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Software Implementation of Greedy Optimized MPS Sequences

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Abstract

Multi-dimensional magnetic particle spectrometers provide fast and high quality hybrid system matrix measurements, using different DC offsets to emulate the same saturation that magnetic nanoparticles are exposed to in a real scanner or during particle characterization. In this work, we address the challenges of minimizing sign changes of DC sources with H-bridges and slow rise times. We provide a generic offset sorting scheme for an arbitrary number of channels. Our implementation allows a variety of devices to be controlled using the same software interface.

I. Introduction

Hybrid system matrices are a useful tool for magnetic nanoparticle (MNP) characterization and scanner calibration [1, 2] in magnetic particle imaging (MPI). Using electrically controlled multi-dimensional DC offset fields, it is possible to emulate different positions in a selection field for a MNP sample measured in an magnetic particle spectrometer (MPS). This enables a reduction in acquisition times. Further reductions require sequence design and system software that minimizes waiting times due to specific electrical implementations, such as H-bridges that switch the polarity of DC sources or different settling times per channel until an offset is reached and stable. We formulate two distinct problems for multi-dimensional MPS, the first focuses on the measurement order of orthants spanned by H-bridges and the second on a greedy sequence to reduce time losses when waiting for offset level stability. The resulting algorithm is realized as a flexible implementation in the open-source MPI system control framework MPIMeasurements.jl [3], which plans a greedy time-optimized acquisition sequence for multi-dimensional system matrices for varied combinations of offset channels.

II. Methods and Materials

In the following we describe ordered sequences of offset values, which we will denote as $(x_1, x_2, \ldots)$. To allow for more complex sequences we loop and nest sequences, which we denote as $((a_i)_{i=1}^2, b_j)_{j=1}^2 := (a_1, a_2, b_1, a_1, a_2, b_2)$.

Without loss of generality we will consider a 3D hybrid system matrix of size $N_x \times N_y \times N_z$ with three offset channels for the x, y and z direction.

The offset sequences for a straight-forward Cartesian sequence of such a 3D matrix looks as follows:

$$s_c = (((c_a)_{i=1}^{N_x})_{j=1}^{N_y})_{k=1}^{N_z}, c_a \in \{x_i, y_j, z_k\}.$$

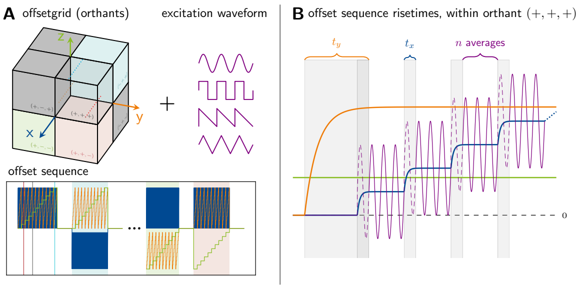

Figure 1: Sequence overview for 3D hybrid system matrices. Subfigure A shows the grouping of offsets into orthants and an excerpt from the resulting sequence of offsets. Within each orthant dimensions are traversed from longest to shortest risetime as shown in subfigure B.

Here, x_i denotes the i-th offset for the x channel, likewise for y and z. Each sequence has a length of $N = N_x N_y N_z$ and each offset is held for the same duration, which for convenience we consider to be a multiple of the excitation period.

Such a Cartesian approach is not feasible if sign changes of offset channels are implemented with H-bridges. Each such change bisects the offset coordinate system at its zero crossing, as shown in Figure 1, A. Since the switch time is usually considerably larger than the excitation period, one should reduce the number of changes. The minimum number of H-bridge switches required for M channels with sign changes is 2^M. The offsets have to be reordered into orthants of the M-dimensional subsystem during measurements and stored in Cartesian order afterwards.

Within an orthant the offsets are not instantly level and require time to stabilize, which we call the rise time. This time can differ per channel based on hardware or the distance between two consecutive offsets. Only signals during stable offsets are useful for hybrid system matrices. An example with three averages can be seen in Figure 1, B. The overall time spent in unstable levels should also be reduced. Let x_i^+ denote the N_x^+ positive and zero offset values and t_x the number of drive field cycles that fit in the rise time of channel x.

To reduce the rise times within an orthant, we sort the channels according to their rise time. Each channel must hold its level until it is stable. In addition, a channel can either hold its value or remain at 0, while the channels with longer rise times are not yet stable. Consider the example orthant for all positive offsets with $t_x \leq t_y \leq t_z$ we have

$$\hat{s}_x^{(+,+,+)} = ((x_i^+ \vee 0)_{p=1}^{t_z - t_y}, \quad ((x_i^+ \vee 0)_{p=1}^{t_y - t_x}, \quad ((x_i^+)_{p=1}^{t_x}, x_i^+)_i)_j)_k$$
$$\hat{s}_y^{(+,+,+)} = ((y_j^+ \vee 0)_{p=1}^{t_z - t_y}, \quad ((y_j^+)_{p=1}^{t_y - t_x}, \quad ((y_j^+)_{p=1}^{t_x}, y_j^+)_i)_j)_k$$
$$\hat{s}_z^{(+,+,+)} = ((z_k^+)_{p=1}^{t_z - t_y}, \quad ((z_k^+)_{p=1}^{t_y - t_x}, \quad ((z_k^+)_{p=1}^{t_x}, z_k^+)_i)_j)_k$$

It should be noted that this greedy approach is time-optimal in many cases. In particular, it is optimal if the number of offsets per orthant is the same for each channel.

III. Results and Discussion

The described sequence design has been implemented in a measurement protocol in MPIMeasurements.jl [3]. The protocol is capable of controlling MPS with arbitrary combinations of offset channel with and without H-bridge, as well as sinusoidal and arbitrary excitation waveforms. Appropriate electrical control signals for the H-bridges can also be generated, and data averaging is performed inplace to avoid excessive memory usage during acquisition.

The software interface aims to support multiple devices and different hardware with a large range of parameters and specifications. It has been used to generate hybrid system matrices with the systems described in [1] and [4]. The first system has three offset channels with H-bridges and three excitation field channels, while the second system has one offset channel with an H-bridge and a second channel combining offset and excitation field without an H-bridge.

IV. Conclusion

In this work, we have shown a flexible and dimension-agnostic sequence implementation for hybrid system matrix acquisition. In the future, we plan to consider additional optimization factors within an orthant such as mean power consumption and heating factors.

Author's statement

Conflict of interest: Authors state no conflict of interest.

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