Chapter 1

INTRODUCTION

In this chapter, a brief introduction to the problems of medical image reconstruction considered in this thesis and basic concepts studied has been presented. Related work, the main contributions of the thesis and the organization of the thesis has also been stated.

In Section 1.1, presents the background of medical imaging system, the motivation and problem description for the present work in image reconstruction algorithms has been discussed in section 1.2. In section 1.3, thesis objectives have been described. Section 1.4 presents the main contributions of the thesis. Finally, Section 1.5 highlights the organization of the thesis.

1.1. Background

Medical imaging is a powerful method for the diagnosis of diseases in the internal organs of the human body. Advancement in computer technology leads to the development of better medical imaging equipment so that more accurate functional and anatomical information can be obtained in a non-invasive way. Image reconstruction algorithms play a significant role in many medical imaging modalities like CT/PET etc. In order to obtain a high quality reconstructed images from the collected projection data, an excellent image reconstruction algorithm is needed. CT image quality is dependent on a number of parameters in the acquisition of the projectional raw data, such as the intrinsic resolution of the camera, choice of collimator, geometry of the gantry set-up, timing of the study acquisition, and patient-derived factors such as body habitus and movement during study acquisition (D.L. Bailey *et.al,* 2005).

Since the discovery and application of X-Rays by Wilhelm Rontgen (1895), medical imaging has grown and much improved (Anderson and Kak, 1984)]. This includes multi-dimensional modalities such as X-ray computed tomography, ultrasonic imaging (Gordan *et. al.*, 1970), and magnetic resonance imaging or MRI (Fessler, 2006). Different disciplines including physics, engineering computer science, mathematics, and medicine have contributed to the evolution of medical imaging. Since the introduction of the Gamma camera by (Qi J *et. al.*, 2006), nuclear medicine now provides two imaging modalities, positron emission tomography (PET) and single photon emission computed tomography (SPECT). The word “tomography” is derived from the Greek τομοσ (tomos), to cut or slice, and γραφος (graphy), to write. Some image modalities focus on revealing structures (X-ray tomography) whereas others on revealing function (functional MRI or fMRI, PET, SPECT).

In literature, various image reconstruction algorithms are developed in the last few decades. These are mainly divided into two classes, namely, analytical methods (F. Natterer *et.al*, 2001) and iterative techniques (Gilbert P *et. al.*, 1972). Analytical methods based on a continuous sampling and the reconstruction process consists of the direct inversion of the measurement equation using the Radon transform. The most frequently used in this category is the filtered back-projection algorithm (FBP) (J. Devaney, 1982).This algorithm is fast but it provides poor image quality, streak artifacts and low signal-to-noise ratio because of limited number of projection sets. Alternatively, iterative methods have shown great potential to reduce the radiation dose while maintaining the image quality in CT as compared with the FBP reconstruction algorithm.

Iterative methods are based on iterative error correction techniques. There are different ways to implement these iterative methods. The main difference depends upon initial guess matrix, computation of the projections, physical corrections model (scattering, random, attenuation, etc.), and the error corrective update computation in the estimated projections (Qi J *et. al.*, 2006).These iterative reconstruction methods are classified into two categories namely, conventional iterative algebraic reconstruction methods and statistical iterative reconstruction (SIR) methods. The conventional iterative algebraic methods, reconstruct the images by solving set of linear equations. Examples are the algebraic reconstruction technique (ART) (Anderson and Kak, 1984), Simultaneous Algebraic Reconstruction Technique (SART) (A.H. Anderson *et.al.,* 1984), the Simultaneous Iterative Reconstruction Technique (SIRT) (Gilbert, 1972), and others. It requires less data than FBP methods and is more robust to the effects of noise, but need much more computation.

The iterative statistical reconstruction methods reconstruct images by iteratively maximizing likelihood function. Examples are maximum likelihood expectation maximization (MLEM) (Shepp and Vardi, 1982)], Median Root Prior (MRP) (Alenius S, Ruotsalainen, 1989), Ordered Subsets Expectation Maximization (OSEM) (Hudson and Larkin, 1994) algorithms and their variants (Fessler, 2006; Jun Ni et. al., 2011; Yuan Sun. et. al., 2012; Marcel Beister et. al. 2012; Shaifali Pande et. al., 2013). They play an important role on the quality of the images produced by PET/SPECT since they can perform better with noisy, incomplete data, accurate system modelling, image prior knowledge, and as an alternative to the analytical and algebraic methods, being less sensitive to noise and sparse view inputs. However, the major drawbacks associated with statistical algorithms are their slow convergence, the choice of an optimum initial point, and ill-posedness. In this work, we continue the discussion on the solution of these problems.

1.2. Motivation

The motivation behind the work presented in this thesis is the medical application of emission computed tomography (ECT). ECT is used in clinical diagnosis to detect abnormalities such as cancer, tumors, or organ deficiencies. The development and design of an efficient framework for the medical image reconstruction is one of the challenging problems in medical imaging. With the emergence of various medical imaging modalities for the diagnosis of diseases in the internal organs of the human body, image reconstruction algorithms become a major role to obtain a high quality reconstructed image. This concepts needed for research and implementation of statistically based iterative reconstruction methods are spread far and wide over the literature, in journals with homes in engineering, mathematics, physics, radiology, and statistics. This thesis is an attempt to bring together in one place many of the key ingredients.

The problem of reconstructing medical images related to the image formation process which is performed as a result of several raw data measurements of the energy/radiation around the body of a patient. This problem belongs to the class of an inverse problem that is inherently ill-posed in nature i.e. a solution does not necessarily exist (e.g. due to extreme cases of excessive noise), or the solution may not be unique. The main challenge of an inverse problem is related to the fact that the region of interest (e.g. the distribution of radioactivity inside the patient, for PET) is not directly available for measurements. The amount of data available from the scanners is incomplete (sampling) and inaccurate (statistical noise), that produces the reconstructed images as blurred and having streaking artifacts. These results corrupt the appearance of boundaries, hide fine structures, and may lead to misinterpretation and poor diagnostic outcomes. In order to overcome the limitation of incomplete data, our goal is to exploit the statistical iterative reconstruction algorithms and develop new improved extensions. The improvement that we aim related to both speed of reconstruction and the quality of the reconstructed image.

Another main concern with these medical imaging scanners in medicine is the radiation dosage the patient receives during a scan versus the accuracy of the reconstructed image. A low radiation generally produces a lower quality image than when higher amounts of radiation are used, hence the need for improved reconstruction techniques is necessary. With better reconstruction methods, random noise that occur during the acquisition process are reduced, and higher quality images are produced. This allows for good tissue identification (for medical diagnosis), and patients are exposed to less radiation.

This thesis treats image reconstruction as an inverse problem of the following form:

We are given a finite-length measurement vector y**,** from which we want to recover a function f that describes some property of an object. For example, in emission tomography, f represents the 3D spatial distribution of a radiotracer. A very general block diagram for image reconstruction problems is as follows:

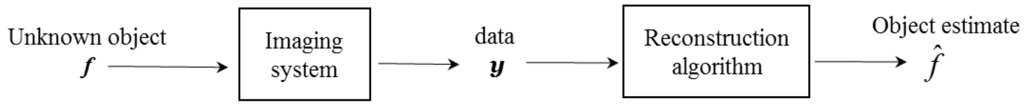

Fig. 1.2: General block diagram of image reconstruction

To design image reconstruction algorithms usually we begin by modeling the deterministic aspects of the imaging system, *i.e.*, modeling the measurements $\hat{y}(f)$ that would be recorded ideally in the absence of noise. In practice, the measurements are always contaminated by noise; in some cases the measurement noise is well modeled as being additive, as illustrated by the following diagram.

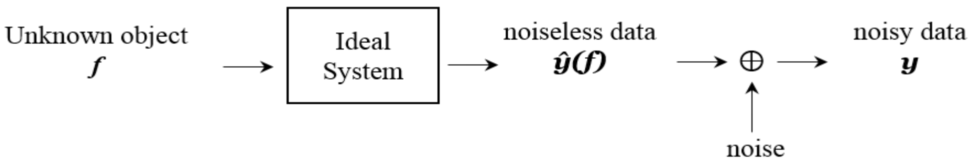

Fig. 1.22: Block diagram of noisy measured data

We can never determine f exactly for noisy data, but we can try to find an estimate $\hat{f}$ that hopefully is a useful approximation of f. In choosing $\hat{f}$, often we have two conflicting goals. First, we would like $\hat{f}$ to "fit the data," *i.e.*, we would like some measure of data mismatch $d(\hat{y}(\hat{f}), \boldsymbol{y})$ to be small. Second, we do not want to fit the *noise* in the data, *i.e.*, we want $\hat{f}$ to be compatible with any prior expectations about the characteristics of f. For example, often we assume that f is smooth or piecewise smooth.

In statistical methods for inverse problems, typically we determine an estimate $\hat{x}$ of the parameter vector x by minimizing a cost function of the following form:

$$\hat{x} = \underset{x \in X}{\arg\min}\, d\left(\hat{y}\left(\hat{f}\right), y\right) + R(x), \qquad (1)$$

where *R(x)* is a *regularizer* (*e.g.*, a roughness penalty) that controls the trade-off between spatial resolution and noise.

The principal topics of this thesis are all present in the equation (1). To perform image reconstruction, one must consider the following components.

- System model $\hat{y}(f)$. For any given f, what would noiseless measurements be? This depends on the sensor physics.
- Log-likelihood / data fit term $d(\hat{y}, \boldsymbol{y})$. This term depends on the statistical model for the measurements.
- Regularization method / prior $\mathrm{R}(\boldsymbol{x})$. How do we control noise without degrading desired signal features?
- Object model parameterization $y = A \cdot x$, *where A is the point spread function (PSF) or the system matrix*. One must compromise between accuracy and computation time.
- Constraint set X. For example, in tomography usually f is nonnegative.
- Minimization algorithm (argmin). How do we ensure convergence to the minimizer, and how to provide rapid convergence? Ideally the choice of the cost function and the iterative algorithm should be kept distinct, *i.e.*, the cost function should be chosen based on models and statistical principles, and then the algorithm should be chosen based on how fast it minimizes the chosen cost function.

As an example, Fig.1.1 shows a simulation of a true object $\boldsymbol{x}^{\mathrm{true}}$, and noisy and blurry data $\boldsymbol{y}$ for an image reconstruction problem, as discussed in Chapter 2. Also discuss two reconstruction algorithms; one computed by a non-iterative, non-statistical method and the other by an iterative, statistical method described in Chapter 2.

1.3. Objectives of the thesis

The main objective of this thesis is to develop an effective and efficient framework for medical image reconstruction. The success of design and development of efficient hybrid-cascaded framework for medical image reconstruction relies on the selection of optimum initialization point, handle the issue of ill-posedness by using suitable regularization term, and accelerate the convergence time as well as to improve the quality of reconstructed images.

To design and develop a new, effective and efficient framework with application in medical imaging domain, in particular for the image reconstruction problems. What makes a good image reconstruction is a good approach for deal-ing with the missing and inconsistent measurements. The incomplete data problem is the main challenge that arises in the case of medical image reconstruction, since the information of the distribution of radioactivity inside the patient is not directly available, but only some measurements of a transformation of this information. In order to overcome the limitation of incomplete data, our goal is to exploit the Statistical Iterative Reconstruction (SIR) such as Maximum Likelihood Expectation-Maximization (MLEM) based reconstruction algorithms and develop new improved extensions. The improvement that we aim is related to both speed of reconstruction and the quality of the obtained image. We will develop this goal in the context of CT, PET and SPECT image reconstruction.

Another main goal of this thesis is to develop an improved statistical sinogram restoration models for low dose CT reconstruction. We address this problem due to its potential harmful effects of X-ray radiation dose including lifetime risk of genetic, cancerous and other diseases have raised high importance in many clinical applications, the minimizing the radiation risks being a key step for most of them. We aim to offer an efficient approach to the low-dose sinogram restoration problem in medical imaging in order to radiation dose reduction of CT examinations. To do so, modified CONVEF-based P–M approach is used as a prior term to deal with the issues of low dose CT image reconstruction. The presented reconstruction model has many desirable properties, such as superior noise robustness, reduced computational cost, the improved denoising effect and better edge & structure preserving properties. It can also overcome the staircase effect effectively. The proposed model performs well in low dose X-ray CT image reconstruction.

1.4. Contributions

The main contributions of this thesis are as follows:

- To investigate and present the quantitative analysis of various regularization priors available in reconstruction literature to deal with the problem of ill-posedness and recommendation for selecting an appropriate prior to be used with MLEM and its variants.

- Proposed a new PDE based variational approach for MLEM algorithm using Euler-Lagrange minimization technique for medical image reconstruction.
- Development and implementation of a regularized statistical approach for CT/PET/SPECT image reconstruction. The improvement that we aim is related to both speed of reconstruction and the quality of the obtained image.
    - a new family of statistical algorithms was proposed for PET/SPECT image reconstruction;
    - the algorithms were tested and validated on synthetic data;
    - a comparative study of proposed method with the state-of the-art reconstruction methods: SART, MLEM, MRP, and OSEM.
- Design and Development of a new efficient hybrid-cascaded framework for medical image reconstruction. Following frameworks and their experimental results are presented:
    - A flexible generalized framework using SIR methods for PET/SPECT image reconstruction. (General Model)
    - An efficient framework for MLEM based SIR method. (Model-1)
    - An efficient framework for MRP based SIR method. (Model-2)
    - An efficient framework for OSEM based SIR method. (Model

The above proposed methods are implemented, and their results are validated on simulated phantom and real data image. The comparative studies of the above propsed models with other state-of-the-art PET/SPECT reconstruction methods are also presented. After, critically comparing the results of all three proposed methods, it is obsererved that the OSEM based hybrid-cascaded framework (accelerated version of MLEM) outperforms better with respect to other proposed models on common projection data.

- Development and implementation of an effective approach for statistical sinogram smoothing for low-dose CT reconstruction.

The results are validated on the simulated phantom and real data image. A comparative study of the proposed method with other state-of-the-art low-dose X-ray CT reconstruction methods is also presented qualitatively and quantitatively. From the obtained results, it is observed that the proposed method performs better in comparison to other existing methods.

The works presents in the thesis, brings important contributions to computer vision and medical imaging domains. Detailed studies of the literature were performed for all the research areas addressed in this thesis. The proposed methods and algorithms have been rigorously validated and compared with recent state-of-the-art methods. The contributions of this thesis are both theoretical and applicative.

1.5. Organization of the thesis

Throughout this thesis the main objective is to design and develop an effective and efficient framework for PET and SPECT as well as low dose X-ray CT image reconstruction. The overall thesis is organized into six chapters. The abstract of each chapter 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** presents the theoretical background & literature survey related to medical imaging system. 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. In **Chapter 4**, we have discussed the major drawbacks associated with statistical iterative reconstruction algorithms. 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. Also, in the last section of the chapter, comparative study of all three proposed methods and final conclusion is presented. **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. In **Chapter 6,** we summarize main findings of this thesis and give future perspectives of the research in this thesis.