



Cairo University

3D IMAGE RECONSTRUCTION TECHNIQUES FOR CONE BEAM COMPUTED TOMOGRAPHY

By

Mohammed Abdulraheem Mohammed Almasani

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE
in
Biomedical Engineering and Systems

**FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2015**



Cairo University

3D IMAGE RECONSTRUCTION TECHNIQUES FOR CONE BEAM COMPUTED TOMOGRAPHY

By

Mohammed Abdulraheem Mohammed Almasani

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE in
Biomedical Engineering and Systems

Under the Supervision of

Prof. Dr. Yasser M. Kadah

.....

Professor of Biomedical Engineering
Biomedical Engineering and Systems
Faculty of Engineering, Cairo University

**FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2015**

3D IMAGE RECONSTRUCTION TECHNIQUES FOR CONE BEAM COMPUTED TOMOGRAPHY

By

Mohammed Abdulraheem Mohammed Almasani

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE
in
Biomedical Engineering and Systems

Approved by the
Examining Committee

Prof. Dr. Yasser M. Kadah,
Professor of Biomedical Engineering, Faculty of Engineering,
Cairo University.

Principal Advisor

Prof. Dr. Ahmed M. Badawi,
Professor of Biomedical Engineering, Faculty of Engineering,
Cairo University.

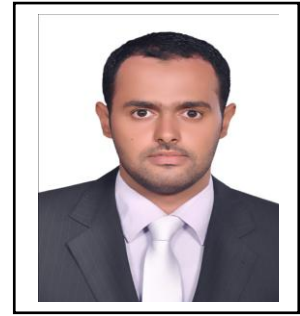
Internal Examiner

Prof. Dr. Mohamed Ibrahim El-Adawy,
Professor of Electronics and Communications Engineering,
Faculty of Engineering, Helwan University.

External Examiner

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2015

Engineer's Name: Mohammed Abdulraheem Mohammed Almasani
Date of Birth: 05/11/1986.
Nationality: Yemeni.
E-mail: mohammedalmasani@yahoo.com
Phone: +20-1150519152 / +967-777677013



Registration Date: 1/10/2012
Awarding Date: / /
Degree: Master of Science
Department: Biomedical Engineering and Systems

Supervisors: Prof. Dr. Yasser M. Kadah

Examiners: Prof. Dr. Yasser M. Kadah (Cairo University).
Prof. Dr. Ahmed M. Badawi (Cairo University).
Prof. Dr. Mohamed Ibrahim El-Adawy (Helwan University).

Title of Thesis:

3D Image Reconstruction Techniques for Cone Beam Computed Tomography.

Keywords:

CBCT; Cone-beam; Projections; Analytical reconstruction methods; Iterative reconstruction methods.

Summary:

Computed Tomography (CT) is a widely used imaging technique in medical diagnosis. It relies on collecting data about an object from multiple views representing its projections and subsequently using these data to construct an image. Among the latest advances in CT is the utilization of cone-beam geometry of x-ray projections is used instead of the usual planar fan beam. This technique is called Cone Beam CT (CBCT) and promises even faster yet safer 3D imaging compared to previous CT technologies. These advantages come at the expense of a more challenging reconstruction problem that is still an active research area to optimize for speed and image quality. Present reconstruction methods are classified into two main categories, namely; analytical and iterative methods. In this thesis, we study the performance of the leading reconstruction methods from both categories and investigate modifications in their parameter selection. We also compared their quality, speed and dose quantity of x-ray radiation using analytical phantoms. The results indicate that the reconstructed volumes produced from the iterative methods provide better quality but at the cost of a higher computational complexity. We develop a parallel computing version of the algorithms and show that the computation time can be improved using multi-core processing. The results of this work provide a framework for optimizing the quality, computation time, projection data required and hence the patient dose.

Acknowledgement

In the name of ALLAH the most Merciful the most Gracious; all thanks to ALLAH the Lord of the Heavens and Earth. I wish to express my gratitude to my supervisor, **Prof. Dr. Yasser M. Kadah** who was helpful and offered invaluable assistance, support and guidance. I would also to thank him for his great efforts and constant care.

Finally, my sincere thanks go to my family and friends.

This thesis is dedicated to my Parents, Brothers, Wife, Son (Ahmed), Family and my Friends.

Table of Contents

ACKNOWLEDGEMENT	I
DEDICATION	II
TABLE OF CONTENTS	III
LIST OF TABLES	VI
LIST OF FIGURES	VII
LIST OF SYMBOLS	X
LIST OF ABBREVIATIONS	XIII
ABSTRACT	XV
CHAPTER 1 : INTRODUCTION	1
1.1 CBCT CLINICAL APPLICATIONS.....	1
1.2 PROBLEM OVERVIEW	2
1.3 THESIS OBJECTIVE	2
1.4 THESIS ORGANIZATION	3
CHAPTER 2 : OVERVIEW OF CBCT	5
2.1 INTRODUCTION	5
2.2 TYPES OF CT SCANNERS	7
2.2.1 Pencil / Parallel Beam System	7
2.2.2 Fan Beam System	8
2.2.3 Cone Beam System	8
2.3 PRINCIPLES OF IMAGE RECONSTRUCTION	9
2.3.1 Radon Transforms	9
2.3.2 Filtered Backprojection	10
2.3.3 Fan Beam Reconstruction	11
2.3.4 Cone Beam Reconstruction	13
2.4 ADVANTAGES OF CBCT	13
CHAPTER 3 : PROJECTIONS DATA GENERATION	15
3.1 INTRODUCTION	15
3.2 RAY TRACING	18
3.2.1 Siddon's Algorithm	18
3.2.1.1 Calculate Range Of Parameter Values (α_{\min} , α_{\max})	20

3.2.1.2	Calculate Range Of Indices	21
3.2.1.3	Calculate Parametric Sets	21
3.2.1.4	Merge Sets	22
3.2.1.5	Calculate Voxel Length	22
3.2.1.6	Calculate Voxel Indices	22
3.2.2	System Geometry	23
3.3	TRANSFORMATION	25
3.3.1	Translation	25
3.3.2	Rotation	26
3.4	OBJECT ROTATION	26
3.5	RESULTS OF PROJECTIONS	27
3.6	SUMMARY	34
CHAPTER 4 : RECONSTRUCTION TECHNIQUES		35
4.1	INTRODUCTION	35
4.2	FDK METHOD	35
4.2.1	Weighting	37
4.2.2	Filtering	37
4.2.3	Backprojection	37
4.3	ART METHOD	42
4.4	MART METHOD	47
4.5	WHY ART AND MART NEEDS FEWER PROJECTIONS THAN FB (FDK)	47
4.6	SUMMARY	48
CHAPTER 5 : RESULTS AND DISCUSSION		49
5.1	INTRODUCTION	49
5.2	RECONSTRUCTION OF DIFFERENT OBJECTS USING FULL SCAN DATA	49
5.3	DECREASE NUMBER OF PROJECTIONS DATA	57
5.4	DISCUSSION	65
5.4.1	LIMITATIONS	66
5.4.2	COMPARISON WITH RELATED WORK	66
CHAPTER 6 : STUDY OF PARALLEL COMPUTING IMPLEMENTATION		69
6.1	INTRIDUCTION	69
6.2	PARALLELIZATION ANALYSIS	70
6.3	MATLAB PARALLEL COMPUTING MODEL	70
6.4	IMPROVE RESULTS PERFORMANCE	71
6.5	DISCUSSION	72

CHAPTER 7 : CONCLUSIONS AND FUTURE WORK	73
7.1 CONCLUSIONS	73
7.2 FUTURE WORK.....	74
REFERENCES	75
APPENDIX A : OSCaR SOFTWARE TOOL	81

List of Tables

3.1	Time consumption of projection generation for different object sizes with and without vectorization process for full scan (360 projection slices).	32
3.2	Computation time corresponding to the number of projections.	33
5.1	Different measurements in each reconstruction techniques using Full Scan projections data after 10 iteration.	57
5.2	RMSE and IQI for each FDK, ART and MART using different number of projections data.	58
5.3	Computation time of reconstruction processes for each methods.	63
5.4	Comparison with related work in terms of computation time or RMSE.	67
6.1	Computation time before and after parallel computing for 128x128x128 object size, one iter. in seconds.	71

List of Figures

1.1	Cone-beam computed tomography system [2].	2
2.1	Basic CT units.	6
2.2	Rotation of x-ray tube with detectors around the patient [3].	6
2.3	Types of x-ray beam geometry (Parallel beam versus Fan beam) [6].	7
2.4	Types of x-ray beam geometry (Fan beam versus Cone beam).	8
2.5	Fan beam versus Cone beam acquisition [2].	9
2.6	Parallel-beam acquisition [10].	10
2.7	Back projection operation for a single projection view [6].	11
2.8	Scheme of a CT scanner with fan beam geometry [10].	12
2.9	Rebinning from a fan beam to a parallel beam [10].	12
2.10	Cone beam acquisition [10].	13
3.1	The line integral across the disc is the length of a chord times the density [11].	16
3.2	The projections are usually different at a different view-angle [11].	16
3.3	sinogram is a representation of the projections on the s - θ plane [11].	17
3.4	The projections are weighted by the line-length within each pixel [11].	18
3.5	Block Diagram of the Siddon's Algorithm [15].	19
3.6	Schematic representation of the ray tracing with Siddon's Algorithm [16].	20
3.7	System geometry [6].	23
3.8	Cone Beam CT scanning configurations. a) Standard source to detector distance with large detector size. b) Small detector size with small covered area. c) Small detector size with appropriate covered area.	24
3.9	Positive rotation angles [6].	26
3.10	A set of projection images at different angles.	27
3.11	Cone beam projections at angles 0° , 45° and 90° for object of ones. The verification of these projections using simple data line passes through middle of the projections images.	29
3.12	Cone beam projections at angles 0° , 45° and 90° for object of gray values. The verification of these projections using simple data line passes through upper and lower parts of the projections images.	30
3.13	Cone beam projection for digital Shepp-Logan head phantom angles 0° , 45° and 90° with horizontal line of data.	31
3.14	Two cases with and without vectorization corresponding to Table 3.1.	32
3.15	A graph of data corresponding to the Table 3.2 between number of projections and their computation time.	34
4.1	Steps of FDK algorithm.	36

4.2	Schematic representation of the FDK method [18].	36
4.3	Different filters types in frequency domain.	38
4.4	Voxel driven back projection algorithm [20].	39
4.5	Projection for one 3 x 3 slice at angle $\theta = 0^\circ$ and $\theta = 90^\circ$	40
4.6	Backprojection for one 2 x 3 sinogram.	40
4.7	2 distinct images that can yield same projection at angle 0.	40
4.8	(A) Projection data are given. (B) Backprojection allows one to find values for 9 pixels. (C) Original image, whose projections are given in A, is shown. (D) Result is presented.	41
4.9	(A) Two projections. (B) Filtering of projections using ramp filter yields negative values. (C) Original image. (D) Image obtained after backprojection of filtered projections.	42
4.10	An example with 9 unknowns and 9 measurements [11].	43
4.11	Linear Algebra matrix form with sparse.	44
4.12	The ART algorithm.	45
4.13	Original Image and its projection data.	46
4.14	ART example.	47
5.1	Three different slices views of 3D volume [36].	49
5.2	Central reconstruction slices (cube of only ones values) for original volume and FDK, ART and MART methods using full scan 360 projections with 10 iterations. ..	50
5.3	Central reconstruction slices (Shepp-Logan head phantom) for original volume and FDK, ART and MART methods using full scan 360 projections with 10 iterations. ..	51
5.4	Middle line data of the Shepp-Logan head phantom in all reconstruction methods. ...	52
5.5	Horizontal middle line data of coronal slices for all reconstruction techniques compared with original slice.	53
5.6	Vertical middle line data of sagittal slices for all reconstruction techniques compared with original slice.	54
5.7	2-Norm error of the Shepp-Logan head phantom in all reconstruction methods.	55
5.8	Limited number of projections data (360, 180, 120, 90, 45) in each FDK, ART and MART methods using 10 iterations.	59
5.9	RMSE versus different number of projections data for all image reconstruction methods.	60
5.10	IQI versus different number of projections data for all image reconstruction methods.	60
5.11	2-Norm error for different number of projections data.	61
5.12	Effects of reducing the number of projections data on the profile intensity.	62
5.13	Computation time for each reconstruction methods.	63
5.14	RMSE versus number of iteration for ART and MART methods.	64
5.15	IQI versus number of iteration for ART and MART methods.	64
5.16	RMSE versus number of iteration with different values of λ in ART and MART.	65
6.1	Serial computing [48].	69

6.2	Parallel computing [48].	70
6.3	Mechanics of parfor-loops with workers [49].	71
6.4	ART and MART reconstruction computation time before and after parallel computing.	72
A.1	Pre-processing GUI stage in OSCaR tool.	82
A.2	Reconstruction GUI stage in OSCaR tool.	82

List of Symbols

μ	Attenuation coefficient of the object.
A	Coefficient matrix.
a_{ij}	Segment length of the path towards the detector bin i within the pixel j .
D	Half of the object diagonal.
d_{12}	Distance from point 1 (x-ray source) to point 2 (detector element).
d_x, d_y, d_z	The distance from one plane to the next one in each direction.
E	Correction of the calculated projection.
$f(x, y)$	2D object.
$f_{i,j}$	Reconstructed Volume pixels.
$g_{i,j}$	Original volume pixels.
i_{min}, i_{max}	Range of voxel indices in x -axis.
j_{min}, j_{max}	Range of voxel indices in y -axis.
k_{min}, k_{max}	Range of voxel indices in z -axis.
λ	Relaxation factor which controls the convergence rate.
$L(\beta, u)$	The line across the object
$L_{detector}$	detector length.
M_{ART}	Number of projections images in ART method.
M_{FB}	Number of projections images in FDK method.

P	Projection vector.
$P(i, \theta)$	Projection at specific ray i at angle θ .
$P_\alpha(\gamma, \varphi)$	Cone beam projections.
$P_\alpha(\gamma)$	Fan beam projections.
$P_\beta(u)$	Projection of pencil beam at a specific angle β and distance u .
$P^F_\alpha(\gamma, \varphi)$	Filtered projection.
$P^W_\alpha(\gamma, \varphi)$	Weighted projection.
θ	Angle of projection view.
SDD	Source to detector distance.
T	Transformation matrix.
t_x, t_y, t_z	Translation distances on the directions x , y and z respectively.
u	Distance from ray to the centre of rotation.
W	Intersection length of ray within voxel.
X	Unknown voxels of the object.
x_j	The j th pixel in 2D or j th voxel in 3D.
A	Angular position of the x-ray source (rotation angle).
α_{max}	Parameter value of the exit point of the ray through the voxel grid.
α_{min}	Parameter value of the entrance point of the ray through the voxel grid.
$\alpha_x, \alpha_y, \alpha_z$	Parameter values of the ray intersection with the x , y and z direction planes.
β	Angle of pencil beam.
γ	Angle of fan beam.