UNDERTAKING FROM THE CANDIDATE

I, ***Shailendra Tiwari***, research scholar under the supervision of ***Prof. Rajeev Srivastava***, Professor, Department of Computer Science and Engineering, Indian Institute of Technology (Banaras Hindu University), Varanasi, hereby declare that the work incorporated in the present thesis entitled "***Design and Development of Efficient Framework for Medical Image Reconstruction***" submitted by me for the degree of ***Doctor of Philosophy*** is a record of first-hand research work done by me during the period of study.

Further, I do undertake the responsibility for the mistakes, error of facts and misinterpretations (if any) in the thesis which is entirely original and my own work.

Date: (Signature of the candidate)
Place: IIT(BHU), Varanasi (Shailendra Tiwari)

CANDIDATE’S DECLARATION

I, ***Shailendra Tiwari***, certify that the work embodied in this Ph.D. thesis is my own bonafide work carried out by me under the supervision of ***Prof. Rajeev Srivastava,*** for a period of 4 years 2 months from July, 2011 to September, 2015 at the *Department of Computer Science and Engineering*, *Indian Institute of Technology (Banaras Hindu University, Varanasi*. The matter embodied in this Ph.D. thesis has not been submitted for the award of any other Degree/Diploma.

I declare that I have faithfully acknowledged, given credit to and referred to the research workers whenever their works have been cited in the text and the body of the thesis. I further certify that I have not willfully lifted up some other’s work, para, texts, data, results, etc. reported in the journals, books, magazines, reports, dissertations, theses, etc., or available at websites and included them in this Ph.D. thesis and cited as my own work.

Date: (Signature of the candidate)
Place: IIT(BHU), Varanasi (Shailendra Tiwari)

CERTIFICATE FROM THE SUPERVISOR

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

(Dr. Rajeev Srivastava)
Professor
Department of Computer Science and Engineering
(Supervisor)

(Dr. K. K. Shukla)
Professor and Head,
Department of Computer Science and Engineering

ANNEXURE-F

(see Clause XIII.1 (c) and XIII.2 (b) (iv))

COURSE WORK / COMPREHENSIVE EXAMINATION COMPLETION CERTIFICATE

This is to certify that **Mr. Shailendra Tiwari**, a bonafide research scholar of Department of Computer Science and Engineering, Indian Institute of Technology (Banaras Hindu University), has worked for 16 credits and successfully completed the Ph.D. course work examination which is a part of his Ph.D. programme.

Date:

(Signature of the Head of the Department)

Place: IIT(BHU), Varanasi

ANNEXURE-G

(see Clause XIII.2 (b) (v))

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Title of the Thesis: ***Design and Development of Efficient Framework for Medical Image Reconstruction.***

Candidate's Name: ***Shailendra Tiwari***

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Signature of the Candidate

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LIST OF ABBREVIATIONS

2D/3D	Two/ Three dimensional
AD	Anisotropic Diffusion
ART	Algebraic Reconstruction Techniques
BM3D	Block-matching and 3D filtering
CAV	Component Averaging Methods
CONVEF	CONvolutional Virtual Electric Field Anisotropic Diffusion
CP	Correlation Parameter
CS	Compressed Sensing
CT	Computed Tomography
ECT	Emission Computed Tomography (PET/SPECT)
EM	Expectation Maximization
FBP	Filtered Backprojection
FOM	Figure of Merit
FOV	Field of View
FT	Fourier Transform
GMRF	Gaussian Markov Random Field
GVF	Gradient Vector Flow
INGVF	Inverse Gradient Vector Flow
IR	Iterative Reconstruction
kV	Kilo Voltage
LOR	Line of Response
LS	Least Squares
MAD	Minimum Absolute Deviation

MAP	Maximum *A Posteriori*
MART	Multiplicative Algebraic Reconstruction Techniques
mAs	Milliampere-second
MedAD	Median Anisotropic Diffusion
MLEM	Maximum Likelihood Expectation Maximization
MRF	Markov Random Field
MRI	Magnetic Resonance Imaging
MRP	Median Root Prior
MSSIM	Mean Square Similarity Index
NRMSD	Normalized Root Mean Square Deviation
OSEM	Ordered Subsets Expectation Maximization
OS-MRP	Ordered Subsets Median Root Prior
PDE	Partial Differential Equation
PET	Positron Emission Tomography
PL	Poisson Likelihood
PPB	Probabilistic Patch Based
PSF	Point Spread Function
PSNR	Peak Signal to Noise Ratio
PWLS	Penalized Weighted Least Square
QM	Quadratic Membrane
RMSE	Root Mean Square Error
SART	Simultaneous Algebraic Reconstruction Techniques
SIR	Statistical Iterative Reconstruction
SIRT	Simultaneous Iterative Reconstruction Techniques
SNR	Signal to Noise Ratio
SPECT	Single Photon Emission Computed Tomography
SVD	Singular Value Decomposition
TV	Total Variation

LIST OF SYMBOLS

y^n	*Updated image after n^{th} MLEM iteration*
L^k	*Updated image after k^{th} iteration of SART*
N_{calc}^k	*Calculated projections at k^{th} iteration*
x_{calc}^n	*Calculated projections at n^{th} iteration*
x_{true}	*True projections,*
Q_θ	*Filtered projection*
$\bar{f}$	*The average gray scale of all pixels in reconstructed image*
β	*An isotope dependent decay constant*
$\phi(\lVert\nabla x\rVert)$	*Energy function defined in terms of gradient norm of the image*
e_j^k	*Projection Error*
$P_\theta(t)$	*Projection view at different angle θ*
σ	*Standard deviations*
f_{ORIG}	*The corresponding original numerical phantom image,*
$C(\nabla f)$	*The diffusion function,*
∇f	*The local image gradient and*
f_{REC}	*The reconstructed image,*
$\hat{f}$	*Estimated Object*
$\hat{F}(r,\theta)$	*The Fourier transform of $F(r,\theta)$*
(t, s)	*Rotated coordinate system*

$\lvert r \rvert$	*Ramp filter*
$\sum$	*Summation*
$\mu(s; E)$	*linear attenuation coefficient*
A	$M \times N$ *Projection/system matrix*
b	*linear vector representing a sinogram*
$d(\hat{y}, \mathbf{y})$	*Log-likelihood / data fit term*
f	*linear vector representing recon image*
$f(x, y)$	*2D Image Slice*
$g(l, \theta)$	*sinogram or Radon transform*
I_d	*integrated X-ray intensity for a given detector*
K	*gradient threshold*
M	*The total number of detector tubes*
N	*The total number of image pixels*
N_i	*the pixel value (detected counts emitted)*
$R(\mathbf{x})$	*Regularizer (e.g., a roughness penalty)*
$R\{\ \}$	*Radon transform*
t	*is the iteration step*
w_i	*weighting factor*
X	*Constraint set*
x	*image vector*
$\mathbf{x}^{true}$	*true object*
y	*projection vector*
λ	*relaxation parameter*

LIST OF KEYWORDS

Acceleration techniques

Anisotropic Diffusion

Computed tomography

Emission Computed tomography

Image Reconstruction algorithms

Iterative Methods

Maximum Likelihood Expectation Maximization

Median-Anisotropic Diffusion

Medical Imaging

Noise Reduction

Ordered Subset Expectation-maximization algorithms

Positron emission tomography

Signal to Noise Ratio

Single-photon emission computed tomography

Statistical Iterative Reconstruction

Statistical Sinogram Smoothing

X-ray Computed Tomography

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PREFACE

Computed Tomography (CT) is an effective and indispensable imaging tool for medical image reconstruction application. It comprises positron emission tomography (PET) and single photon emission computed tomography (SPECT). It provides functional and anatomical information about physiological processes. The goal of CT is to reconstruct the distribution of the radio-isotopes in the body by measuring the emitted photons. Tomographic image reconstruction using statistical methods (e.g. MLEM, MRP, OSEM etc.) can improve the image quality over the conventional filtered backprojection (FBP) method. Statistical Iterative Reconstruction (SIR) method offers many advantages like incorporating physical effects and physical constraints, modeling of complex imaging geometries, appropriate noise models, imaging at lower X-ray doses etc. over FBP. But, the use of statistical methods is limited due to many practical problems like sourse intensity fluctuation, scattering effects, attenuation, noise contamination etc. The major drawbacks associated with these methods include the problem of slow convergence, choice of optimum initial point, ill-posedness etc. They also require huge computation and complex modeling. To address above mentioned issues, simple and computationally efficient methods based on accurate statistical models are yet to be explored. The objective of this thesis is to design and develop efficient SIR frameworks for two different applications: First, for normal dose PET image reconstruction by using provision for proper initialization and spatial regularization term to alleviate above mentioned drawbacks of SIR methods. Secondly, for low dose X-ray CT image reconstruction by using statistical sinogram restoration method to minimize the radiation risks in clinical practice. The efficient hybrid cascaded framework proposed for first application leads to a reduction in reconstruction time, accelerates the convergence and provides enhanced results using the less projection data. It also makes the algorithm robust to the initial guess image. The obtained results have proven the suitability of the designed framework for the undertaken objective. Second framework performs well in low dose X-ray CT image reconstruction by offering several desirable features like superior noise robustness, reduced computational cost, the improved denoising effect and better edge & structure preserving properties, overcome of the staircase effect effectively.

First framework consists of the properties of the maximum likelihood expectation maximization (MLEM) algorithm and its variants. After the mathematical analysis of these algorithms, it is observed that the choice of optimum initial input data, pixel updating coefficients, and stopping (convergence) criteria play a significant role during the update of reconstructed image from current n^{th} iteration to next $(n+1)^{th}$ iteration. For the analysis of the properties of these algorithms, a PET and SPECT scanner geometry are simulated using MATLAB Tools. To validate the proposed method, different mathematical computer generated test phantoms and real test images are utilized.

For image reconstruction using iterative techniques, the calculation of the transition or system matrix is essential. The transition matrix describes the transition law between the measured projection data and the estimated image vector. It fully depends on the geometrical characteristics of the PET scanner. For its calculation, a software code, based on a parallel projection method, has been developed. The parallel projection method is preferred for comparison of analytical, statistical and state-of-art methods due to its lower complexity.

Finally, three different hybrid cascaded framework based on statistical iterative reconstruction algorithms (e.g. MLEM, MRP, and OSEM) have been proposed for PET and SPECT imaging modalities. Their performances are evaluated on computer generated test phantoms and standard thorax real test image. The obtained results are compared with those of previously reported methods. It is observed that the proposed methods perform better in terms of visual image quality and detail preservation. For quantitative analysis, various performance measures such as: SNR, PSNR, RMSE, CP, MSSIM are used. After, critically comparing the results of all three proposed methods, it is found that the OSEM based hybrid-cascaded method (accelerated version of MLEM) outperforms with respect to other proposed models on common projection data. Hence, we conclude that an OSEM based hybrid-cascaded framework is an efficient method for PET and SPECT image reconstruction. The proposed framework is independent of the image size and topology but it is strongly dependent on the number of detected counts. Therefore, the use of this proposed method in the image reconstruction of real PET and SPECT studies is possible.

Further, the role of the low dose X-ray CT image reconstruction algorithm was further studied, and it is found that the potential harmful effects of X-ray radiation including lifetime risk of genetic, cancerous and other diseases have raised growing concerns to patients and medical physics community. Therefore, minimizing the radiation risks is strongly desirable in clinical practices. To realize this objective, numerous studies have focused on radiation dose reduction of CT examinations. Sinogram smoothing using non-linear modified anisotropic diffusion (AD) based statistical iterative methods have been proposed, which have shown great potential to reduce the radiation dose while maintaining the image quality in X-ray CT as compared with the FBP reconstruction algorithm.

Furthermore, three sets of digital phantoms and one real test image i.e. Shepp-Logan head Phantom, (128×128 pixels), PET Test phantom (128×128 pixels), SPECT Test phantom (128×128 pixels) and Medical thorax image (128×128 pixels), are used for the simulation and validation purposes. For each one of the phantoms employed, simulated data sets have been generated, at different activity distribution levels. The algebraic and statistical iterative reconstruction algorithms (e. g. SART, MLEM, MRP, and OSEM) are used to reconstruct the projection data. In order to compare the reconstructed and true images, various performance measures including signal-to-noise ratio (SNR), the root mean square error (RMSE), the peak signal-to-noise ratio (PSNR), the correlation parameter (CP), and mean structure similarity index map (MSSIM) are used for quantitative analysis. The SNR, RMSE and PSNR give the error measures in reconstruction process. The correlation parameter is a measure of edge preservation in the reconstructed image. The MSSIM is a measure of preservation of luminance, contrast and structure of the image after the reconstruction process, which is necessary for medical images. The brief descriptions of the various chapters of the thesis are given as follows:

Chapter 1 provides the introduction, motivation and problem description for the present work including thesis scope/objectives, and contributions. Finally, the chapter concludes with the organization that describes the coverage of chapter in the thesis.

Chapter 2 discusses the theoretical background related to medical image reconstruction. It gives an overview of the physics, geometries of imaging systems, more specifically generation and detection techniques. The basic concepts of ill-posedness, ill-conditioned problems in reconstruction methods and the formulation of various reconstruction problems are also discused. A brief discoussion about the state-of-art of SIR image reconstruction techniques used in various medical imaging modalities like CT/PET/SPECT etc. is also presented. Further, in the last section of the chapter qualitative analysis and behavior of these reconstructions algorithm are provided. Analysis of different simulated test phantoms and standard digital test images are also presented for quantitative analysis.

In **Chapter 3**, various priors have been studied. This chapter focuses on improving statistical iterative reconstruction algorithms by incorporating a suitable prior knowledge of the object being scanned. Some statistical maximum likelihood (ML) based approach for CT, PET, and SPECT image reconstruction methods are proposed. The proposed method investigates and presents various choices of regularization priors used in standard SIR reconstruction methods like MLEM, MRP, and OSEM in literature. Experimental analysis has been performed over own created mathematical test phantoms and benchmark Shepp-Logan head phantom plus real thorax test phantom. The results have been compared with existing methods using six quantitate measures that are signal-to-noise ratio (SNR), the root mean square error (RMSE), the peak signal-to-noise ratio (PSNR), the correlation parameter (CP), and mean structure similarity index map (MSSIM).

In **Chapter 4**, we have discussed the major drawbacks associated with statistical iterative reconstruction algorithms include the problem of slow convergence, choice of optimum initial point and ill-posedness. To alleviate these issues, in this chapter, we have proposed three different hybrid-cascaded efficient frameworks for MLEM, MRP and OSEM based SIR reconstruction algorithms. The proposed framework is based on two consecutive modules viz. Primary and secondary. We have performed experiments over three different simulated mathematical test phantoms and one standard thorax image. The results have been evaluated and compared with existing methods in terms of visual analysis as well as quantitative analysis using SNR, PSNR, RMSE, CP, and MSSIM performance measures. Hence, in the last section of the chapter, after comparison with all three proposed methods, we have conclude that OSEM based efficient hybrid-cascaded framework which is an accelerated version of MLEM performs better with the projection data which dedicated to PET and SPECT imaging scanner.

Chapter 5 presents a low dose image reconstruction method for computed tomography (CT). The theoretical background, issues and challenges of low dose CT reconstruction are discussed. To address the issues in this chapter, we have proposed statistical sinogram restoration models for low dose CT reconstruction. To examine the efficacy and usefulness of proposed models an appropriate qualitatively and quantitatively analysis using simulated test phantom and standard digital image. The obtained results justify the applicability of the proposed method.

In **Chapter 6,** we summarize main findings of this thesis and give future perspectives of the research out in this thesis.