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Adaptive Permissible Region Strategy for Magnetic Particle Imaging

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Abstract

Magnetic particle imaging (MPI) is a new kind of molecular imaging technique which is designed to locate the superparamagnetic iron oxide (SPIO) with high resolution and sensitivity. The inverse problem of MPI is a challenging problem and many reconstruction methods have been proposed. In this paper, we proposed the adaptive permissible region (APR) strategy to promote the reconstruction efficiency. We apply APR strategy on Kaczmarz method and verify its performance with OpenMPI data set. As a general strategy, APR strategy can obviously reduce the reconstruction time in all conditions, and even promote the reconstruction result with proper parameter.

I. Introduction

Magnetic particle imaging (MPI) is a new molecular imaging technology, which can non-invasively image the superparamagnetic iron oxide (SPIO) with high sensitivity and resolution. The MPI technique based on the movement of field free region (FFR) and the nonlinear response signal of SPIO [1]. To reconstruct the concentration of tracer from the measured signal, the inverse problem of MPI should be solved.

There are several reconstruction methods proposed to solve the MPI inverse methods. The X-space method [2] and the system matrix (SM) method [3] are two common reconstruction methods for MPI. Comparing to the X-space method, the SM reconstruction method can reach better reconstruction results with more reconstruction time. Several strategies like frequency selection [4] and block averaging accelerate [5] are applied on MPI reconstruction to reduce reconstruction time. It is still an important problem to further reduce the MPI reconstruction time, and even accomplish 3D real time MPI image with large field of view (FOV).

The permissible region strategy is a widely used strategy to reduce the computation complex and reconstruction time for several imaging techniques, such as, the fluorescence molecular tomography and X-ray computed tomography [6, 7]. This strategy is designed to compress the solution space and reduce the scale of solution with prior information, but in most conditions, it is difficult to select a proper permissible region. Thus, this strategy is usually used to reconstruct the targets in specific organs, like head or liver.

In recent years, a flexible region selection method on finite element mesh is proposed to acquire better reconstruction result [8]. This method gives an available region selection method and can be combined with permissible region strategy.

In this article, we introduce an adaptive permissible region (APR) strategy for MPI reconstruction. This strategy can apparently reduce the reconstruction time and even acquire high-quality reconstruction result. We give the details of APR strategy, and introduce the combination of this strategy and Kaczmarz method. We also verify the effect of APR strategy with experiments, and discuss the advantages and disadvantages of APR strategy.

II. Methods and materials

II.I. Inverse Problem of MPI

For the MPI technology, the system matrix S is usually used to connect the particle concentration c and the frequency components of the measured signal u [3]. This connection can be described as the linear system of equations:

$$Sc = u, \tag{1}$$

which system matrix $S \in \mathbb{C}^{m\times n}$, particle distribution $c \in \mathbb{R}^{+n\times 1}$ and measured signal $u \in \mathbb{C}^{m\times 1}$. In order to take into account the ill-conditioning of the system matrix and the noise of the measurement signal, 1 is usually transformed to the least-squares problem with regularized item:

$$c = \mathop{\mathbf{arg\,min}}_{c\geq 0} ||Sc - u||_2^2 + ||c||_2^2 \tag{2}$$

The reconstruction of MPI can be equivalent to solve 2, which means to recover the particle distribution c based on the system matrix S and the measured signal u, the iteration method . The Kaczmarz method is a common minimization method to solve this inverse problem in MPI. This method can approach the fixed point, which is the solution of linear system equations, with the iteration equation:

$$c_{i+1} = c_i - \frac{\langle s_j, c_i \rangle - u_j}{||s_j||_2^2} s_j \tag{3}$$

where $i = 1,2,3,\cdots,N$ when the iteration number is denoted by N and $j = 1,2,3,\cdots,m$ when $S \in \mathbb{C}^{m\times n}$.

II.II. Adaptive Permissible Region Strategy

In APR strategy, we first apply a fast reconstruction to acquire a coarse reconstruction result. In this research, we use Kaczmarz method with iteration number $N = 1$ to finish coarse reconstruction. With this coarse result c, we can divide the permissible region R_p through the threshold τ, which is a super parameter. To reduce the noise and make sure the region results more accuracy, we also process the R_p with Open operation and Dilate operation [9].

With an accuracy permissible region, we then compress the system matrix S and construct a new system matrix $\tilde{S}$ through selecting the columns that containing in R_p:

$$\tilde{S} = \{S(:,r)|R_p(r) > 0\} \tag{4}$$

Comparing to the original system matrix S, the new system matrix $\tilde{S}$ have less scale and this can greatly reduce the computation time of reconstruction. We then reconstruct the final result $\tilde{c}$ with $\tilde{S}$ and u with Kaczmarz method with iteration number $N = 9$.

The proposed APR strategy consists of the following steps:

1. Fast reconstruct with original system matrix S and measured signal u, acquire the coarse solution c.
2. Normalized the result c, delineate the permissible region R_p with c and a threshold τ.
3. Process the R_p with morphological operation.
4. Compress the system matrix S to R_p and acquire a new system matrix $\tilde{S}$ with a lower scale.
5. Reconstruct the final result $\tilde{c}$ with $\tilde{S}$ and u.

III. Experiments

To verify the performance of APR strategy, we separately apply the Kaczmarz method (KZ) and the Kaczmarz method with adaptive permissible region (APR-KZ) on the OpenMPI data set [10]. We use the system matrix S that griding to 37x37x37 and the scan sequence is 3D Lissajous. The measured signal of the resolution phantom with three channels is used after filtering with threshold $SNR = \sqrt{10}$. The parameters of both methods are set to same value, and the threshold τ of APR-KZ is test from 0.01 to 0.05. When threshold τ is higher than 0.05, the final result will be distortion and the quality will decrease, so we only perform the value lower than 0.05.

To evaluate the reconstruction result, we also construct the truth result through the phantom model containing in the OpenMPI data set. To acquire more accuracy result, the size of truth result is 128x128x128 and all the reconstruction result are resize to the same size with bilinear interpolation method.

IV. Results

The reconstruction results of the two methods with iteration number $N = 20$ and $\tau = 0.01, 0.05$ are shown in Fig 1. The reconstruction result of APR-KZ method with low value of τ is approaching to the KZ method, and the result have less noise and more clearly edge when the value of τ is larger.

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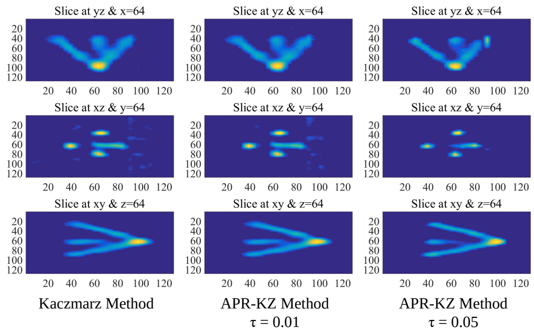

Figure 1: The slices of reconstruction result.

Three evaluation indexes are calculated: the normalized root mean squared error (RMSE), structural similarity (SSIM) and reconstruction time with the truth result. The evaluation result of two method is shown in Fig 2, and all the reconstruction method is with iteration number $N = 20$ and the regularization parameter $\lambda = 0.01$.

From the evaluation index, we can find that the APR strategy can obviously reduce the reconstruction time, and even promote the SSIM of result. The nRMSE of APR-KZ method rise abnormally when the τ increased. From image result, this performance may be caused by the lost of the blurred part in reconstruction result.

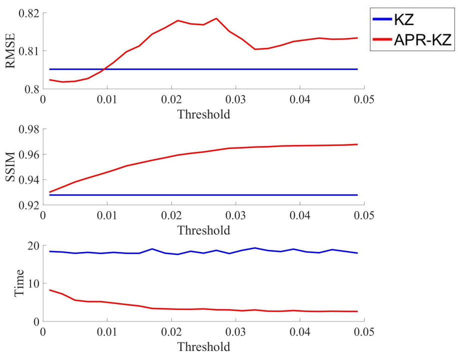

Figure 2: The evaluation indexes of reconstruction result.

V. Discussion

In experiment, we use same reconstruction parameter and iteration number to compare two method. The Kaczmarz method with APR strategy can obviously reduce the reconstruction time and promote the SSIM of result in all conditions. The parameter τ in low value can lead to the result similar to the KZ method, and leads to a clearer and sharper result in high value. However, when the parameter τ is so large, the blurred parts of result will be reduced, and have the risk of lost details information. A proper parameter needs to be selected to suit the specific tasks and condition.

VI. Conclusion

In this article, we proposed the APR strategy, which can reduce the reconstruction time and promote the reconstruction result. It can be applied to various situations, and combined to various of reconstruction method. This strategy even can become a general strategy in all kinds of reconstruction tasks in MPI.

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Author's statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Not applicable. Ethical approval: Not applicable.

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