

Image reconstruction using adaptive mesh refinement based on adaptive thresholding in electrical impedance tomography



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HIGHLIGHTS

- An adaptive mesh refinement technique is applied to two-phase flow imaging using EIT.
- An optimal threshold is automatically computed by Otsu's method.
- The total number of unknown variables is reduced.
- The accuracy of reconstructed images is improved using the proposed method.

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ABSTRACT

As an alternative noninvasive technique, electrical impedance tomography has been employed to visualize two-phase flows, because of its fast response for monitoring flow processes. However, it still suffers from poor resolution of reconstructed images due to non-linearity and ill-posedness of the inverse problem. To overcome this problem, in this paper, an adaptive mesh refinement method based on an adaptive threshold technique is proposed to improve the image resolution of the Gauss-Newton method without any prior information. Both numerical and experimental studies have been carried out and the results show that the proposed method has better performance as compared to the conventional method.

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1. Introduction

Understanding two-phase flows is essential for the design and safe operation in many industrial applications. Electrical impedance tomography (EIT) has been used as an alternative non-invasive modality to visualize two-phase flows (Haegel et al., 2011; Jones et al., 1993), because of low cost and fast response for monitoring flow process. The image reconstruction in EIT is composed of the forward and the inverse problems. In the forward problem, the voltages on the electrodes mounted on the domain boundary are calculated with the assumed conductivity/resistivity distribution (i.e. phase distribution) and the known boundary conditions. In the inverse problem, the conductivity/resistivity distribution is updated to minimize the difference between the calculated and the measured electrode voltages. This process is repeated until the preset criteria are satisfied. However, reconstructed images

still suffer from poor spatial resolution due to non-linearity and ill-posedness of the inverse problem. To overcome this problem, the inverse algorithms with various techniques have been proposed, for example, prior information (Vauhkonen, 1997), mesh refinement technique (Molinari et al., 2002), grouping method (Cho et al., 2001; Kim et al., 2004), total variation regularization (Borsic et al., 2007), etc. In this paper, we are interested in algorithms with adaptive mesh refinement, which are described in more detail.

Usually in EIT, the inverse problem uses coarser meshes than the forward problem because the inverse solution is more time consuming. If a pre-selected inverse mesh is too coarse, it may lead to poor resolution of the reconstructed images. Therefore, to have better resolution for the reconstructed images, inverse mesh has to be refined properly. It would be desirable if only regions of interest (ROIs), for example, bubbles or voids, could be refined adaptively, not over the whole domain. However, it is difficult to determine the ROIs without any prior information.

In order to improve the resolution of reconstructed image, various methods have been developed by several researchers regarding mesh refinement strategy in electrical tomography. Molinari et al.

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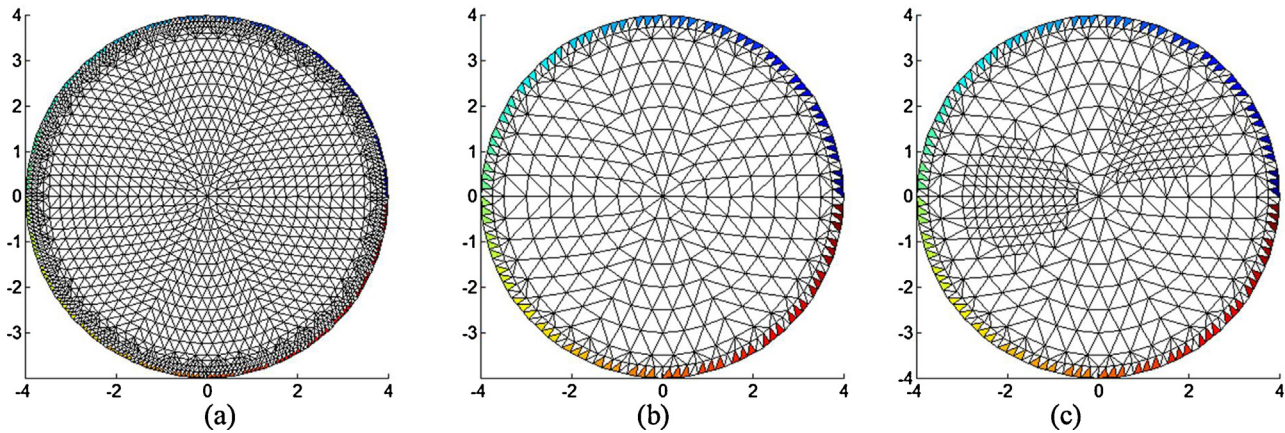


Fig. 1. The FE meshes used in this study: (a) forward fine mesh with 3104 elements, (b) inverse coarse mesh with 776 elements and (c) adaptive mesh with 1042 elements (one of examples). The colored regions in the boundary represent 32 electrodes. (For interpretation of the references to color in this text, the reader is referred to the web version of the article.)

(2001) proposed an adaptive mesh refinement algorithm based on a *a posteriori* error estimate, in which the mesh structure was automatically adapted to the reconstructed image by producing finer meshes in areas where there were sharp conductivity gradients in the image. In their method, the mesh was refined where the error estimate was larger than a pre-defined threshold value. Molinari et al. (2002) updated their previous method, which did not require user interaction and prior information about boundaries or approximate material distributions. In their method, the mesh is automatically refined in the regions with high conductivity gradients using the χ^2 -statistics based on the logarithmic conductivity differences, observed and predicted voltages. Peng and Mo (2003) proposed an adaptive mesh refinement method to produce finer meshes by comparing with a pre-selected threshold and the modules of wavelet coefficients based on estimated impedance distribution. If the module was larger than the threshold value, the finite element (FE) mesh of the relative local region was refined by *h*-refinement (Burnett, 1987), i.e. the element is refined locally by adding node points. Kim et al. (2005) developed a boundary estimation algorithm for the detection of phase boundaries by employing an adaptive mesh regeneration technique to fit the mesh structure to the estimated phase boundary. In their approach, the resistivity value of each phase is assumed to be known and the phase boundaries were expressed as truncated Fourier series. Based on the coordinates of phase boundaries, they generated an FE mesh such that there were no mesh-crossing elements on the phase boundary. Wang et al. (2007) developed an adaptive mesh refinement strategy by producing finer meshes in areas with sharp permittivity gradients based on total variation (TV) in solving the inverse problem. Usually, the TV functional is often used as a penalty term in the regularization of inverse problems. In their paper, TV regularization was used to detect jump changes in permittivity distribution. A few mesh edges were selected as being 'interested' based on the pre-determined threshold from TV regularization term plotted against sorted permittivity vector. The permittivity gradient between the neighboring elements sharing the 'interested' edge was much bigger than that of the other edges, which meant that those elements attached with the selected edges had sharp discontinuities and were needed to be refined. In their method, the complexity of the reconstruction depended on the selection of a threshold that was defined in advance. Sawicki and Okoniewski (2010) developed a 3-D adaptive mesh refinement technique to evaluate proper modeling of skin contact electrodes. In this method, each cell (element) with an appropriate error value higher than an experimentally chosen threshold value was refined.

Mesh refinement strategies in previous works have been conducted based on a pre-defined threshold value. A threshold may be dependent on the number, the distribution, and the shape of the anomalies in the domain. In the worst case, improper threshold may deteriorate the image reconstruction performance. Therefore, to solve this problem, a threshold should be selected adaptively according to the situation. In this paper, adaptive mesh refinement technique based on an adaptive threshold is proposed to improve the image reconstruction performance without any prior information. An optimal threshold is selected automatically by using Otsu's method (Otsu, 1979). Otsu's method is one of adaptive threshold techniques, which is used in this paper to roughly separate the background from anomaly regions (ROIs) based on a resistivity profile estimated by one-step Gauss-Newton (GN) method in a given flow domain (Kim et al., 2011). Based on an adaptive threshold value, the elements within ROIs are refined and the elements within the background regions are grouped. Inverse mesh that employs the adaptive mesh refinement method is used with iterative GN method to estimate the resistivity distribution. Both numerical and experimental studies have been carried out to validate the performance of the proposed method and their results are compared with the conventional method without employing refinement procedure.

2. Method

2.1. Forward problem

The EIT forward solver computes boundary voltages based on a given conductivity distribution and injected currents through the electrodes placed on the periphery of the object to be imaged. The finite element method is employed to obtain the forward solution, and the governing equation and the boundary conditions are omitted in this paper. For details about FE model solution for the EIT forward problem see Vauhkonen (1997).

2.2. Iterative Gauss-Newton method

The relationship between the boundary voltages U and the resistivity distribution ρ is nonlinear. To solve this nonlinear inverse problem, the following objective function can be formulated

$$\Phi(\rho) = \frac{1}{2} \|U(\rho) - V\|^2 + \frac{1}{2} \alpha \|\mathbf{R}(\rho - \rho^*)\|^2 \quad (1)$$

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