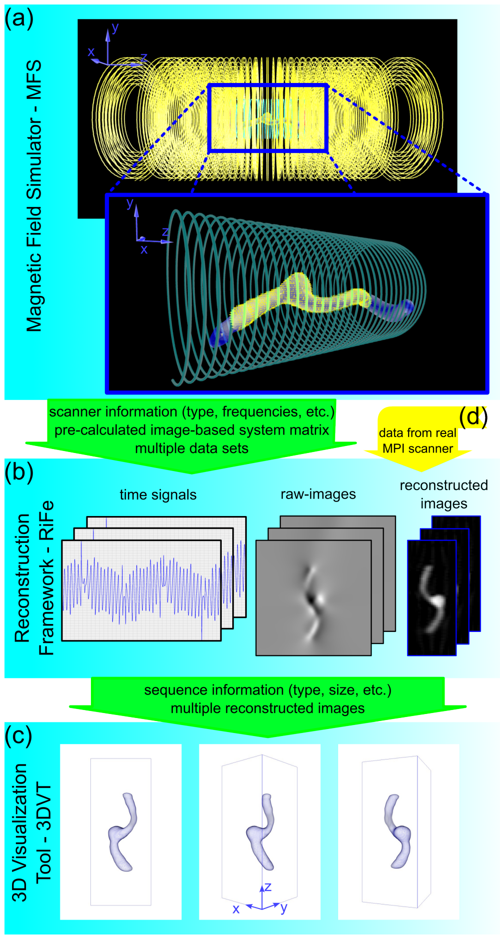


Figure 2: Example of a 3D simulation of an aneurysm phantom imaged with a Traveling Wave (TW) MPI scanner. (a) In the MFS, the entire scanner is simulated, and the data sets are generated. (b) Each data set is reconstructed (image-based system matrix reconstruction) and visualized with the 3DVT (c). Instead of simulated input data, data streams from real MPI scanners can be used too (d).

# III. Results and Discussion

In Figure 2, the simulation of a full Traveling Wave (TW)MPI [18] device running a 3D rSSM (rotating slice-scanning mode) sequence [19] scanning an 3D aneurysm model (3D STL) is sketched. All necessary parameters, such as frequencies and magnetic field strengths, are defined by a real MPI scanner. The simulation can be used for validating and adapting the reconstruction and visualization steps before using real data stream within the same framework (see Figure 2d).

A short demonstration of the presented software can be found at https://youtu.be/Cfae-rJ13DM.

The framework consists of three stand-alone packages, where each package is optimized for a specific purpose. The MFS package is used for signal generation emulating real MPI scanners. In combination with the reconstruction (RiFe) and visualization frameworks (3DVT), the entire process can be optimized prior before real experiments. For rapid data transfer all software modules are interconnected via MMF. However, it is also possible to use a proprietary data format without complex headers, which allows for easy connection to other software, e.g., Matlab (Mathworks, USA).

The software settings are optimized primarily for speed. However, the tool has adjustable computation accuracy, which can be tailored to the available hardware or application, e.g., running on laptops or for educational purposes.

# IV. Conclusion

The presented simulation framework allows the simulation of entire 3D MPI scanners from hardware design to image reconstruction. The easy-to-use interface, the short calculation times and the modular processing chain allows fast development of novel scanner approaches. By changing the input data source, e.g., from

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simulation with the MFS to real MPI data, this framework allows a rapid validation and optimization of reconstruction processes.

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## Author's statement

Conflict of interest: Authors state no conflict of interest.

## Data and Code availability

An executable software version is available on request: Patrick.Vogel@physik.uni-wuerzburg.de. For more information visit https://mfs5.avicula.biz.

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