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Image nonlinearity and non-uniformity corrections using Papoulis - Gerchberg algorithm in gamma imaging systems

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Abstract. In this paper, the authors describe a novel technique for image nonlinearity and non-uniformity corrections in imaging systems based on gamma detectors. The limitation of the gamma detector prevents the producing of high quality images due to the radionuclide distribution. This problem causes nonlinearity and non-uniformity distortions in the obtained image. Many techniques have been developed to correct or compensate for these image artifacts using complex calibration processes. The presented method is based on the Papoulis - Gerchberg (PG) iterative algorithm and is obtained without need of detector calibration, tuning process or using any special test phantom.

1. Introduction

Image non-uniformity and nonlinearity corrections exist in many imaging systems at different spectral regions such as visible, infrared optics, X-ray as well as gamma radiation. In the Gamma imaging, one reason for the mentioned problem is due to photomultiplier tubes (PMT) undergoing gain shifts when spatial orientation changes with respect to an external magnetic field [1-2]. These effects can be produced due to several reasons related to a magnetic field e.g. earth's magnetic field. The maximal gain shifts occurs when the PMT rotates through an angular orientation generating a 90° angle with the azimuth and the orthogonal direction which is relative to the external field. It causes a one percent change in the secondary emission ratio per dynode which results in a change of more than 10% in the charge gain of the PMT. Consequently, detector assemblies with inadequate magnetic shielding can experience gain shifts sufficient to cause significant angle-dependent spatial non-uniformities, some appearing in the shape of a half-moon, and some as changes in the observed count rate as a function of angle [3-5]. Another cause is due to thermal gradients in detector housing, which can produce changes in uniformity and other artifacts [6]. Image non-uniformity is very sensitive to the uniformity of the electric field in scintillation cameras. There are two primary reasons for it in flood field images produced from Anger scintillation cameras: one third is caused by photo-peak energy-axis shifts at different points in the field of view [7,8] and the remaining two-thirds are primarily due to spatial nonlinearities (distortion).

Nowadays uniformity requirements are more stringent and correction circuits do not correct the collimator non-uniformities. Spatial non-uniformities in scintillation cameras and collimator defects

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may produce count losses. In circular detector orbits cases, these manifest themselves as concentric ring or "bull's eye" artifacts and become even more complicated artifacts for noncircular orbits [9].

In our paper, we refer to the limitation of the gamma detector mentioned above, which prevents the producing of high quality images. We present a novel technique aiming for gamma imaging correction which uses both Gaussian smoothing for low pass filtering and the use of the Papoulis - Gerchberg algorithm for extracting a high resolution images from the non-uniform acquired data. The method is performed on the acquired raw image exploit areas of high resolution to fill up low resolution parts and try to minimize calibration processes both on a daily basis and the less frequent ones.

2. Gamma imaging distortion function

In order to understand the method used, we need to understand the distortion function caused in the gamma detectors as seen in Fig. 1a. We noticed that this distortion function is localized at each PMT position and is similar to a Gaussian smoothing function. It means that at the center of the PMT, it has a high sampling rate and at the edges it has a lower rate. The PG algorithm has two requirements for full reconstruction. One is that it needs sufficient high resolution sampling data from the original, non-distorted image that meets the PG full reconstruction condition, and the second is to know the precise bandwidth, σ, of the original image. In our case both conditions are met and therefore the PG algorithm is found to be very suitable for the PMT distortion case.

3. Mathematical overview using the Papoulis - Gerchberg algorithm

The Papoulis - Gerchberg algorithm method for super-resolution is based on work done by Papoulis [10] and Gerchberg [11]. Gerchberg proposed to perform signal reconstruction given a priori knowledge of the signal diffraction limit and only a portion of its spectrum. In Papoulis work he showed how to extrapolate a band limited signal from part of the original signal, i.e., determining the transform. The Papoulis-Gerchberg algorithm has been used in a modified form by Vanderwalle et al. [12] to super-resolve images when multiple low-resolution (LR) registered images are available and Chatterjee [13] used only a single LR image for the same purpose.

Now, let us express the distortion function as in Eq.1 where we use a distorted image denoted by *g(x)* which is built from high-resolution image, *f(x)*, undergoing a distortion expressed by the function *d(x).* The distortion function is actually built from a basic Gaussian distortion function which mimics the PMT distortion and distort local areas in the original image according with the PMT hexagonal array arrangement or any other arrangement that exist in Gamma cameras. Hence, we have partial sampling data that causes the non-uniformity and non-linearity.

$$g(x) = f(x) \cdot d(x) \tag{1}$$

The image distortion results in a local clustering with barrel like distortions. The barrel like distortion has both high resolution data on the center and low resolution data on the boundaries. To make a distortion function that mimics the PMT array we use the following function,

$$d(x) = PMT_{Gaussian}(x) * \sum_{i=0}^{i=n} \delta(x - x_i) \tag{2}$$

where * designates a convolution operation. Here we used a Gaussian shape and on the overall result we apply the Papoulis–Gerchberg (PG) algorithm to obtain the reconstructed image.

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Note that we assume having sufficient high resolution data to meet the PG algorithm requirements for full reconstruction. The PG algorithm is described briefly in Eq. 3 and Eq. 4. At first, the given image is Fourier transformed (usually after some noise is added to the inaccurate portion of the image to enable fast convergence), then in the Fourier plane one imposes the known low frequency data regions on the result and keeps the rest of the pixels as is. Next, an inverse Fourier transform is generated and, as in Eq. 3, one imposes the known data regions on the result and keeps the rest of the pixels as is. Next, as in Eq. 4, in the Fourier domain – the true low frequency data is imposed and the rest is kept, and so on.

$$g_n(x)=\begin{cases} g_{n-1}(x), & x\in\left[g_0(x)=0\right] \\ g_0(x), & x\in\left[g_0(x)\neq 0\right]\end{cases} \quad\Rightarrow\quad G_n(\nu)=\int_{-\infty}^{\infty} g_n(x)e^{-2\pi i x\nu}dx \tag{3}$$

Note that, ν is the Fourier transform coordinate and the G_n, G_{n-1} are the Fourier transforms of the nth and (n-1) iterations of the distorted function, $g_0(x)$, and P_σ is the original bandwidth window which is known a priori.

$$G_{n+1}(\nu)=G_n(\nu)\cdot \underbrace{P_\sigma(\nu)}_{\sigma\text{- Original image Bandwidth}} \quad,\quad P_\sigma(\nu)=\begin{cases}1, & |\nu|\leq\sigma \\ 0, & |\nu|\geq\sigma\end{cases}$$
$$\Rightarrow\quad g_{n+1}(x)=\int_{-\infty}^{\infty} G_n(\nu)e^{2\pi i x\nu}d\nu \tag{4}$$

Now, the reconstructed image is obtained by iterating until the error criterion is reached.
In our simulations we incorporate low pass Gaussian filter that helps smoothing the result prior to the reconstruction GP process as seen in Eq. 5.

$$g_0(x)=LPF_{Gaussian} * g(x) \tag{5}$$

4. Results using the Papoulis - Gerchberg algorithm

The proposed method was simulated with a distortion function that mimics the PMT distortion pattern that exists in the Gamma image. The Gamma imaging methods cause non-uniformity as seen in Fig. 1(a) while the required uniformity should be seen as in Fig. 1(b). Furthermore, local pincushion and barrel like distortions causing the image to have wave-like shapes instead of straight lines are also present. This distortion can be easily seen in Fig. 2(a) and Fig. 2(d) while the required result should be as seen in Fig. 2(b) and Fig. 2(e). When both linear and uniformity image correction are present in the image it should be seen as in Fig. 2(c) and Fig. 2(f).

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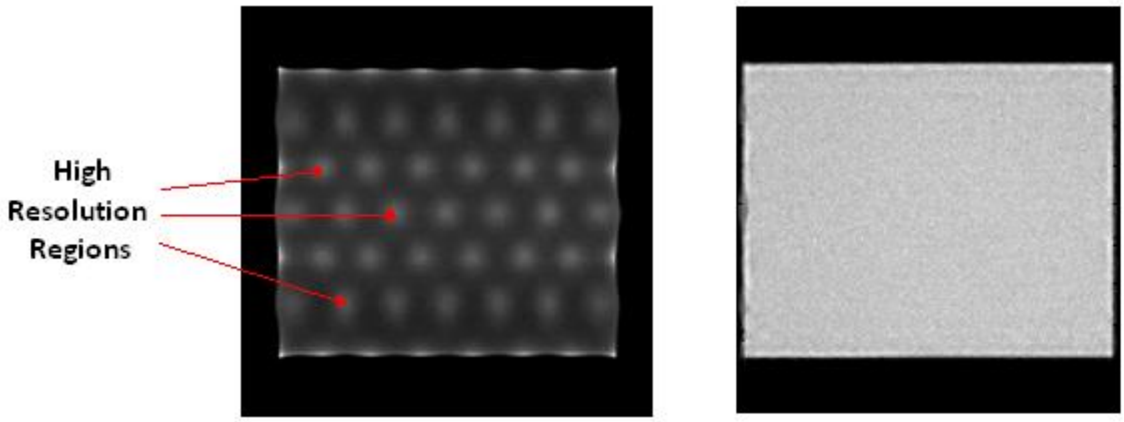


(a) (b)

Figure 1. (a) Gamma distorted image with non-uniformity areas (b) Field flood sample for corrected uniform and linear image

In order to convert the gamma-distorted image to the original image we use the connection between the high-resolution regions of the detector and the linear and uniform one. Furthermore, we enhance the reconstruction result by applying a Gaussian smoothing kernel. The chosen kernel size was relative to the size of the high-resolution regions.

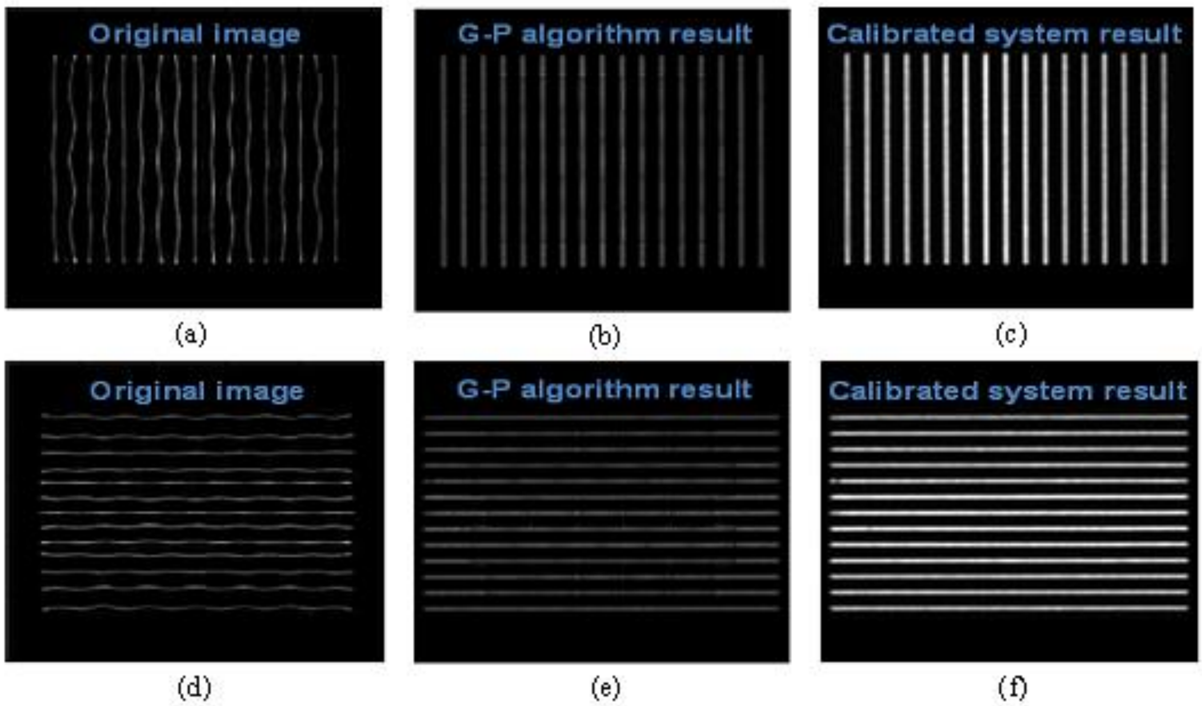
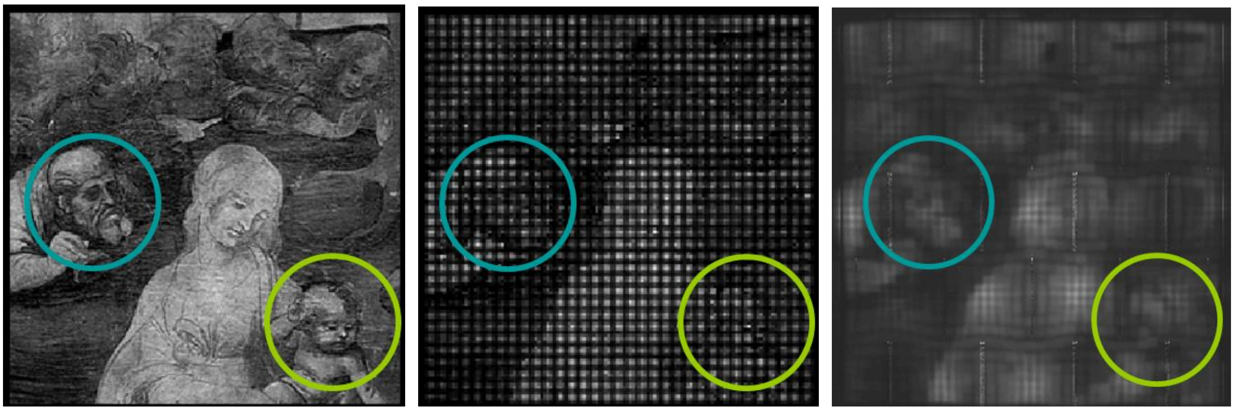


Figure 2. The (a), (d). The original distorted image; (b), (e). The corrected image results from the G-P algorithm technique; (c), (f). The reference system results of the calibrated system.

In gamma imaging, unlike optical imaging, linearity refers to the ability of the system to maintain straight line in lead bar phantom. The measurement parameter is estimated by measuring the amount of deviation from straight line in mm as seen in Fig. 2(a) and Fig. 2(d). The outcome of the PG algorithm as simulated by the authors, are shown is Fig. 2(b) and Fig. 2(e) and the calibrated results for achieving uniformity are shown in Fig. 2(c) and Fig. 2(f). It was found that the correlation between the PG algorithm linearity correction results and the reference calibrated system results was 74.34% for the vertical lines image and 68.87% for the horizontal lines image. Notice that after uniformity correction the correlation should be higher.

To show that the method can correct distortions not just for linear shapes, but also for more complex images, we introduce the Leonardo da Vinci's "Adorazione dei Magi" famous painting as our target image. Fig. 3 shows details from this famous painting by da Vinci. In Fig. 3(a) we see the original image, where regions of interest are circled.



(a) (b) (c)

Figure 3. (a) Part of Leonardo da Vinci's "Adorazione dei Magi" (1481); (b). Simulated gamma camera distorted image; (c). The corrected image results when applying Gaussian smoothing prior the Papoulis - Gerchberg algorithm technique.

In Fig. 3(b) we observe the image obtained by simulating the gamma camera operation. We re sample the image and applied the PMT distortion function and the smoothing function which result in gird like shape. Note that in Fig. 3(c) one can see the corrected image after using the PG algorithm which is used to correct the low resolution regions. However, the linearity correction was only partially corrected and barrel like distortion still partially exist.

5. Conclusions

In this paper, the authors presented a new technique for gamma imaging correction. The method reconstructs the original image by correcting the nonlinearity and non-uniformity in the image. This method aims to reduce the need of complicated calibration process with test phantoms. Further work should be done on real time Gamma image to examine method accuracy. This improvement is accomplished by using only the Papoulis - Gerchberg algorithm and by using the existing connection between the high resolution regions of the detector and a linear and uniform region of the captured image. The proposed concept was validated numerically. It was also shown that the method can be applied not only for gamma imaging but also for optical imaging systems having non-uniformity problems.

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