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Dual modality electrical impedance and ultrasound reflection tomography to improve image quality

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Abstract

Electrical impedance tomography (EIT) is relatively new. It is a very promising technique to be developed especially in the medical field. The advantages of EIT are that it is non-ionizing, simple, and portable and that it produces a high contrast image. Unfortunately, this modality does not have the capability to generate a high-resolution image. Almost all imaging modalities has both advantages and disadvantages. Combining one modality with another is hence expected to cover the weaknesses of each other. The problem is how to develop the concepts, measurement systems and algorithm of dual modalities, particularly electrical and acoustical. The electrical modality can produce high contrast and the acoustical modality can produce high resolution. Combination of these will enhance the image resolution of EIT. High image resolution from the ultrasound reflection tomography is used as the prior information to improve the image resolution of the EIT. Finite Element Model (FEM) can be arranged by non-uniform elements, which are adapted to the boundary. Element models with higher density are arranged at the boundaries to obtain improvements of resolution and the model elements with lower density arranged at other locations to reduce the computational cost. The dual modality EIT with Ultrasound Reflection (EIT-UR) can produce high resolution and contrast image. The resolution improvement can also accelerate the convergence of the Newton-Raphson reconstruction methods.

Keywords: Improved quality, electrical impedance tomography, ultrasound reflection imaging, multimodal imaging, image resolution, image contrast.

Introduction

Electrical Impedance Tomography (EIT) is a technique used to obtain conductivity distribution by injecting current and measuring voltage on the surface of the object. EIT has many advantages, include portability, real time acquisition, non-invasiveness, and low cost and it generates a functional image (Yaqin, 2010). However, the disadvantage of EIT is the low-resolution image. To improve imaging resolution, it has been developed by combining the two modalities between electrical conductivity techniques that have high contrast and magnetic fields or ultrasound imaging techniques that have a high resolution. Several techniques that have been conducted are magnetic resonance electrical impedance tomography (MR-EIT), magnetoacoustics, electroacoustics, acoustoelectrics, and electrical impedance ultrasound reflection tomography (EIT-URT).

MR-EIT is an imaging technique that combines EIT and MRI (magnetic resonance imaging). EIT can produce high contrast images based on electrical impedance and MRI can produce high-resolution images. The utilized technique in the MR-EIT is a magnetic resonance current density imaging (MRCDI) (Woo, *et.al.*, 1994). The technique works by injecting electric current in the object and measuring the induced magnetic flux using an MRI scanner. Data noise of the magnetic flux is dependent on the performance of the current source. Therefore, the performance of current source greatly affects the image quality. The magnetic induction B and electric current density J can be used to obtain an electric current path so that the conductivity

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distribution can be imaged. This is the main reason why MR-EIT is able to eliminate ill-posed problems in EIT.

MAT-MI (Magnetoacoustic Tomography-Magnetic Induction) is an imaging technique that combines ultrasound and magnetism. The study was proposed by Xu and He (2005) by simulations and experiments, to reconstruct electrical impedance by integrating magnetic induced and acoustical signals. The study shows that MAT-MI can reconstruct conductivity of biological tissues with high resolution and contrast.

Wen and Balaban (2004) proposed the technique of electroacoustic imaging. The principle of electroacoustic imaging is an injection of voltage pulses on the object. The voltage pulse will transfer electrical energy to produce heat, which will be converted into acoustic pressure. The study used 400 Volt pulses with 300 ns width. The study dealt with electroacoustic imaging, but it was still limited to the acoustic signal, while the electric signal was not discussed.

A mathematical study of electroacoustics by injecting current has been done. The study proposes a combination between EIT and acoustic tomography. The energy of the electrical current flowing in the body will be absorbed and cause an increase of the temperature. The change in temperature will lead to an expansion effect, thus inducing an acoustic wave. The relationship between rate of variation in energy, absorbed electrical power and electric potential is according to the Joule law. By modeling, the acoustical signal from the body can be generated by injecting an electrical pulse of 3A with a pulse width of 1 µs. The study is still limited to simulations; the experiment has not yet been done (Gebauer and dan Scherzer, 2008).

The reverse of electroacoustics is acoustoelectrics. Kuchment and Kunyansky (2011) proposed and tested the algorithm to reconstruct internal conductivity of biological tissue by using acoustoelectric methods. Numerical simulation showed that the methods could generate high quality images. However, it has not been studied whether an injected acoustic signal can generate an electrical signal in the experimental object.

Yang, *et al.* (2012) proposed Ultrasound Joule Heat Tomography. The technique used an ultrasound pulse to generate an acousto-electric effect. The study had been done by simulation of tumor cases. The simulations were carried out by injecting an alternating current of 200 Hz and 20 mA. The technique was only able to produce a change in conductivity of 10^{-9} S/(m·Pa) so that it required a high accuracy experimental equipment.

Combination between EIT and ultrasound reflection tomography (URT) has been done to monitor cryosurgery. The method used additional URT data to identify some point of boundary anomalies and uses the level set algorithm to reconstruct it. The level set method has the advantage that it can handle multiple objects at once. However, the level set method was only accurate when the objects were under two conditions, in this case the frozen and normal tissue (Soleimani, 2006).

High-resolution images of electrical impedance tomography can be obtained by using adaptive mesh refinement techniques (Dehghani and Soleimani, 2007). The technique works by refining the mesh in the location where the potential changes in the forward problem solution or the conductivity changes in the inversion problem solution (Min and Zhong, 2006). However, this technique still has a problem of disordered mesh elements in size, so that the reconstruction image is not optimal (Molinari, *et al.*, 2002).

We propose ultrasonic reflection as extra data to identify the surface details of an object. The surface of the object is then used as the prior information to build an element model. The element model is not built as a uniform model; close to the boundary surface of the object, it will have a higher density of elements than far from the surface of the object. Therefore, it will be generated a higher resolution image than by the uniform element model. We wanted to see if the method could reconstruct some anomaly objects with different impedance that were suitable to reconstruct a complex object like the chest. The combination between EIT and ultrasound is realistic to be implemented, because the EIT technique and imaging ultrasonic reflection have both been commonly used in the medical field.

Methods

The research used algorithms to solve forward problems by neighboring collection methods (Hua, *et al.*, 1994). The solution of the forward problem involves the Laplace equation, Dirichlet and the Newman boundary. The solution of the forward problem is very important, because it is used to obtain sensitivity or the Jacobian matrix to complete the linear reconstruction or the Newton-Raphson method (Cheney, *et al.*, 1999). The project uses 16 channels with the same size and width of the electrodes as shown in Figure 1 and an EIT experimental device using the module in Figure 2.

The phantom is a cylinder of 21 cm diameter and 6 cm height. There are 16 copper electrodes with width 2 cm and 6 cm height. The phantom is filled with distilled water and the anomaly object. The anomaly objects are made from insulators and conductors. They are a rubber cylinder with diameter 7 cm, aluminum cylinder with diameter 5 cm and a combination of them as shown in Figure 1.

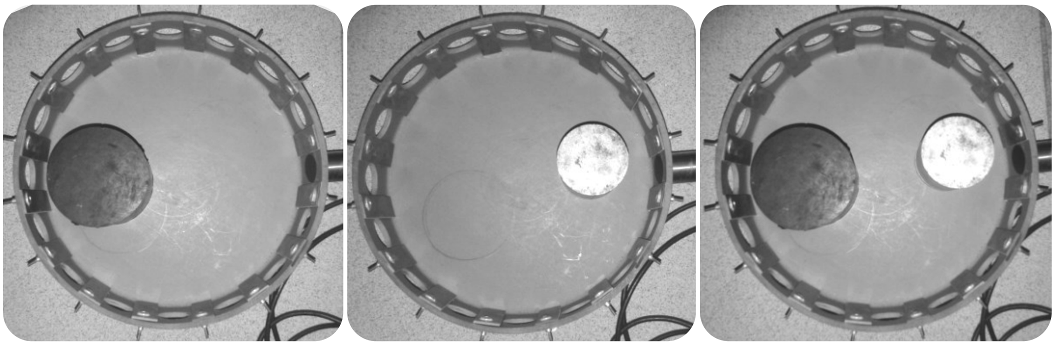


Figure 1: The phantom uses distilled water as medium and (a) insulator, (b) conductor, and (c) insulator-conductor

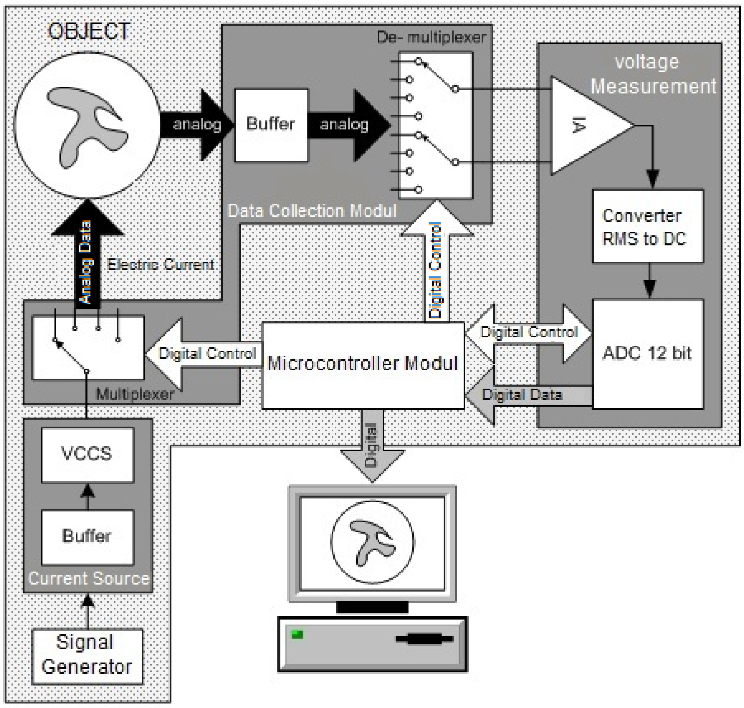


Figure 2: Data acquisition of electrical impedance tomography

The element model has 32 nodes on the surface with equal distances between the nodes. The electrodes can be modeled by connecting two points that are neighboring. The element model can be built from the nodes with element number as necessary, but the condition that has to be met is 32 nodes, because it reflects the number of electrode channels used. The model of uniform elements are shown in Figure 3, whereas models of non-uniform elements are shown in Figure 4.

An ultrasound transducer can be used as the transmitter and receiver by providing voltage pulses on the body of the transducer. It can be used for ultrasound reflection tomography. The configuration of the experimental equipment is shown in Figure 5.

Rotation of the transducer position like a fan beam generates the data collection. Each of the fan beams should provide 15 measurement data points, but only11 are used with the consideration that the four measurement data points at the edge can be ignored. Position data collection is illustrated in Figure 6. The complete data obtained is 16 × 11 measured values.

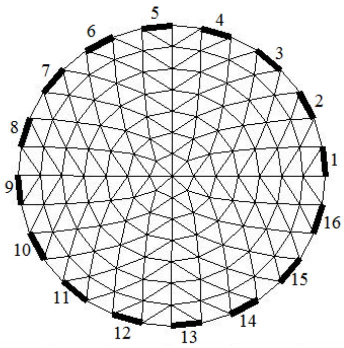


Figure 3: The uniform element model with 141 nodes, 248 elements and 16 electrodes channels

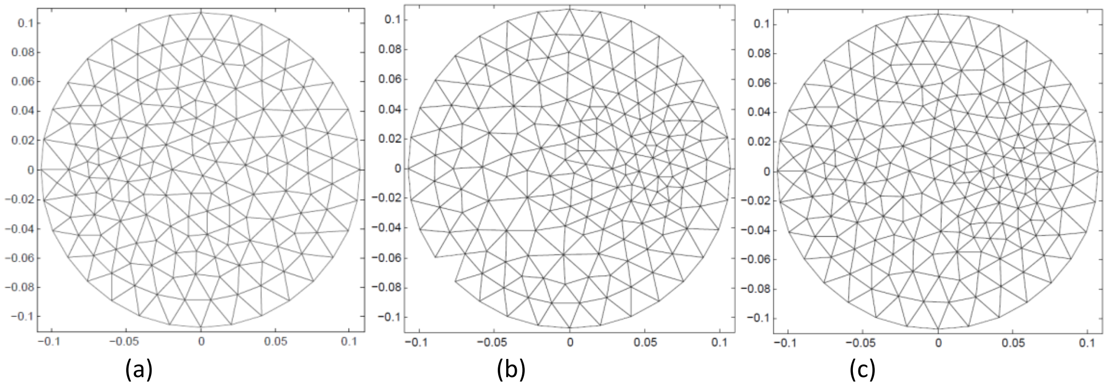


Figure 4: Non-uniform element model with (a) 166 nodes and 298 elements, (b) 179 nodes and 324 elements, and (c) 201 nodes and 368 elements

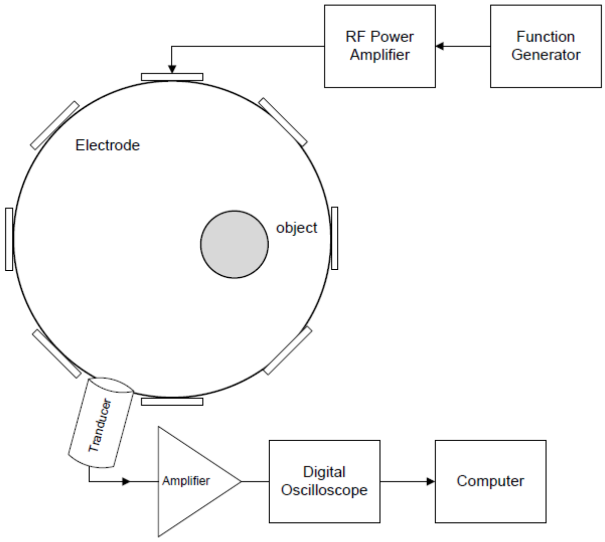


Figure 5: Experiments configuration of ultrasound reflection tomography

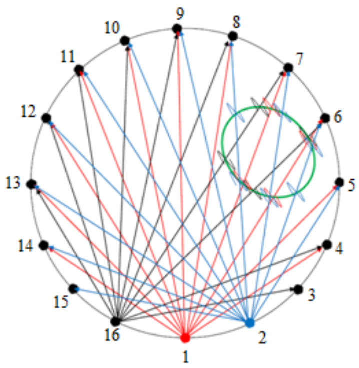


Figure 6: Pattern of data collection

The analysis was performed by comparing the reconstruction image to object references. The reconstruction image and references can be displayed as a line profile. Then the parameters error of the spatial resolution is calculated by comparing the surface of the image reconstruction and the surface of the reference object, which can be written as equation (1). This equation represents the numerical analysis of the spatial resolution of the reconstruction image. The smaller the parameter error of spatial resolution is, the higher the spatial resolution of the image.

$$R_s = \frac{\Delta R_s}{\Gamma} \times 100\% \tag{1}$$

where ΔR_s is the difference between the surface of the reconstruction image and the reference, and Γ is the width of the line profile. Comparing the objective function in the Newton-Raphson method was also performed in this analysis. The smaller the value of the objective function, the better the reconstruction image, because its objective function shows the compatibility between the potential models and measurements.

Results and discussion

Scanning is done on the object experimentally use EIT equipment to obtain the electric potential data shown in Figure 7.

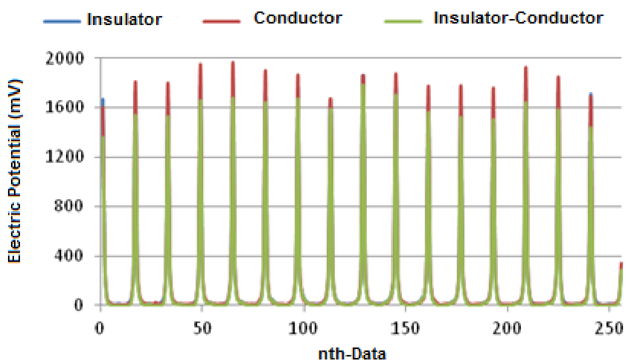


Figure 7: Electrical potential data of experiment scanning on neighboring data collection

Reconstruction elements are built from two element models. The first one is uniform elements and the second one is non-uniform elements. These models of the elements are shown in Figure 3 and 4.

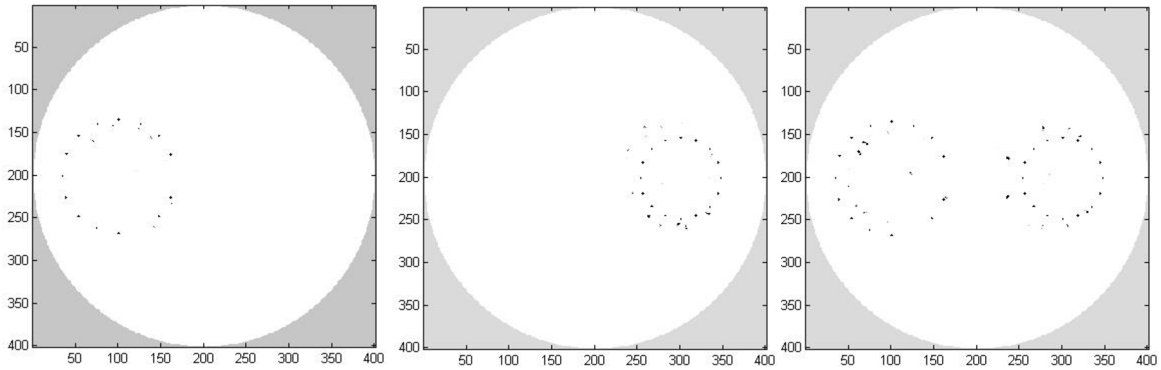
By using the experimental setup in Figure 6, each phantom is scanned to obtain the complete potential data matrix with 16 × 11 size. Potential data of ultrasound reflection is reconstructed to be the 400 × 400 pixels image. Utilization of the back projection method completes the reconstruction process, particularly by using these algorithms:

1. Reflection of signal data
2. Filtering the noise
3. Converting the signal data to absolute data
4. Converting the absolute signal data to envelope data
5. Interpolation of the envelope data
6. Reconstruct all envelope data using back projection methods

The reconstruction image from the reflection data is displayed in the form of its complement in Figure 8.

Visually, Figure 8 generates images that describe the boundary of an object marked by dots along the surface of the internal object. Furthermore, the boundary points of the object is interpolated to obtain the equation of the boundary line. The line equation is used as prior information to build non-uniform elements that are used to enhance the image resolution in electrical impedance tomography.

The experimental potential data in Figure 7 is reconstructed by linear methods and it will produce the reconstruction images in Figures 9 and 10. The reconstruction image of the relative method uses a uniform element model and alpha 0.01, while the non-uniform element models use an alpha of 0.006, 0.005, and 0.05 respectively.



(a) (b) (c)

Figure 8: Reconstruction images of ultrasound reflection. (a) Rubber cylinder in the left side, (b) Aluminium cylinder in the right side, and (c) Rubber and Aluminium cylinder in the left and right side.

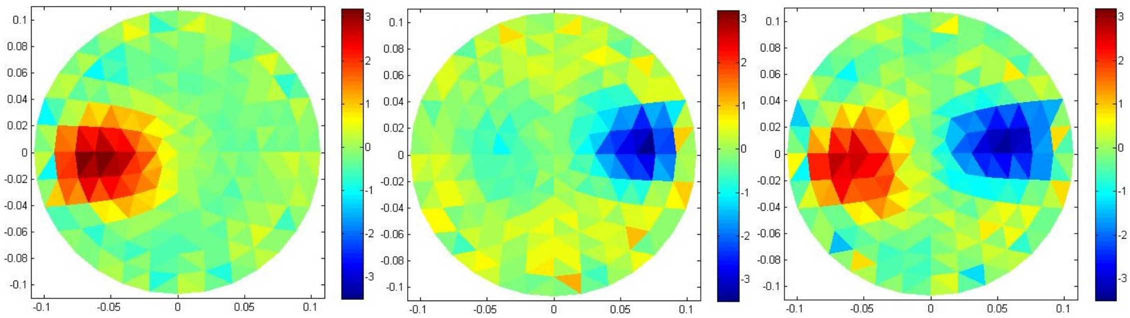


Figure 9: Reconstruction image of the relative method in uniform elements model

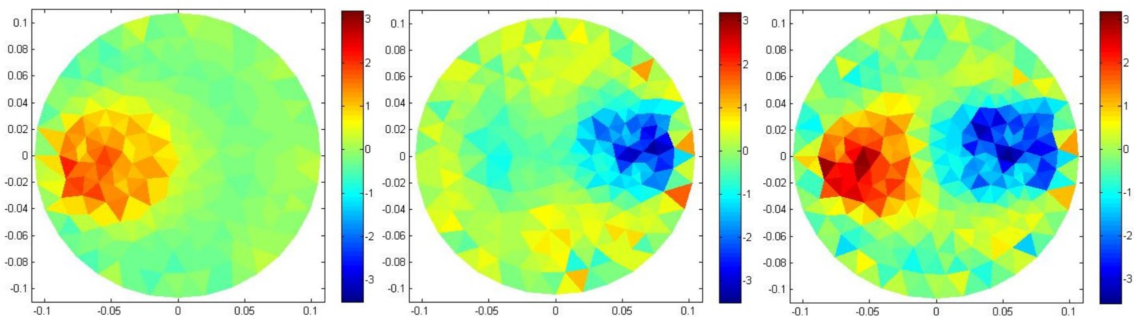
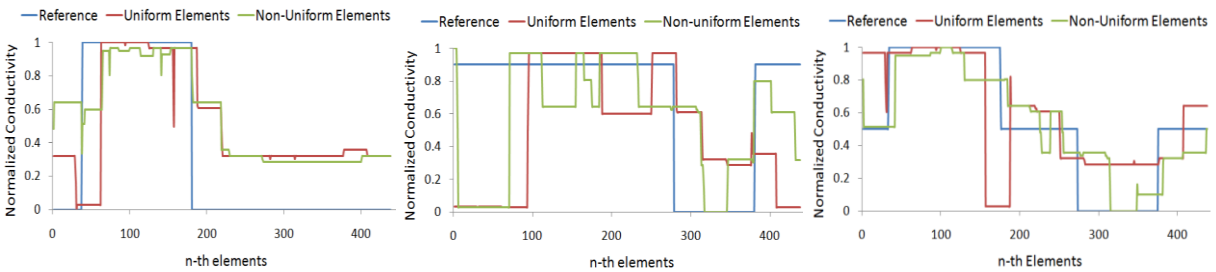


Figure 10: Reconstruction image of the relative method in non-uniform elements model

Analysis of the spatial resolution can be done through the line profile. The reconstruction image in Figure 9 and 10 can be analyzed by means of the line profile shown in Figure 11. If the reconstruction is done by the Newton-Raphson iteration method, potential data in Figure 7 will produce the reconstruction image in Figures 12 and 13. The Newton-Raphson reconstruction method does iteration 5 times, and a regularization constant of 10^{-7} and 10^{-6} is applied to the uniform and non-uniform element models, respectively.

The objective function for five times of iteration using a model of uniform and non-uniform elements are shown in Figure 14. It can be seen that non-uniform element model has an objective function that is smaller than for the uniform element model. This shows that the non-uniform element model is better than the uniform element model.

Analysis of the spatial resolution can be done through the line profile. Hence, the reconstruction images in Figures 12 and 13 can be analyzed to produce their line profiles shown in Figure 15.



(a) (b) (c)

Figure 11: The line profiles of the reconstruction image from uniform and non-uniform elements compared to reference. (a) Insulator, (b) conductor, and (c) insulator-conductor

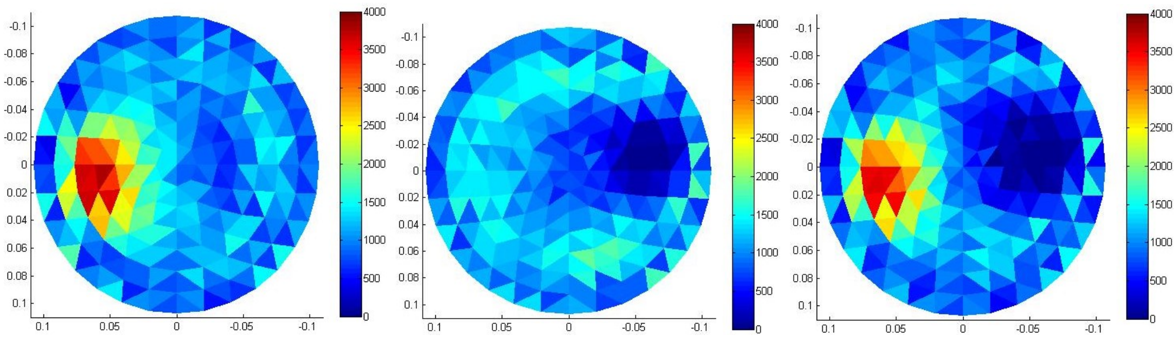


Figure 12: Reconstruction image of the Newton-Raphson method in uniform elements model

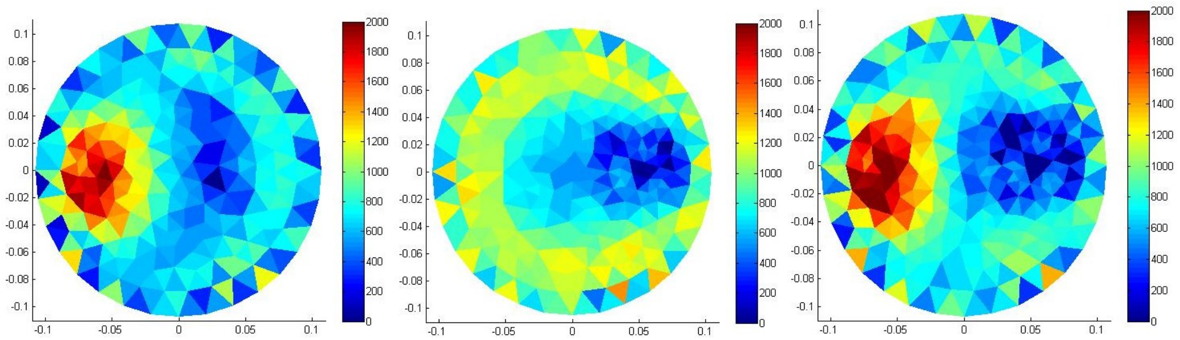


Figure 13: Reconstruction image of the Newton-Raphson method in non-uniform elements model

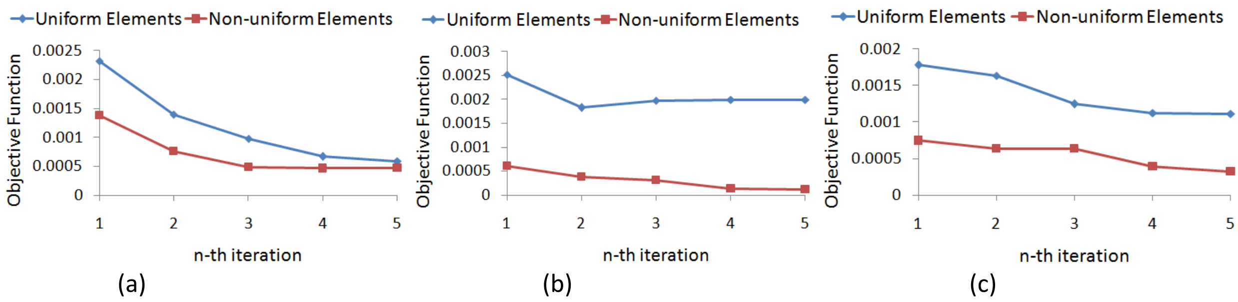


Figure 14: Objective function from iteration process of neighboring collection methods with anomaly objects. (a) Insulator, (b) conductor, and (c) insulator-conductor

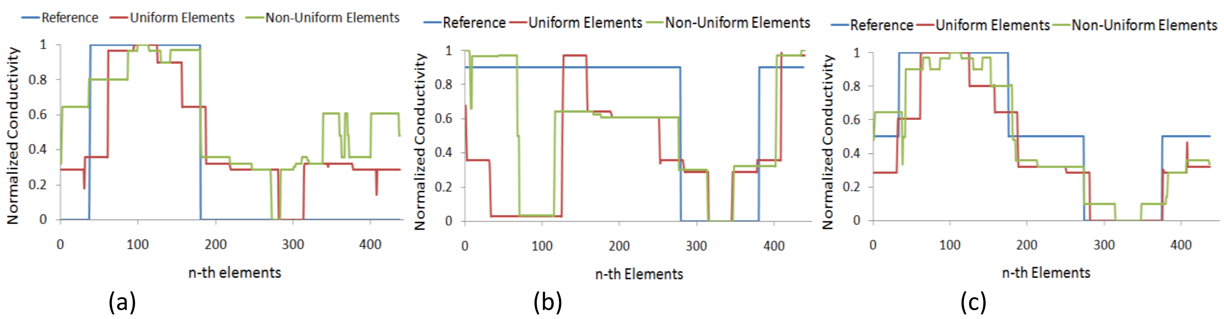


Figure 15: Line profile of reconstruction images from the Newton-Raphson methods of uniform and non-uniform elements compared to reference. (a) Insulator object, (b) conductor object, and (c) insulator-conductor object

Error analysis of spatial resolution with equation (1) can be done on its line profile in Figures 11 and 15 providing the results shown in Table 1.

Table I: Error analysis on spatial resolution of linear and Newton-Raphson reconstruction methods using insulator, conductor or a combination

Elements	Linear reconstr. methods			Newton-Raphson reconstr. methods		
	Insu.	Cond.	Insu-Cond	Insu.	Cond.	Insu-Cond
Uniform	3.5	4.6	4.4	3.3	6.3	1.3
Non uniform	3.1	3.9	3.7	0.22	2.6	1.1

Table I shows that the boundary surface can be used as initial information to model non-uniform elements to obtain the reconstruction image with a spatial resolution better than a uniform element model. Similarly, Figure 15 provides information that the resolution improvement can accelerate the convergence of the Newton-Raphson reconstruction methods.

Conclusion

The image of boundary objects from acoustic modalities can be used as initial condition to determine non-uniform elements in an EIT image. The image has spatial resolution higher than a uniform element model without increasing the number of elements used.

The combination of the two modalities of acoustic and EIT has been tested on linear and Newton Raphson reconstruction methods to produce images with non-uniform elements. The method has reduced the error in the spatial resolution from 3.9% to 2.4%, accelerated the convergence and lowered the objective function in the Newton-Raphson reconstruction.

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