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Robust dynamic inversion algorithm for the visualization in electrical capacitance tomography

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ABSTRACT

Electrical capacitance tomography (ECT) is considered as a promising visualization measurement technique, in which reconstructing high-quality images is crucial for real applications. In this paper, a robust dynamic reconstruction model, which incorporates the ECT measurement information and the dynamic evolution information of a dynamic object, is presented. Under the considerations of the low rank property of an ECT image and the inaccuracies on the sensitivity matrix, the reconstruction model and the measurement data, an objective functional that fuses the ECT measurement information, the dynamic evolution information of a dynamic object, the spatial constraint, the temporal constraint and the low rank constraint is proposed. An iteration scheme that integrates the advantages of the fast composite splitting (FCS) algorithm is developed for solving the proposed objective functional. Numerical simulations are implemented to validate the feasibility of the proposed algorithm.

1. Introduction

Acquiring the spatial material distributions of the inaccessible objects is vital for the monitoring and control of the complicated dynamic objects such as the multiphase flow systems and the combustion processes. Owing to the attractive merits, including the non-intrusive sensing, high temporal resolution, affordable cost, easy operation and high safety, ECT technology is proved to be useful in visualizing the distributions of the flame in the porous media and exploring the complicated dynamic behaviors of the state variables in a multiphase flow system [1–10].

ECT applications require solving ill-posed inverse problems to recover high-quality images from the low-dimensional and noisy observations. These challenging problems necessitate the use of the regularization methods by means of the prior models to capture the detailed information of the natural images. The resolution of the inverse problem can be achieved by minimizing the corresponding objective functionals that consider both a data fidelity term to the observations and the regularization terms reflecting the prior information of the unknown variables. In a word, ECT image reconstruction process consists of two procedures, such as the forward problem and the inverse problem. Under the considerations of the measurement noises and the real measurement requirements, common static ECT image reconstruction model is formulated as [11]:

$$\boldsymbol{S}\boldsymbol{x} = \boldsymbol{C} + \boldsymbol{r} \tag{1}$$

where $\boldsymbol{S}$ represents a matrix of dimension $m \times n$, and it is called as the sensitivity matrix in ECT image reconstruction; $\boldsymbol{x}$ is an $n \times 1$ dimensional vector standing for the permittivity distributions, which indicates the gray level values in the reconstructed images; $\boldsymbol{C}$ stands for an $m \times 1$ dimensional vector defining the capacitance values and $\boldsymbol{r}$

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is an $m \times 1$ dimensional vector indicating the stochastic measurement noises.

In the past years, numerous algorithms, including the static and dynamic reconstruction algorithms, have been proposed for ECT image reconstruction. Popular static reconstruction algorithms include the linear back-projection (LBP) method [12], the algebraic reconstruction technique (ART) [11], the simultaneous iterative reconstruction technique (SIRT) [11], the Tikhonov regularization method [13], the Landweber iteration algorithm [14–16], the offline iteration and online reconstruction algorithm [17], the truncated singular value decomposition method [11], the genetic algorithm [18], the generalized vector sampled pattern matching method [19], the generalized Tikhonov regularization methods [20–23], the simulated annealing algorithm [24], the neural network algorithm [25], the nonlinear Landweber iteration method [26], the level set algorithm [27] and the Calderon method [28]. It is worth mentioning that static reconstruction algorithms are often used to image a dynamic object. Owing to failing to utilize the dynamic evolution information and the temporal correlations of a dynamic object, unfortunately, applying such algorithms to image a dynamic object may not be an appropriate selection. ECT measurement tasks often involve the time-varying objects, and it may be more applicable to image a dynamic object using a dynamic reconstruction algorithm that fuses the dynamic evolution information and the temporal correlations of a dynamic object of interest. In the field of ECT image reconstruction, however, dynamic reconstruction algorithms do not attract enough attention at present. Fortunately, several algorithms, including the particle filter method [29], the Kalman filter method [30], the four-dimensional imaging method [31] and the Ensemble Kalman filter technique [32], had been developed to tackle dynamic reconstruction tasks. Owing to the complexities and particularities of the dynamic reconstruction tasks, overall, investigations of the dynamic reconstruction algorithms are far from perfect and finding an efficient algorithm remains an open problem.

More importantly, due to the ill-posed nature in ECT image reconstruction, the final inversion solution is sensitive to the inaccurate properties on the input data, including the measurement noises from the imperfect measurements, the model deviations from the approximation of the reconstruction model and the sensitivity matrix errors derived mainly from physically implementing an imperfect ECT sensor in real applications and the approximation solution of the sensitivity matrix. Common reconstruction methods often consider the inaccuracy of the capacitance measurement data. Especially, all previous studies depend on the assumption that the measurement noises have bounded energy. Without such assumption, unfortunately, it is hard to ensure a reliable estimation result [33]. Due to the restrictions of the imperfect measurement conditions, obviously, it is hard to satisfy such requirements in real measurements. Differing from existing reconstruction models, in this paper the outliers in the measurement data are emphasized with a motivation of satisfying the requirements of real measurement conditions, and a measurement model that considers the inaccurate properties on the capacitance measurement data, the reconstruction model and the sensitivity matrix is proposed for improving the reconstruction quality.

In the process of implementing the image reconstruction, additionally, common vector-based reconstruction algorithms fail to consider the spatial structure characteristics of a two-dimensional ECT image by arranging a matrix as a vector. Studies indicate that an ECT image often has the low rank property due to the spatial redundancy, and thus utilizing such prior information will facilitate the improvement of the reconstruction quality. Differing from common reconstruction algorithms, one of the main motivations in this paper is to exploit the low rank property of an ECT image to improve reconstruction quality.

One of the major bottlenecks that restrict the improvement of the reconstruction quality is the lack of information. Common reconstruction methods utilize the ECT measurement information, without the considerations of the dynamic evolution information and the temporal correlations of a dynamic object, and thus the improvement of the reconstruction quality is restricted. In this paper, a robust dynamic reconstruction model that integrates the ECT measurement information and the dynamic evolution information of a dynamic object is proposed to increase the quantity of the information and to exploit the temporal and spatial correlations of a dynamic object.

Acquiring high-quality images is crucial for successful applications of ECT visualization measurement method. This paper aims at improving the reconstruction quality, and the main contributions are summarized as follows:

(1) A robust dynamic reconstruction model that incorporates the ECT measurement information and the dynamic evolution information of a dynamic object is presented. Differing from existing static and dynamic reconstruction models, more importantly, the gross errors in the measurement data are emphasized. Particularly, incorporating the dynamic evolution information of a dynamic object does not add the cost of ECT system, which is significantly different from common multimodal systems.

(2) Under the considerations of the low rank property of an ECT image and the inaccuracies on the sensitivity matrix, the reconstruction model and the measurement data, an objective functional that fuses the ECT measurement information, the dynamic evolution information of a dynamic object, the spatial constraint, the temporal constraint and the low rank constraint is proposed, which differs distinctly from the previous reconstruction methods in its motivation and methodology.

(3) An iteration scheme that integrates the beneficial advantages of the FCS algorithm is developed for solving the proposed objective functional. The proposed algorithm can efficiently tackle the optimization problems with composite regularization terms. Numerical simulations are implemented to validate the feasibility of the proposed algorithm. More importantly, the proposed algorithm is a general framework for the solving of the inverse problems