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Portable Low-Cost CT Scanner Prototype Based on Coincidence Measurements

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Abstract: A prototype design of Computed Tomography scanner has been tested. The major system employs a gamma ray source, scintillation detectors, a data logger and a three-dimensional sample position controller. The image resolution is determined by the step size and the diameter of the gamma ray beam which is controlled by the pinhole collimator. This device is being designed as a prototype gamma ray scanner with modifications in the type of radiation being used, electronics setup and the rotation and translation techniques. In this scanner, however, the object is rotated instead of the entire detector-radiator system. The type of radiation being used will not be an x-ray tube, but will be an indirect byproduct of Na-22 $^{+}\beta$- decay. This source emits positrons at the surface of the object which rapidly annihilate with atomic electrons that result in the emission of 2 back-to back 511 keV annihilation photons that can be used to electronically require coincidence between gamma detections and therefore reduce background radiation being detected. It is obvious that tomographic imaging is a complex procedure, thus, the main motivation of the work is to prove the capabilities and performances of a prototype CT scanner based on coincidence measurements, as an imaging system.
Keywords: Coincidence Measurements; CT scanner, Prototype Design; Annihilation Photons.
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Introduction

Computed Tomography (CT) is a method of constructing a two-dimensional (2D) image of the internal structure of a solid body. This method uses computers to construct an image using information obtained from photons that have passed through the body from multiple angles. The algorithms used to calculate the images are called image reconstruction from projection algorithms [1]**.** There are two categories for image reconstruction algorithms, the analytical algorithms and the iterative algorithms [2]. Analytical algorithms have been popularly used for modern 1st - 4th generation CT, because modern CT has to process a large amount of projection data. On the other hand, iterative methods are slow but more accurate than analytical methods. Iterative algorithms can be divided into algebraic algorithms and statistical algorithms [3]. For image reconstruction in this work, filtered back projection [4] or iterative algorithms can be used. Iterative algorithms were chosen because projection data are small. Among statistical algorithms, EM (Expectation Maximization) [5] is used for image reconstruction in this paper. Computed tomography (CT) was first introduced into medical sciences, and lately with the success of the technique, CT began to be used in other areas of knowledge [6, 7, 8]. For example, Pires *et al.* showed that scanning of soil samples was performed with a first generation CT scanner with fixed source–detector arrangement and translation/rotational movements of the samples [9].

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The new design that is being built differs from standard computed tomography scanners in both the radiation source and the translation/rotation method [10]. First, most computed tomography scanners use x-rays generated by the use of a hot cathode x-ray tube. These x-rays are collimated to produce a beam. The new design, however, will not use x-rays but annihilation photons produced by a Na-22 source. This source emits positrons at the surface of the object which rapidly annihilate with atomic electrons that result in the emission of 2 back-to back 511 keV annihilation photons that can be used to electronically require coincidence between gamma detections and therefore reduce background radiation being detected [11]. The reduction of background radiation allows the radiation source to be less active, since the signal does not need to compete with background noise [12]. The second difference in the new design is the way the transmission beam being rotated and translated across the object. In most computed tomography scanners, the object being scanned must remain motionless. This is a requirement, for example, if the object is a human. However, since our preliminary design will not be used on humans, the object itself will be rotated and translated. This change simplifies the mechanical apparatus, since it requires only one object to move rather than rotating and translating both the detectors and the source. Other advantages of the scanner include lower cost and that it would be more portable, as well as that the relatively small size and lack of lead shielding required by the scanner would allow it to be transported by workers to remote areas.

The disadvantages might include the higher energy annihilation photons involved and the more complicated electronics for each in-line detector channel. The more complicated electronics would make repair more difficult to perform. The imaging time would also be very slow compared to modern-day scanners.

Experimental Work

The present measurements are performed using Na-22 radioactive source with an activity of 1μCi. The source is placed in front of data detector (detector 2) as shown in Fig. 1. The energy transition that is being made to change Na-22 nuclei into Ne-22 nuclei is a 1.274 MeV gap that must be jumped by emitting a 1.274 MeV particle. 90.05% of the time, the Na-22 nucleus emits a 1.274 MeV positron. The Na-22 nucleus will also emit a 1.274 MeV gamma ray in order to make the transition. Due to atomic electrons, the positron will then be captured to form positronium. This positron-electron annihilation results in the production of two back-to-back 511 keV annihilation photons. We can use this fact to our advantage when building a computed tomography scanner. Each annihilation photon that reaches the detector has a annihilation photon traveling in the opposite direction. By placing the coincidence detector (detector1) behind the Na-22 source and directly across from the data detector, an electronic setup can be built that will require a coincidence between a transmitted annihilation photon and the corresponding annihilation photon traveling in the opposite direction. In requiring such a coincidence, the majority of background events can be eliminated. Instead of requiring a very intense source to produce a useable signal to noise ratio by enhancing the signal, the signal-to-noise ratio is maintained by reducing the background noise. Therefore, a weaker and safer source can be used.

The mechanical part of the scanner which was built in the workshop of the Department of Physics/ University of Jordan is a complex sample holder driven by three powerful stepper motors; (M1, M2 and M3), all fixed onto a main metallic frame, and controlled by computer software. The first motor drives the sample in a forward and backward direction on a 20 cm linear track. The second stepper motor is used to rotate the sample holder to any angular position, from 1° to 360°. In a similar way, the third stepper motor is used to allow up and down translational motion of the sample holder, as shown in Fig. 2.

Measurements were taken to begin construction of this novel design, and the performance of the scanner is tested by scanning a cylindrical vessel of water (density = 1g/cm^3) of 10cm diameter and a steel nut (density = 7.85 g/cm^3) of 5cm inner diameter and 10cm outer diameter. The capability of this proposed setup to distinguish between different densities can be highlighted.

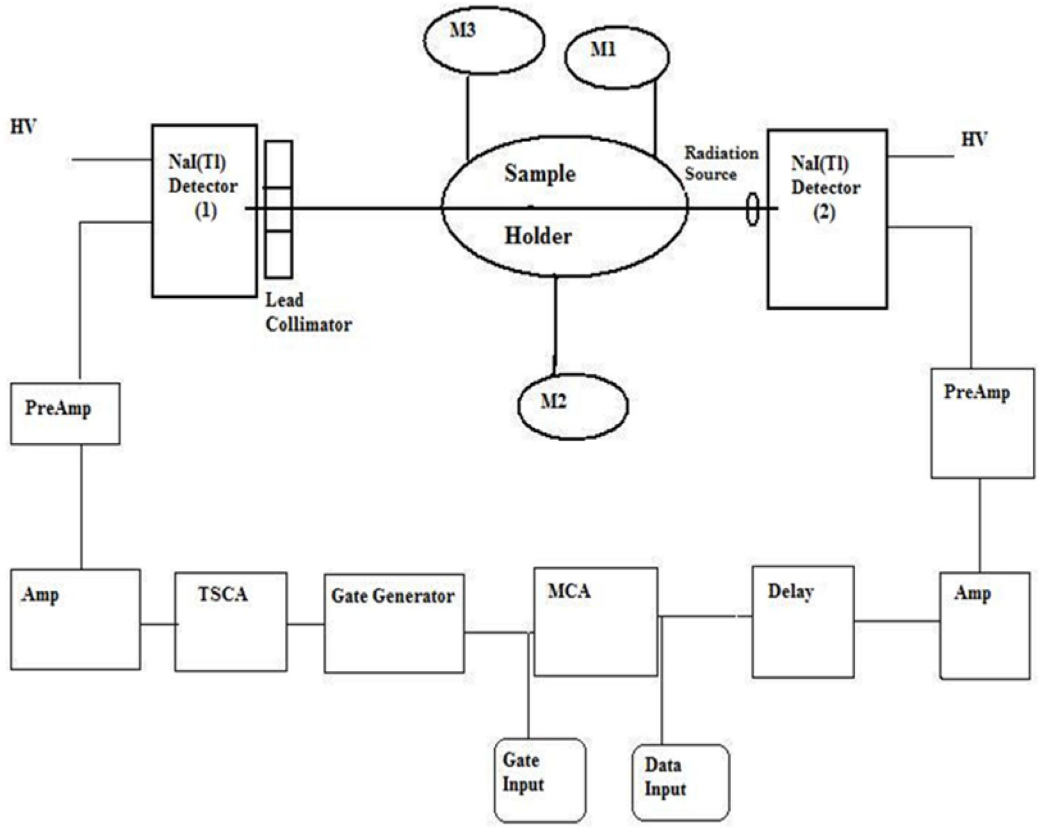

FIG. 1. A schematic diagram showing the electronic circuit involved in data collection.

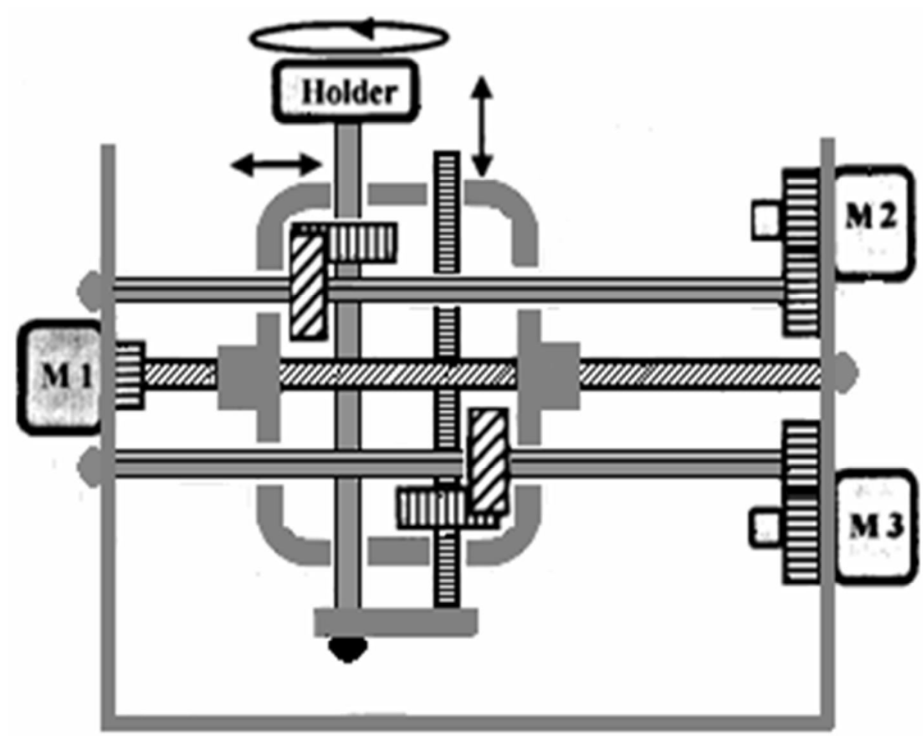

FIG. 2. Mechanical construction showing the side view of the scanner.

Results and Discussion

The energy resolution of the detectors was measured and calculated. Both detectors collected the energy spectrum of Na-22 source, and using this spectrum the energy resolution of the detectors was found 8.4% and 9.5% for the coincidence and data detectors, respectively.

Spatial resolution is described by the full width at half maximum (FWHM) complemented by the full width at tenth maximum (FWTM) of the line spread function of the detector. The limit of the spatial resolution is set by the intrinsic resolution, R_i. It describes the ability of the system to transfer the spatial distribution of the absorbed energy in the detector to a readable image, and it depends primarily on the statistical fluctuation in the number of light photons hitting the detector [11]. The spatial resolution is also heavily dependent on the collimator resolution R_c, and for high resolution the collimator holes should be as long and narrow as possible. R_c is dependent on the distance from the collimator, and the value of R_c increases in an approximately linear manner with increased distance for a parallel-hole collimator. Therefore, it is important that the collimator is as close to the sample as possible. Spatial resolution is also dependent on scatter and septal penetration, to a less degree, and the contribution of these effects is called R_{sc}. The total spatial resolution can be calculated as:

$$R_{tot.} = \sqrt{R_i + R_c + R_{sc}} \qquad (1)$$

In this work, the full width at half maximum (FWHM) has been measured for the spectrum several attempts sufficient to collect a spectrum on a multi- channel analyzer (MCA), and the average value was 5mm. Although it is not a good result, it is suitable enough for a home-made scanner.

Data collection time, in this case, is mostly dependent on the amount of time it will take to collect enough data for each measurement in order to acquire a particular amount of error for that data. While measuring the number of annihilation photons, there is a statistical error equal to the square root of the number of counts. In this work, the accepted error is ten percent; therefore each measurement will require one hundred counts. The number of gamma detections can be calculated using the next formula [11].

$$N_{det.} = N[(\frac{\Delta\Omega}{4\Pi})(\varepsilon_1)(\varepsilon_2)(C_1)(C_2)Exp[-\mu x]] \qquad (2)$$

where N is the number of disintegrations in the nucleus resulting in at least one gamma emission which was known to be 3.7×10^4 disintegrations per second, $\frac{\Delta\Omega}{4\Pi}$ is the geometric solid angle of the detections, $\varepsilon_1$and ε_2 are the detector's efficiency that can be determined for this type of detectors to be 64% [11].

C_1 and C_2 are the photopeak fractions of both detectors which were measured to be 40%, μ is the coefficient of attenuation for the material being scanned and x is the distance through which the annihilation photons have to travel. Calculations of the geometric solid angle of the detections are made depending on using one micro-Curie Na-22 source. The calculated value is approximately 1.29×10^{-4}. Arranging the last calculations, the number of detected radiations can be calculated, and the average time required for each measurement is 841.75 seconds. In this work, 20 translations are required to completely cover the scanned body of water. The number of rotations required for this particular setup is determined. In a higher resolution scanner, there would be one rotation for every degree in a half circle. However, since the width of the beam in this case is larger, it will require more rotation per angle in order to avoid overlap. The beam angle is rotated 5.74 degrees which requires 32 rotations. The whole number of translational and rotational measurements has been calculated. The total time required to perform the scan is determined to be 538720 seconds. This is equal to 6.23 days of continuous scanning.

Fig. 3 shows the reconstructed image of the water body using the (EM) reconstruction method on a matrix of 64x64 pixels. The image shows that the examined cross-sectional views of the sample (transverse planes) have a homogeneous density which describes the water content of the vessel. In spite of the limitation of the imaging time and spatial resolution of the proposed system, the reconstructed image is reasonable.

Fig. 4 shows another example of the scanner output of a reconstructed image of a steel nut of 5cm inner diameter and 10cm outer one by the same reconstruction method. The images demonstrate the good image quality obtained by the scanner and its ability to distinguish between different densities.

The last two images can be taken in the saggital and coronal planes, which are left as a future work, since we are interested now in testing the performance of this design in transverse plane.

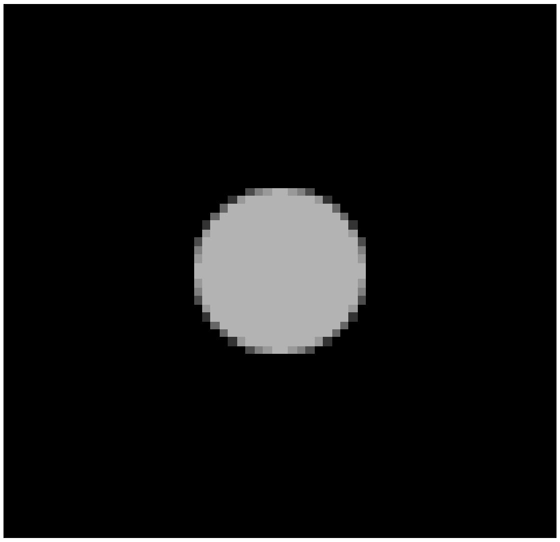

FIG. 3. A reconstructed image of a cylindrical vessel of water.

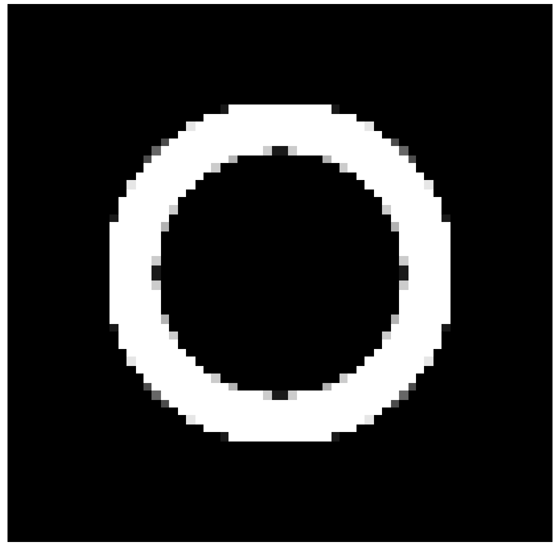

FIG. 4. A reconstructed image of a steel nut.

Conclusions

The energy resolution was found 8.4% for detector (1) and 9.5% for detector (2). Spatial resolution and detector efficiencies were determined. Through a series of calculations, it was found that a complete scan using the condition described would theoretically take about 6.23 days. Although it is not a good result, it is suitable enough for this appropriate design of scanners.

In spite of the limitation of the imaging time and spatial resolution of the proposed system, the reconstructed images are reasonable and can be considered as a novelty compared to those obtained from other standard transmission CT scanners.

The collimation and filtering out background noise could also be achieved by using the combination of the coincidence detector and data detector.

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