Automated Scaling Region of Interest with Iterative Edge Preserving in Forward-Backward Time-Stepping

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DECLARATION

The work presented in this thesis, to the best of my knowledge and belief, original and my own work, except as acknowledged in the text. The thesis has not been accepted for any degree and is not concurrently submitted in candidature for any other degree.

______________________________

Name : Juliana Binti Nawawi

Date : 16 May 2019
DEDICATION

Dedicated to my beloved parents
ACKNOWLEDGEMENT

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Thanks again to those who have been directly or indirectly involved in completing this research work and thesis.
ABSTRACT

The thesis reported on a deterministic inverse scattering method in time-domain to reconstruct dielectric profiles of an unknown embedded object within its peripheral region. Image reconstruction of geometrically simple objects taken after breast profiles and lung(s) model are solely done by simulation executed in single computing. In effort to alleviate the nonlinearity problem of inverse scattering, the inversion technique has been integrated with varied types of techniques to improve the inversion solution. The extended algorithm would only increase the computational cost, nevertheless would never eliminate the nonlinearity problem that degrade the inversion solution. The reconstruction process started in a coarse region which then rescaled down according to object geometry configuration. This is accomplished by combining an inversion technique of Forward-Backward Time-Stepping (FBTS) with an Automated Scaling Region of Interest (AS-ROI) method. Edge preserving techniques comprises of edge preserving regularization and anisotropic diffusion are integrated into the combined FBTS and AS-ROI to further increase the accuracy level in the profiles’ intensity. Accuracy of reconstructed object is validated by using mean squared error (MSE), relative error (RE) and Euclidean distance (ED) that measure the precision in terms of pixels’ intensity, size and localization. Results exhibited significant improvement in the accuracy level of reconstructed images with a combined method of FBTS and AS-ROI. AS-ROI has successfully increased the pixels precision in relative to FBTS about 10.33% for breast model and 25.17% for lung model. The accuracy increment by AS-ROI is due to better fields penetration as exterior pixels are replaced with background layer of low profiles. In the combined rescaled and regularized method in FBTS, edge preserving smoothing filter and regularization are alternately imposed on the improved reconstructed profiles by AS-
ROI. Therefore, the accuracy is further increased to 18.58% and 40.68%, respectively for breast and lung model. In term of size estimation, average error in object’s radius is analogous to accuracy level measured in MSE. It indicates that efficiency of AS-ROI is highly relied upon the accuracy of FBTS estimation in reconstructing image profiles prior to rescaling process. Apart from that, accuracy in size estimation differ for varied shapes due to number of pixels at the boundary. Average RE is 61.94% for a circular shape in breast model, meanwhile attains RE of 4.17% for a U-shape object. The highest RE for a single circular tumour’s size in lung model is 62.5%. However, object localization by AS-ROI is 100% for a circular and U-shape object in breast model. Nevertheless, AS-ROI attains an average ED of 2.3 for lung model. Computational time decreases accordingly with the reduced number of pixels involved after the rescaling process. Reduction in the computational time is 13.06% for breast model, nonetheless 28.74% for lung model. Significant time reduction observed for lung model is benefited from considerable number of pixels that has been removed from the original image. The inclusion of edge preserving techniques into the combined AS-ROI with FBTS however has slightly increase the computational time about 5.87% and 4.69% for breast and lung model, respectively. Nevertheless, it compensates the computational cost for higher accuracy of image profiles’ intensities.

**Keywords:** Automated Scaling Region of Interest (AS-ROI), edge preserving techniques, Forward-Backward Time-Stepping (FBTS), image reconstruction, inverse scattering
**Penskalaan Automatik Rantau Kepentingan dengan Pemuliharaan Sempadan Berulang dalam Forward-Backward Time-Stepping**

**ABSTRAK**

Tesis ini melaporkan kaedah serakan songsang yang bersifat tentu dalam domain masa untuk membina profil dielektrik objek yang tidak diketahui dalam rantau sempadan objek tersebut. Pembinaan imej bagi objek dengan geometri mudah yang diambil daripada profil dielektrik payudara dan model paru-paru (paru) dilakukan dengan simulasi yang dilaksanakan dalam pengkomputeran tunggal. Dalam usaha untuk mengurangkan masalah ketidakstabilan bagi serakan songsang, teknik penyongsangan telah disepadukan dengan pelbagai jenis teknik untuk memperbaiki penyelesaian penyongsangan. Pertambahan algoritma hanya akan meningkatkan kos pengiraan, namun tidak akan menghapuskan ketidakstabilan yang akan menjejaskan penyelesaian teknik penyongsangan. Proses pembinaan profil bermula di dalam rantau dengan anggaran kasar dan kemudian dikecilkan mengikut konfigurasi geometri objek. Ini dicapai dengan menggabungkan teknik songsangan Forward-Backward Time-Stepping (FBTS) dengan kaedah Penskalaan Automatik Rantau Kepentingan (AS-ROI). Kaedah pemuliharaan sempadan dalam imej terdiri daripada penormalan pemuliharaan sempadan dan penyebaran anisotropic diintegrasikan ke dalam gabungan FBTS dan AS-ROI untuk meningkatkan tahap ketepatan dalam keamatan profil. Ketepatan objek yang telah dibina disahkan dengan menggunakan ralat min kuasa dua (MSE), ralat relatif (RE) dan jarak Euclidean (ED) yang mengukur kejitalan dari segi keamatan piksel, saiz dan petempatan. Keputusan menunjukkan peningkatan ketara dalam tahap ketepatan untuk imej yang telah dibina dengan kaedah gabungan FBTS dan AS-ROI. AS-ROI telah berjaya meningkatkan ketepatan piksel sebanyak 10.33% untuk model payudara dan 25.17% bagi model paru berbanding FBTS.
Peningkatan dalam ketepatan oleh AS-ROI adalah disebabkan kadar penembusan medan yang lebih baik kerana piksel luaran digantikan dengan lapisan dasar yang mempunyai nilai profil rendah. Di dalam gabungan kaedah penskalaan dan penormalan di dalam FBTS, penapis pemuliaraan sempadan dan penormalan diaplikasikan kepada imej yang telah dibina dan ditambah baik oleh AS-ROI. Oleh itu, ketepatan meningkat kepada 18.58% dan 40.68%, masing-masing untuk model payudara dan paru. Dari segi penganggaran saiz, purata ralat bagi radius objek adalah berkadar dengan tahap ketepatan yang diukur dalam MSE. Ini bermaksud kecekapan AS-ROI sangat bergantung kepada ketepatan pengiraan FBTS dalam membina semula profil imej sebelum proses pengecilan rantau pembinaan profil. Selain itu, ketepatan dalam penganggaran saiz berbeza untuk bentuk yang berlainan disebabkan jumlah piksel pada sempadan bentuk tersebut. Purata RE adalah 61.94% untuk bentuk bulat dalam model payudara, manakala objek berbentuk U mencapai RE sebanyak 4.17%. Nilai RE tertinggi untuk saiz sebiji tumor bulat dalam model paru adalah 62.5%. Namun begitu, ketepatan lokasi objek dengan AS-ROI adalah 100% untuk objek bulat dan bentuk U di dalam model payudara. Walau bagaimanapun, AS-ROI mencapai purata ED sebanyak 2.3 untuk model paru. Masa yang diambil untuk pemprosesan berkurangan selaras dengan pengurangan jumlah piksel yang terlibat selepas proses pengecilan rantau pembinaan profil. Pengurangan pemprosesan masa adalah 13.06% untuk model payudara, manakala 28.74% untuk model paru. Pengurangan masa yang ketara diperhatikan untuk model paru adalah disebabkan banyak piksel yang dibuang daripada imej asal. Penerapan teknik pemeliharaan sempadan ke dalam gabungan AS-ROI dan FBTS walau bagaimanapun telah meningkatkan sedikit masa pengiraan lebih kurang 5.87% dan 4.69% masing-masing untuk model payudara dan paru. Walau bagaimanapun,
gabungan tersebut menyeimbangkan peningkatan kos pengiraan untuk mencapai ketepatan profil yang lebih tinggi.

**Kata kunci:** Penskalaan Automatik Rantau Kepentingan (AS-ROI), kaedah pemuliharaan sempadan, Forward-Backward Time-Stepping (FBTS), pembinaan imej, serakan songsang
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LIST OF ABBREVIATIONS

2D  Two-Dimensional
3D  Three-Dimensional
ABC Absorbing Boundary Condition
ADI Alternative Direction Implicit
AS-ROI Automatic-Scaling Region of Interest
CFL Courant Friedrichs Lewy
CPML Convolutional Perfectly Matched Layer
CSI Contrast Source Inversion
DART Discrete Algebraic Reconstruction Technique
DE Differential Evolution
DEI Despeckling Evaluation Index
ED Euclidean Distance
FBTS Forward Backward Time-Stepping
FCC Face-Centered-Cubic
FDTD Finite-Difference Time-Domain
GA Genetic Algorithm
GPR Ground Penetrating Radar
HIE Hybrid Implicit-Explicit
IMSA Iterative Multi Scaling Approach
MOM Moments of Method
MRI Magnetic Resonance Imaging
MSE Mean Squared Error
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<th>Full Form</th>
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<td>New Integral Equation</td>
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<td>RE</td>
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<td>ROI</td>
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<td>SAR</td>
<td>Synthetic Aperture Radar</td>
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<td>Subspace-Based Optimization Method</td>
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<td>TCIA</td>
<td>The Cancer Imaging Archive</td>
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<td>TE</td>
<td>Transverse Electric</td>
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<tr>
<td>TM</td>
<td>Transverse Magnetic</td>
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CHAPTER 1
INTRODUCTION

1.1 Inverse scattering

There are many situations where there is a need to interpret an unknown object with limited known data for deduction. This can be described as inverse problems, which arise in medical field to reconstruct internal structure of human body [1, 2], non-destructive testing to detect cracks or quality of material structure [3], geophysical prospecting [4] that can be applied to find oil mines or other green resources, as well as for archaeology [5]. In these mentioned examples, none of required information can be directly obtained from the object as in forward problem. Nevertheless, it is indirectly measured as the unknown object or scatterer is embedded inside of a substance. Inverse problem can be described as to portray image contrast and geometry of an embedded scatterer by manipulating the electromagnetic fields from which it originates, as illustrated in Figure 1.1.

Figure 1.1: Portray physical properties with partially known fields

\footnote{The unknown object is also defined as scatterer in this thesis}
Figure 1.2 summarizes few related matters to inverse scattering. Inverse problem can be classified into two categories; inverse obstacle scattering (impenetrable medium) and inverse medium scattering (penetrable medium) in which geometry and material properties are sought [6, 7]. Unknown scatterer to be solved with inverse scattering is categorized by its dimensional size in relative to incident field wavelength [8]. Extended scatterer is to define object of at least similar size to incident field wavelength. Point-like scatterer is referring to object that is physically smaller than the wavelength.

Inverse scattering method, as the name implies, generally initiated with results which refers to partially known scattered fields originated from the unknown object, to find causes of the result that is the unknown object itself. Obviously, it is rather ill-posed in nature due to the fact that one has to characterize the object’s physical properties merely based on fields measurements outside the object and numerical assumption from optimization process. Some information of the physical properties may not be retrieved entirely at the receiving points that encircling the object. The result could be either in good solution or just trapped in local minima due to lack of stability.

Being ill-posed or extremely dependent on the data solution would cause small agitations due to noise during measurement process of the actual object yields overwhelmingly volatile outcome [9]. On top of that, the solution is characterized by nonlinear relation between the scattered fields and dielectric profiles [10]. The term ill-posed is defined by Jacques Salomon Hadamard’s rules [9], in which instability of inverse scattering cannot be eliminated even it is combined with other algorithms for better solution [11].
Figure 1.2: Overview of inverse scattering
1.1.1 Deterministic Inversion Solution

Inverse scattering problem can be unravelled either with deterministic or stochastic solutions. Regardless of optimization solutions utilized for the inversion, the effectiveness relies on its ability to minimize the cost functional, complexity level, appropriate number of parameters involved, as well as convergence criterion [12]. Classical methods that have been well-developed over past decades can be categorized as deterministic algorithm divided into nonlinear and linear solutions, which still widely discussed in recent years [12].

Deterministic solution is quite synonym to nonlinear optimization, in which some of the proposed methods are gradient based method [11, 13], Contrast Source Inversion (CSI) [14], Subspace-Based Optimization Method (SOM) [15, 16] and New Integral Equation (NIE) method [17]. The process is initiated by assigning initial guess values as an estimation for the object’s profiles, in which some are empirically determined [11, 13], roughly determined [15, 17] and some are calculated [14]. The solution progresses iteratively towards convergence. Conventional deterministic gradient based method compares measured scattered fields outside the sought objects to be determined with computed scattered fields originates from artificial object for optimization [18, 19]. Conjugate gradient method and Polak–Ribière Polyak search directions are employed in most deterministic solutions to determine the object profiles [11, 13, 14, 16, 17]. Most deterministic solutions solve forward problem to obtain scattered fields at each iteration, nevertheless is not required in CSI thus reduce the complexity and computational burden [14].

There are two obvious limitations with deterministic solution. First, there ought to be priori knowledge of the scatterer such as its material type and profiles boundary [16, 20]. Estimation in initial guess must be approximate to the actual object contrast setting [16, 17, 21]. This could be unrealistic under certain circumstances, considering that the sought object
is supposed to be unknown. Secondly, most algorithms are implemented in iterative manner which might suffer from high computational burden particularly for higher dimensional problem [16, 17, 20, 21]. However, the end results are often quite promising despite its limitations.

Linear or weak scattering method is based on approximation of the scatterer to linearize the relation between the scattered fields and object profiles. Conservative linear methods are Born or Rytov approximations, that attain the linear relation by assuming very low contrast between layers of object and background with low and high frequency, respectively [8]. These methods only can provide rough estimation on the object.

1.1.2 Stochastic Inversion Solution

State of art to solve inverse scattering problem is by stochastic method or known as population-based optimization to find global minimum in inversion technique. It overcome limitation of deterministic algorithm in which eliminate dependency on the properties of the unknown scatterer [12, 22]. Some proposed stochastic methods to solve inverse scattering problem are Genetic Algorithm (GA) [23, 24], Particle Swam Optimization (PSO) [23, 25] and Differential Evolution (DE) [25].

It can provide dielectric properties\(^2\) contrast distribution even in complex shape other than locate the scatterer based on probability [23]. Global minimum is searched for to reduce probability of being trapped in false solution. The convergence can be achieved faster since solution is searched in several points in each iteration [22]. Stochastic approach has been proven robust to noise and able to overcome nonlinear optimization limitation, which does

\(^2\) Dielectric properties is a synonym of dielectric profiles or image contrast, comprising relative permittivity and conductivity
not require close approximation of initial guess to obtain good reconstruction results [23, 26]. The overall process does not require gradient and direction as in nonlinear optimization.

However, some may have limitations such as optimization untimely converged and poorly performed for local search which found in GA [27]. Study by [24] which previously utilizes gradient based method [28, 29] also proved that GA unable to supersede the gradient based method particularly for inhomogeneous media with large unknowns. DE which found superior than PSO in terms of speed and accuracy in shape reconstruction [25], nevertheless has no tools to extract and apply global information of the search space [30].

1.1.3 Formulation Domain for Solution Implementation

Formulation to solve inverse scattering can be implemented in continuous time-domain or frequency-domain. Several frequency-domain inversion approaches have shown quite satisfying results subjectively or numerically proven [2, 31]. Advantage of single frequency or monochromatic source in inversion technique is that it can reduce difficulties and complexities in reconstructing dispersive model [2]. Finding from [32] in brain stroke monitoring suggests that, large bandwidth provides insignificant contribution in the result, since useful bandwidth for brain image reconstruction is narrow. However, major limitation of solution in frequency-domain is extreme nonlinearity at high frequency to attain better resolution of image profiles [19].

Study by [33] proposed multi-frequency technique to overcome resolution problem of monochromatic source with continual procedure from low to high frequency. Time-domain obviously has a lot to offer than frequency-domain approach since it operates at broad range of frequencies which in turn provides abundant valuable information. This can be seen in [34], which has demonstrated that the time-domain results are much better than