GAMMA-RAY EMISSION COMPUTED TOMOGRAPHIC IMAGE RECONSTRUCTION FOR NON-DESTRUCTIVE EVALUATION AND ASSAY OF NUCLEAR WASTE

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ABSTRACT

The combination of Transmission Computed Tomography (TCT) with Emission Computed Tomography (ECT) is used in non-destructive examination and assay (NDE&NDA) of low activity nuclear waste drum characterization. ECT facilitates reconstruction of the radioactivity distribution in a waste package. ECT reconstruction requires the approximate density distribution of materials in terms of effective linear attenuation coefficients at the specified energy within a given matrix which may be obtained by TCT. A high energy Digital Radiography and Computed Tomography (DR&CT) imaging system is being developed at Isotope applications division, BARC to carry out NDE&NDA of low activity nuclear waste drums up to 208-L (55 gal) capacities. As part of the initial studies, an iterative algorithm based on Maximum Likelihood Expectation Maximization (MLEM) has been used to reconstruct the radioactivity distribution from a set of parallel projections, which takes into account Poisson nature of photon detection. The reconstruction code requires to be validated for spatial and contrast resolutions. This paper presents the performance evaluation of reconstruction code using computer generated phantoms and preliminary experimental data.

Keywords: Digital Radiography and Computed Tomography (DR&CT), Non-Destructive Evaluation (NDE), Non-Destructive Assay (NDA), Maximum Likelihood Expectation Maximization (MLEM)

INTRODUCTION

Characterization of nuclear waste drums requires the identification and quantification of radioisotopes inside waste drums to satisfy repository and regulatory guidelines prior to disposal [1]. The combination of Transmission Computed Tomography (TCT) with Emission Computed Tomography (ECT) is used in non-destructive examination and assay (NDE&NDA) of low activity nuclear waste drum characterization. In ECT, Single Photon Emission Computed Tomography (SPECT) facilitates reconstruction of the radioactivity distribution in a waste package. SPECT is a two step process. In first step, the data are acquired for different projection angles by considering geometrical factors, physical effects and noise properties. The second step is to process this data for estimation of radioactivity distribution over the scanned plane known as image reconstruction process. The image reconstruction algorithms use in emission tomography are iterative methods. Iterative algorithms are well suited to handling various configurations of data acquisition, physical models of emission and detection process. They greatly reduce the streaking artefacts that are common in analytical reconstruction and are better able to handle missing data. They generally produce reconstructions that can be used for quantification. The main limitation in using iterative algorithms is the execution speed [2-3]. A high energy Digital Radiography and Computed Tomography (DR&CT) imaging system is being developed at Isotope applications division, BARC to carry out NDE&NDA of low activity nuclear waste drums up to 208-L (55 gal) capacities. As part of the initial studies, an iterative algorithm based on Maximum Likelihood Expectation Maximization (MLEM) has been used to reconstruct the radioactivity distribution from a set of parallel projections [2-5]. The reconstruction code requires to be validated for spatial and contrast resolutions. This paper presents the performance evaluation of reconstruction code for parallel-beam geometry using computer generated phantom and preliminary experimental data. Section 2 describes brief overview of the reconstruction theory and reconstruction algorithm used for simulation and experimental results. Interactive software module development is explained in section 3. Section 4 contains the description of the phantom used to evaluate the quality of reconstructed images using normalized mean square error (NMSE) and the correlation coefficient (CC). Conclusions and future work are discussed in the last section.

IMAGE RECONSTRUCTION THEORY

Let f(x,y) and μ(x,y) denote the emission source of radionuclide distribution and attenuation coefficient map in the (x,y) plane. Let θ|| = (cosθ, sinθ) and θ⊥ = (-sinθ, cosθ)
are two unit vectors. Mathematically the projection data \( p(s,0) \) acquired on the line referenced by \((t,0)\) at a view angle \(\theta\) can be defined by the attenuated radon transform \([5]\) by the following formula:

\[
R_{\theta}(s,0) = \int_{-\infty}^{\infty} f(s+0t)\exp(-\int_{s}^{s+0t} \mu(s+0t)\,dt)\,dt = p(s,0)
\]

(1)

The attenuated radon transform in the discrete form is shown as follows \([6]\):

\[
R_{\theta}(f) = \sum_i f_i e^{-\mu_i} = p_i
\]

(2)

Where \{\(i\) : \(j = 1,2,\ldots, J, J = N \times N\}\) is unknown intensity of pixel \(j\) and \(N\) is the number of pixels in the image. \(f_i\) is the measurement in the \(i\)th detector and \(f_i\) is the total number of detectors in all projection angles. \(a_i\) represents the probability that a photon emitted from pixel \(j\) is detected in detector and is dependent to physical modal, collimator specification and radiation detection geometry. \(K_i\) contains indices of pixels which are intersected by the line. \(r_{ij}\) and \(\mu_i\) are respectively the path length of the ray \((i,j)\) in the pixel and attenuation coefficient in the pixel. Path lengths are calculated because they do not depend on the object to be measured. Linear attenuation coefficient depends on gamma ray energy and material density in the pixel and it can be determined from the TCT data. MLEM algorithm is more intensively used to inverse the equation (2). This algorithm is a statistical approach that takes into account the statistical nature of photon detection. ML-EM algorithm \([5]\) can be described by the following equation:

\[
f^k_{ij} = \frac{\sum_i f_i}{\sum_i f_i} \sum_i \frac{p_i}{f^k_i} \left( e^{-\mu_i} \right)^k
\]

(3)

In the above formula, \(f^k_{ij}\) is the intensity of pixel \(k\) in iteration.

**Assay Calculation**

After reconstruction of attenuation compensated emission image \(f\) at gamma ray energy, the total assay for the interested radionuclide can be calculated by summing the counts in all the pixels of \(f\). The source strength for that radionuclide can then be determined from the total counts \([7]\).

\[
\text{Activity (\(\mu\)Ci)} = \frac{\text{Total counts} \times t}{\text{Ray time} \times \text{Detector efficiency} \times \text{Branching ratio}} \times 3.7 \times 10^6 \times \left( \frac{\text{cm}}{\text{mm}} \right)
\]

(4)

**INTERACTIVE SOFTWARE MODULE DEVELOPMENT**

Based on the theory discussed in the previous section, a software module has been developed. The module is for emission tomographic reconstruction from acquired projection data. The code requires projection data file in a predefined format. A view of the Graphical User Interfaces (GUIs) is shown in figure 1(a). The module requires geometrical parameters like total number of projection angles, number of samples per projection, diameter of the reconstruction circle which is the size of the drum in our case, reconstruction grid size etc. The results of the simulation and experiment are used to validate the reconstruction code. All the calculations were done on a standard PC with 2.67 GHz Intel Core 2 Duo processor and 2 GB RAM. The CPU time for simulation for 128 x 128 grid was 0.69 sec per projection.

**COMPUTER SIMULATION OF WASTE DRUM CROSS-SECTION**

In the absence of physical measurements, simulation is needed to insure that the tomographic theoretical models are valid and the coding accurately describes these models. Simulation study is carried out as follows. (a) Generate a mathematical phantom \(f\) and measure projections, \(p = R_f\) (b) Generate an initial image \(f_0\) in our case it is taken as sinogram average value and estimate projections. (c) Compare the measured projections with estimated projections as a ratio. The ratio is used to modify the current estimate to produce an updated estimate. (d) Do the reconstruction by iterations until the number of iterations is greater than a predefined number.

In our simulation methodology, a mathematical phantom is generated to evaluate the spatial resolution and contrast performance of ECT algorithm. Phantom represents cross-section of a 208-L (55gal) drum of inner diameter 571 mm (22.5 inch) and height of 838 mm (33 inch). The drum wall composed of 1.2 mm thick stainless steel \([0.462 \text{ cm}]\). For numerical simulation purpose, the phantom was discretized on 128 x 128 square grid. 128 projections were generated over 360 degrees with angular step size of 2.8 degree. The linear attenuation values are at 1 MeV energy. The activity phantom consists of a set of Uranium disk sources of different sizes and activities at different locations on line passing through centre and lines making 45 degrees with respect to x-axis see figure 1(b). All radioactive isotopes have linear attenuation coefficient 1.460 \(\text{cm}^{-1}\). All internal sources are fixed in position by a matrix of concrete \([0.213 \text{ cm}]\). The phantom will be used to probe the ability of the algorithm to reproduce fast-varying, smaller details and low-contrast objects from its background. The drum wall, packing material, and uranium disks are clearly visible in the simulated attenuation image (figure 1(c)). The simulation and experimental results and discussion are presented in the next sections.

**Simulation Results and Discussion**

The quality of the reconstructed images has been evaluated both visually and quantitatively. The correlation coefficient (CC) and normalized mean square error (NMSE) were calculated to test the reconstructed image as well as to determine the number of accepted iterations and projections. The correlation between the original phantom \(f(i,j)\) and reconstructed image \(\hat{f}(i,j)\) has been calculated for testing the quality of the reconstructed image. The correlation coefficient is:

\[
\text{CC} = \frac{\sum_{i,j} \sum_{i,j} f(i,j) \hat{f}(i,j)}{\sqrt{\sum_{i,j} \sum_{i,j} f^2(i,j) \sum_{i,j} \sum_{i,j} \hat{f}^2(i,j)}}
\]

(5)
Larger NMSEs represent a greater deviation of the pixel values from the true value and hence a poorer image quality. The results presented in figure 3(a)-(b) showing the effect of the number of iterations and number of projections with CC and NMSE values. As the number of iterations increase, the reconstructed image quality is improved. But this improvement is very small after a certain number of iterations. In our case the phantom is reconstructed with high accuracy after 35

\[ \text{NMSE} = \frac{\sum_{i,j} (f(i,j) - \hat{f}(i,j))^2}{\sum_{i,j} f^2(i,j)} \]  

Fig. 1 : (a) GUI window layout showing all components to reconstruct ECT images from experimental data (b) Right top represent cross-section of phantom through drum (c) Right bottom is the simulated attenuation map of phantom (256 x 256).

Fig. 2 : Comparison of reconstructed images for different projections and iteration numbers.

The correlation is equal to 1 if the images are identical, and less if some difference exists. The NMSE is estimated from the original image and reconstructed imagewhich can be expressed as follows

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iterations (accepted). The NMSE value is decreasing as the number of projections is increasing. After 90 projections (accepted) there is very small improvement in the quality of the reconstruction. So 90-100 projections are enough for the reconstruction. As it is expected, the quality of the reconstruction is improved by increasing the number of projections and number of iterations [figure 2].

EXPERIMENTAL RESULTS AND DISCUSSION

The following experiment has been carried out to obtain activity image and measure activity using reconstruction algorithm with real data. In the experiment, a medium CT scanner was used to acquire data with first-generation scan geometry. A Cs-137 (~ 9.5 μCi) disk- shaped radioactive source of 25mm diameter was placed at the centre of the axis of rotation. The detector system consists of a NaI(Tl) detector and nuclear-spectroscopy instrumentation. A 10mm-aperture lead collimator was placed at the front of the detector. The detector was mounted on fixed support and can be dislocated manually. The detector started at the initial position and moved along the linear path in discrete steps at particular orientation of the rotating stage (Ns). The sinogram data set consisted of 40 projections (i.e. Np = 40) at 9° intervals over 360° and 32 ray sums (i.e. Ns = 32) with 8-mm translational step size. Counts were taken at each step for 60s to obtain maximum counts for 662 keV energy peak.

ECT results for 662 keV energy peak are shown in figure 7. Emission tomographic image is reconstructed on 32 x 32 grid. Image reconstruction is done using the iterative MLEM algorithm. The location and shape of the Cs-137 disk source are recovered as expected in the reconstructed image [figure 3(d)]. The source activity measured in the scanned plane is 2.1 μCi which is lower than the original activity (~ 9.5 μCi).

CONCLUSIONS AND FUTURE WORK

An emission tomographic reconstruction module has been created for non-destructive assay of low activity nuclear waste drums up to 208-L (55 gal) capacities in facility at IAD, BARC. The hardware for this system is currently under development. Reconstruction is based on MLEM iterative algorithm. Simulation has been carried out to evaluate the spatial resolution and contrast performance of the algorithm prior to physical experiments. Simulation also used to optimize the number of iterations and projections. The location and shape of the sources has been recovered as expected in the reconstructed images. Our future work will focus on the implementation of reconstruction algorithm on General Purpose Graphics Processing Unit (GPGPU) for reduction in computation time.

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