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Data-driven reconstruction method for electrical capacitance tomography

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A B S T R A C T

The appealing superiorities, including high-speed data acquisition, nonintrusive measurement, low cost, high safety and visual presentation, lead to the success of the electrical capacitance tomography (ECT) technique in the monitoring of industrial processes. High-accuracy tomographic images play a crucial role in the reliability of the ECT measurement results, which provide the powerful scientific evidences for investigating the complicated mechanisms behind the behaviors of the imaging objects (IOs). Beyond the existing numerical algorithms that are developed for the solution of the inverse problem in the ECT area, a data-driven two-stage reconstruction method is proposed to improve the reconstruction quality (RQ) in this paper. At the first stage, i.e., the learning stage, the regularized extreme learning machine (RELM) model solved by the split Bregman technique is developed to extract the mapping between the tomographic images reconstructed by the some algorithm and the true images according to a set of training samples. At the second stage, i.e., the prediction stage, a new IO is reconstructed by the same algorithm used in computing training samples, and then the imaging result is considered as an input of the trained RELM model to predict the final result. The performances of the proposed reconstruction method are compared and evaluated by the means of the numerical simulation approach using the clean and noisy capacitance data with different noise levels (NLs). Quantitative and qualitative comparison results validate the practicability and effectiveness of the proposed data-driven reconstruction method. Research findings provide a new insight for the improvement of the reconstruction accuracy and robustness in the ECT area.

1. Introduction

High-precision images are crucial for the reliability of the ECT measurement results, which provide the powerful scientific proofs for the investigation of the complicated mechanisms behind the behaviors of IOs and the monitoring of industrial processes. The practicability and effectiveness of the reconstruction technique are greatly important in the ECT imaging area. A variety of algorithms have been put forth for ameliorating the visualization quality. Popular imaging techniques include the linear back-projection technique [1], the Tikhonov regularization (TR) method [2] and its variants [3–6], the Landweber technique [7–9], the offline iteration and online reconstruction (OIOR) algorithm [10], the truncated singular value decomposition method [11], the algebraic reconstruction technique (ART) [12], etc., and see [13–25] for more details about other imaging algorithms. Recently, owing to the importance of the image reconstruction problem, new imaging techniques, including the robust principle component analysis method [26], the sparse representation based imaging technique [27], the soft-thresholding iterative method [28], the sparsity-inspired image reconstruction algorithm [29], etc., have been proposed to improve the precision and reliability of the reconstruction results.

The above reconstruction techniques have made great contributions to real-world applications of the ECT measurement method. But, one of the dilemmas in the ECT measurements is the low reconstruction precision, which brings the great challenges on practical measurement tasks. It is greatly desired to find an efficient numerical method to ensure a high-accuracy reconstruction. Currently, a variety of numerical strategies have been introduced for improving the accuracy and reliability of the reconstruction results, which can be approximately summarized as follows:

(1) The reformulation of the reconstruction model.

The ECT image reconstruction problem is essentially nonlinear. Two kinds of imaging models, i.e., the linearization model and the nonlinear model, are available for modeling the ECT imaging

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problem. Some researches propose to employ the nonlinear imaging model or modify the sensitivity matrix or introduce the imprecision of the imaging model to make reconstruction results better.

(2) The design of the loss function and the utilization of the prior information.

In order to overcome the influences derived from the ill-posed attribute and the inaccurate properties of the input data, the ECT imaging task is often converted into an optimization problem. A popular representation is the TR method, in which the ECT image reconstruction task is cast to be a minimization problem. The method concludes two main key parts, i.e., the data fidelity term and the regularization term that integrates the prior information and promotes solutions with desirable properties. Research findings have proven that the introduction of the priors of solutions can greatly increase the reconstruction precision. This issue has been intensely studied, and diverse priors have been abstracted to fuse into the imaging model to ameliorate the visualization precision and the reliability of imaging results. In a word, the design of the loss function is crucial for the optimization-based imaging algorithm, and it directly influences the reconstruction result.

(3) The integration of the ECT measurement information and the dynamic evolution information of the reconstruction targets.

The integration of the ECT measurement information and the dynamic evolution information from the physical models that the imaging targets obey will increase the quantity of information, thereby leading to the amelioration of the reconstruction accuracy. In practical measurements, the IOs always obey physical models and can be described by a set of mathematical equations. Commonly, we can get the dynamic evolution information via solving the governing equations according to the given conditions, e.g., initial conditions, boundary conditions, geometrical conditions, physical properties, etc. Besides, it should be pointed out that the method does not significantly add the measurement cost.

(4) The development of the iteration scheme.

As far as the optimization-based imaging techniques, developing a fast and stable computation method is especially important. Presently, various strategies or skills have been developed for accelerating the convergence of a computational method and ensuring the numerical stability. However, it is necessary to highlight that the development of the iteration scheme is related to the loss functions. The design of the loss function is a critical problem in the light of the fact that it significantly influences the quality of an inversion solution.

Although above strategies have been shown to be effective in dealing with simple imaging tasks, their limited capability may cause difficulties when coping with more complicated reconstruction targets. There are still formidable challenges before desirable imaging results can be realized. Naturally, a pivotal problem will arise, i.e., are other methods or strategies available for improving the precision and reliability of the reconstruction results? In practical applications, we find that there is a difference between the tomographic images from a certain reconstruction method and the true images. Is there a relationship between the two? If the answer is yes, a series of problems will arise, e.g., how to exact such mapping relationship? How to utilize such relationship to improve the reconstruction precision and increase the reliability of the imaging results?

With the above motivations in mind, beyond existing imaging techniques, in this study we put forth a data-driven reconstruction method to increase the precision and reliability of reconstruction results, and the main highlights can be summarized as follows:

(1) Beyond existing ECT reconstruction techniques, we put forth a data-driven two-stage imaging framework to improve the accuracy and reliability of reconstruction results. Above all, the proposed reconstruction method provides a new way for effectively utilizing the prior information from previous measurements or numerical simulation results.
(2) The proposed reconstruction method includes two stages. At the first stage, i.e., the training stage, the RELM model solved by the split Bregman method is developed to extract the mapping between the reconstruction images from some algorithm and the true images in the light of a set of training samples. At the second stage, i.e., the prediction stage, a new IO is reconstructed by the identical algorithm used in computing the training samples in accordance with the provided new capacitance data, and then the reconstruction result is regarded as an input of the trained RELM model to predict the final visualization image.
(3) Numerical experiments are performed to validate the effectiveness and superiority of the proposed data-driven reconstruction method. Moreover, research findings of the paper provide a new methodology for improving the accuracy and reliability of the reconstruction result in the ECT imaging area, which may be useful for analogous problems in other areas.

In view of the research objective, we organize the remnants of this paper as follows. We revisit the ECT imaging model in Section 2. Beyond existing imaging techniques, in Section 3 we put forth a data-driven reconstruction method. In Section 4, the RELM model solved by the split Bregman algorithm is developed to abstract the mapping between the reconstructed tomographic images and the true images according to a set of training samples. Section 5 performs numerical experiments, qualitative and quantitative comparison results are discussed. Finally, the research conclusions are summarized in Section 6.

2. Reconstruction model

Before presenting the proposed data-driven imaging method, we firstly revisit the mathematical model about the ECT imaging problem.

According to the results of the theoretical studies, the electrical field inside an ECT sensor can be described by the following differential equation [1]:

$$\nabla \cdot [\varepsilon(x,y)\nabla\phi(x,y)] = 0 \tag{1}$$

where the dielectric constant and the electrical potential distributions are defined as $\varepsilon(x, y)$ and $\phi(x, y)$, respectively.

Accordingly, the following equation is introduced to formulize the relationship between the capacitance and permittivity distribution [9]:

$$C = -\frac{1}{V}\iint_{\Gamma} \varepsilon(x,y)\nabla\phi(x,y)\mathrm{d}\Gamma \tag{2}$$

where the potential difference between the source and detector electrodes is defined as V; Γ means the electrode surface.

The primary purpose of the image reconstruction is to estimate unknown variable, $\boldsymbol{x}$, from the given sensitivity matrix, $\boldsymbol{S}$, and capacitance data, $\boldsymbol{y}$, with the consideration of the measurement noise, $\boldsymbol{r}$, which can be approximately summarized as the following mathematical model, i.e.,

$$\boldsymbol{Sx} = \boldsymbol{y} + \boldsymbol{r} \tag{3}$$

where the dimensionalities of $\boldsymbol{S}$, $\boldsymbol{x}$, $\boldsymbol{y}$ and $\boldsymbol{r}$ are $m \times n$, $n \times 1$, $m \times 1$ and $m \times 1$, respectively. It is necessary to note that Eq. (3) is a basic model, and applying different methods to solve it will give rise to different imaging algorithms.

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