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Determining Block Detector Positions for PET Scanners

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Abstract

We present an algorithm for accurate localization of block detectors in a positron emission tomography (PET) scanner. Accurate reconstruction of PET images requires precise knowledge of the physical position and orientation of the detectors. However, in some systems, block detector positioning and orientation can have relatively large tolerances, leading to implicit errors in the coincidence line-of-response (LOR) positioning. To compensate we utilize a rotating point source phantom where the rotational angle of the phantom is used to precisely determine the location of each scintillator crystal within a detector block. The aggregate block positions are then applied to the system model to determine the true location of each LOR. Images reconstructed with the more accurate LOR positioning demonstrate improved image fidelity.

I. Introduction

In order to ensure qualitative and quantitative accuracy in reconstructed PET data, precise knowledge of the physical positions of the individual scintillator crystals is needed. However, the construction of some PET scanners allows for relatively large positioning errors in the placement of the scintillator blocks (e.g. small animal, prototype, or limited production scanners). Physical error in the positioning of the block detectors generally result in errors in PET image reconstruction [2].

To address this problem, we propose to construct a device that will rotate a point source within a PET scanner. Knowledge of the position of the point source will allow us to accurately estimate the physical position and orientation of block detectors. To test our proposed method, a computer simulation was performed using a virtual PET scanner with known positioning errors applied to the block detectors. Our positioning algorithm was then used to estimate the positions of the block detectors in the virtual scanner. Reconstructions of a grid phantom were then performed using the system models for the uncalibrated and calibrated scanner. The reconstructions using the geometric models determined by our calibration algorithm show significant improvements over those reconstructed using the uncalibrated model.

III. Materials

We propose to construct a positioning machine to rotate the point source within the scanner geometry. This machine will consist of a rotating motor and a translational motor. A point source phantom will be attached to a radial arm connected to the rotating motor. As the point source is rotated within the scanner, its angular position will be continually recorded via an encoded message sent to the TTL-in port of the scanner. Our model assumes an accuracy of 0.01 degrees of the rotating point source. When a single rotational acquisition of the point source phantom is completed, the translational motor will move the point source along the z-

axis of the scanner and another rotating acquisition will be taken. This is repeated as necessary to get the statistical counts needed for accurate positioning.

IV. Methods

A virtual computer model of the Micro Crystal Element Scanner (MiCES) [1] was created to generate listmode data from virtual objects placed in the scanner. The modeled scanner consists of 18 block detectors in a ring geometry. Each detector consists of a 22×22 array of scintillator crystals which are $0.8 \times 0.8 \times 10.0$ millimeters, and which have a 0.1 mm septum between each crystal. The diameter of the ring array is 125 millimeters. Random spatial and rotational errors are then applied to each detector to simulate physical mis-positioning of the scintillator crystals. The positioning errors range from zero to five millimeters, and the rotational errors range from zero to three degrees.

A virtual point source phantom was scanned in the mis-positioned model. The plane of rotation is roughly 5 mm into the bore of the scanner to ensure that the plane of rotation intersects all detector blocks. The radius of rotation of the point source is 45 millimeters, which is optimized for the MiCES geometry. Roughly 30 million coincidence events were detected for this acquisition. Once the rotational acquisition was completed, the point source was translated 10 mm along the z-axis, and a second rotational acquisition was performed, resulting in another 30 million coincidence events. Our simulation does not incorporate scattered photons, random coincidence events, photon acolinearity, or machine noise. For a given pair of scintillator crystals, each coincidence event is recorded along with the angle of the point source.

A. Determining Phantom Planar Crystals

We number the detectors 1 through 18, counting counterclockwise from the positive x-axis. For a given detector, crystal column 1 will be the column of crystals with the lowest angular polar coordinates. Our method requires that we determine the scintillator crystals that are intersected by the plane of rotation of the point source phantom. We only consider those crystals that lie at the edge of the detectors, namely columns 1 and 22 for each detector. For those crystal pairs that do not lie in the phantom plane, coincidence events are only recorded for a small range of point source angles. For those crystal pairs that lie within the phantom plane, coincidence events will be recorded for two distinct angular regions of phantom angles, as can be seen in Figure 2. For each crystal pair that exhibits such behavior, a vote is given for that crystal pair to be “in-plane”. The crystal with the most votes in a column of crystals within a detector block is determined to be the in-plane crystal for that column of crystals.

At this point, we have an initial determination of the in-plane crystals for columns 1 and 22 for each detector block. We then determine the in-plane crystals for columns 2 through 21 via linear interpolation.

B. Z-Axis Positioning

After the in-plane crystals have been voted for, we then determine the fraction of each in-plane crystal that lies on each side of the phantom plane. This algorithm requires that we only use those phantom point source angles that place the point source nearest the crystal being analyzed.

For coincidence events that are detected when the point source is near the considered in-plane crystal, we determine the number of coincidence crystals in the opposing detector that are on each side of the opposing in-plane crystal. By using similar triangles, we can determine the fraction of the considered crystal that lies on each side of the phantom rotational plane as is illustrated in Figure 1.

The radius of rotation of the point source ensures that there can be at most seven such opposing crystals (using a physical point source diameter of 0.25 millimeters). Combined with careful determination of the z-positions of the linear motor and the estimated positioning errors, this helps to ensure that the “cone” of response will not extend beyond the boundaries of the opposing detector.

If, for a given in-plane crystal, the similar triangles method reveals that opposing counts are not nearly symmetric on each side of the phantom plane, then this same similar triangles method is applied to the crystals adjacent to the considered crystal. If one of the adjacent crystals has a more symmetric distribution of opposing crystals, then it is likely that it is truly the in-plane crystal, our initial guess being incorrect. In this manner, we are double-checking our guess as to which crystal truly lies within the phantom plane. At the time of this publication, this double-check has not yet been implemented.

After the in-plane crystals for columns 1 and 22 are double-checked and determined to be accurate, the in-plane crystals in columns 2 through 21 are re-computed for each detector via linear interpolation.

By using these computed positions, we create two points on the entrance face of the detector that represent our estimates of the intersection of the phantom plane and the edges of the detector block. Using a second, translated rotational acquisition determines two more such points, and those four points create a parallelogram on the entrance face of the detector block, which we call $\mathcal{P}_1$. (This parallelogram may be slightly misshapen due to errors in the z-positioning estimate.) Since the detector is not yet oriented in space, we assume that $\mathcal{P}_1$ lies in the y-z-plane, and determines a detector that has its bulk along the positive x-axis. We further assume that the centroid of $\mathcal{P}_1$ is the origin. Thus, the normal vector projecting outward from the entrance face of the detector and starting from the centroid of $\mathcal{P}_1$ is the negative x-axis.

C. Triangulation of Detector Edges

As the point source phantom enters the field of view for a given in-plane scintillator pair, coincidence counts begin to register, and we refer to the first recorded position of the phantom as $\mathbf{P}_{min}$. When the point source phantom leaves the field of view of that crystal pair, the coincidence counts stop, and the last recorded position of the phantom is recorded as $\mathbf{P}_{max}$, as is illustrated in figure 2.

Given a long enough scan time, with a large number of coincidence events, we can assume that $\mathbf{P}_{min}$ and $\mathbf{P}_{max}$ closely estimate the edge of the tube of response for a given crystal pair. With an accurate, $\mathbf{P}_{max}$ and $\mathbf{P}_{min}$ for multiple crystal pairs, we can triangulate the corner of a given scintillator crystal, as is illustrated in Figure 3. Multiple triangulations yield multiple estimates of position of the corner of the scintillator crystal. (In order to increase the counts that are obtained for statistical positioning, we can compute $\mathbf{P}_{max}$ and $\mathbf{P}_{min}$ by using coincidences from each crystal adjacent to the in-plane crystal and the entire opposing column of detector crystals. The union of these tubes of response is roughly a triangle, and thus would not greatly effect our calculation of those positions.)

Our currently implemented method computes four such intersection points for each crystal corner. For column 1 of a given detector, the triangulations are computed by using column 22 of detectors $\{D + 4, D + 7\}$, $\{D + 4, D + 8\}$, $\{D + 5, D + 7\}$, and $\{D + 5, D + 8\}$, where D is the currently considered detector. The determination of these lines generated from $\{D + 5, D + 8\}$ ($D=5$) is illustrated in Figure 3. When estimating the intersection points for crystal 22 in each detector, we symmetrically use $\{D + 14, D + 11\}$, $\{D + 14, D + 10\}$, $\{D + 13, D + 11\}$, and $\{D + 13, D + 10\}$, where $\{D + 13, D + 10\}$ is the symmetric analogue to $\{D + 5, D + 8\}$. This process is then repeated for the second rotational acquisition.

For each of these estimates, the z-axis value is determined by the position of the translational motor. Only the x and y values are computed.

D. Registration

For a given detector, we compute the least squares best fit plane to the sixteen edge estimate points. This plane is an estimate of the plane that defines the entrance face of the detector. Each edge estimate is then projected onto this plane, and the centroid of these projections is computed. For each edge estimate point, this centroid is then subtracted, and the normal vector for the best-fit plane is then rotated to match the normal vector of the plane of $\mathcal{P}_1$. This places the best-fit plane in the y-z-plane, with the centroid of the projections at the origin, similar to section IV-B. We refer to the set of transformed edge estimates as $\mathcal{P}_2$, which roughly resembles a parallelogram similar to $\mathcal{P}_1$.

With their centroids and normal vectors aligned, $\mathcal{P}_1$ and $\mathcal{P}_2$ only differ (in essence) by a rotation. We rotate $\mathcal{P}_1$ incrementally from -15° to $+15^\circ$ in increments of 0.1° , and record the sum of the Euclidean distances from the projections of the transformed edge estimates to the appropriate $\mathcal{P}_1$ corner. The minimum of this sum is considered the best rotational fit.

Taking the inverse of the above-mentioned operations places the considered detector at the position in space that we use for our estimate of the true geometry.

E. Computation of Errors

For each detector, we compute the cylindrical coordinates of each of the eight true detector corners and the eight estimated detector corners. We then record the maximum (r, θ, z) difference for that detector. We also compute the mean, standard deviation, and maximum of these values for these values over all detectors.

We then scanned a virtual grid phantom consisting of 0.5 mm spherical sources placed on a 10×10 grid. The listmode data from the grid phantom acquisition was then reconstructed with filtered backprojection using the theoretical geometry, the true geometry, and the solution geometry. Profiles were then taken through each of these reconstructions for quantitative comparison.

V. Results

The mean $\pm$ SD (max) errors for our solution (in cylindrical coordinates) are: $r = 0.46 \pm 0.16$ (0.68) mm; $\theta = 0.13 \pm 0.07$ (0.32) $^\circ$; $z = 0.39 \pm 0.26$ (1.02) mm. The mean value for θ represents approximately one-sixth of a crystal width.

The true and solution geometries are shown together in Figure 5. The reconstructed images from the grid phantom acquisition are shown in Figure 6, and the profiles through those reconstructions are shown in Figure 4.

VI. Discussion

A. Errors

The positioning errors in the model (as large as 5 millimeters and 3 degrees of rotation) represent a “worst case scenario”. We expect that errors of these magnitudes would be rare in the physical application.

For our solution to this geometry, we discovered a single error in the determination of the in-plane crystals (one out of 18×4). The other 71 in-plane crystals were reported correctly. This error resulted in the high maximum z-error (1.02 mm, just over one crystal width). We are

confident that once the “double-check” algorithm from section IV-B is implemented, that such errors will be eliminated.

B. Robustness of the Algorithm

This calibration phantom and protocol is not restricted to ring geometries. Crystal positions in planar geometries can also be determined by this phantom and algorithm.

C. Correction of Real World Statistical Errors

Once the detector response functions for the actual MiCES scanner are measured, we will apply appropriate statistical methods to the phantom angles versus coincidence events curves for the in-plane crystal pairs to compensate for anti-photon acolinearity, scatter, and machine noise. Since the position of the point source phantom is known for each coincidence event, we can reject inter-detector scatter and random events with a high degree of certainty.

We chose to present the results from a single simulation with over 30 million coincidence events per rotating acquisition. Similar results to those presented were achieved with only 5 million coincidences per rotating acquisition.

VII. Conclusion

Our method for detector positioning shows that even when relatively large positioning errors are present, we can compensate for those errors, resulting in improved reconstruction accuracy and image fidelity.

Acknowledgments

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References

1. Lee K, et al. Pragmatic fully 3D image reconstruction for the MiCES mouse imaging PET scanner. *Phys Med Biol* 2004;49:4563–4578. [PubMed: 15552417]
2. Abella, M., et al. Effect of misalignments in small animal PET scanners based on rotating planar detectors. AMI conference poster No. 120; 2006.

Fig. 1.

Computation of the z -coordinates of $\mathcal{P}_1$. The crystal columns in the bottom detector are illuminated in a 2:4 ratio, and thus we use a 4:2 ratio as the dividing point of the in-plane crystal in the top detector.

Fig. 2.

Two in-plane scintillator crystals are illustrated with their tube of response and the circular path of the point source. $P_{\max}$ and $P_{\min}$ estimate the edge of the tube of response.

Fig. 3.

Using the tubes of response from two opposing crystals, we can triangulate the corner of the crystal at the top.

Fig. 4. Reconstruction profiles from Figure 6 using [dotted red] true physical detector positions, [dotted black] theoretical detector positions (uncalibrated), [solid blue] detector positions estimated from our algorithm (calibrated).

Fig. 5.

Comparison of the true detector positions with the solution determined by our algorithm. The detectors outlined in blue are the true physical detector position, while those detectors outlined in red are the positions estimated from our solution.

Fig. 6. Reconstructions of the grid phantom data using [left] true physical detector positions, [center] theoretical detector positions (uncalibrated), [right] detector positions estimated from our algorithm (calibrated). The profiles through the red lines are shown in Figure 4.