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Improving spatial resolution by predicting the initial position of charge-sharing effect in photon-counting detectors

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ABSTRACT: X-ray photon-counting detectors are considered as next generation x-ray detectors because they offer several advantages over conventional energy-integrating detectors, such as the ability to obtain energy information due to the photon-counting capability. In addition, the contrast-to-noise ratio in a photon-counting detector is higher than that of a conventional charge-integration detector due to its direct detection of radiation. Nevertheless, it suffers from charge sharing effect which is caused by diffusion of electrons generated from incident x-rays and k-edge escape photon to other pixels. Due to these phenomena, distortion can occur in terms of the position information and the energy information. In this work, we used the time-over-threshold (ToT) and projection method to compensate for charge sharing. We projected the charge-sharing value of eight neighboring pixels to the center pixel and found the point where the photon had the highest probability of entering the center pixel. We then divided the center pixel into 3×3 sections and found the location where the very first x-ray photon was incident through the projection. Using a timepix chip with CdTe pixels, 50,000 images were acquired for 1.5 seconds at intervals of 30 us with the ToT method. At this time, x-ray irradiation was applied to various materials at 80 kVp and 5 uA.

KEYWORDS: Data acquisition concepts; Inspection with x-rays; Radiation monitoring; Computerized Tomography (CT) and Computed Radiography (CR)

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Contents

1 Introduction

In a pixel-array-type sensor, a signal is incident on a pixel and affects other surrounding pixels. A conventional image sensor has a color filter and a lens for each pixel so that the signal generated by the photons is less likely to spread to the surrounding pixels. X-ray image sensors, on the other hand, cannot produce lenses or filters on the pixels. Thus, in both the indirect and direct methods, the incident signal affects the surrounding pixels, i.e., a crosstalk occurs in indirect x-ray sensors. As the x-ray photons interact with the scintillator, the visible light propagates broadly and spreads to the surrounding pixels. To minimize this phenomenon, the pixel pitch was optimized, and columnar scintillators were developed [1].

In the case of a direct-type detector, a phenomenon called charge sharing occurs. Charge sharing occurs when detector material reacts with x-ray photons and generate charges in a broad cloud form. Charge clouds diffuse into the target pixel as well as surrounding pixels. In addition, charge sharing occurs because the characteristic x-rays from k-shell and Compton scattered x-rays form a second charge cloud [2, 3]. Another contribution is the non-negligible track length of the photon and Compton electrons after photon interaction. They might leave part of their energy in the first pixel and travel to the adjacent pixel where they lose the remaining energy. The charge-sharing effect causes energy distortion and image degradation in photon-counting detectors [3]. This phenomenon occurs in all types of radiation image sensors, but it is considered a serious problem for photon-counting detectors. A photon-counting detector counts photons so that one is counted on the pixel where the actual signal is coming from, and one is also counted on the pixel with charge sharing. Therefore, unlike the low noise level caused by crosstalks in the charge integration method, there is a problem in that noise having the same magnitude as the actual signal occurs every time charge sharing occurs [4].

A physical way to minimize the charge-sharing phenomenon is to make the pixels larger. However, many applications that use x-ray images commonly require high spatial resolution. In industrial PCB inspection, the size of the chips is constantly becoming smaller, and they are becoming more complex. Therefore, it is impossible to use a large pixel detector to minimize charge sharing [5, 6]. Hence, several studies have been conducted to correct the charge sharing. First, in charge-summing mode, the values of neighboring pixels in which charge sharing has occurred are corrected by adding them to one reference pixel [7]. Next, the detector motion method

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captures an image once and moves it by half the pixel pitch in the x and y directions and takes second image. The two images are added to emphasize the original signal of each pixel [5]. In the center-of-mass method, the coordinates of the center of mass are found by using the positions and values of the pixels where charge sharing has occurred. At this time, the reference pixels are divided into smaller sub-pixels to improve the accuracy of the coordinates [6]. Nevertheless, each of the calibration methods introduced in previous studies had its drawbacks.

In this study, we introduce a new correction method to get better image quality by overcoming the disadvantages of previous research. The proposed method estimates the initial incidence position of a photon from the reference pixel by projecting the neighboring pixel values, which is described in section 2. In addition, the performance evaluation and results of the images obtained by the proposed method are described in section 3.

2 Materials and methods

In this study, there are two important conditions for image acquisition. First, the image must be acquired in the time-over-threshold (ToT) mode. Then, the acquisition time of a single frame must be very short and the number of frames must be large enough to reconstruct a fine image.

In a typical counting mode, a pixel value increases by one when an incident photon exceeds a threshold energy. If one photon is incident and charge sharing occurs with two surrounding pixels, the value of all three pixels will be represented as one in the obtained. In this case, however, it is impossible to find the initial incident pixel. In ToT mode, on the other hand, a clock is generated for the duration of the pulse generated according to the energy of the incident photons (see figure 1). The energy of a photon can be measured using the number of clocks that increase in proportion to the width of the pulse [8]. Depending on the number of counted clock ticks, each pixel represents the energy information of the photons. Therefore, it can be used to find the first incident pixel and use it as a reference point [6]. One assumption must be made in the process of determining the reference pixel. It is necessary to assume that the value of the pixel where the photon first enters is larger than the pixel where charge sharing has occurred.

In general, the x-ray imaging method of a photon-counting detector counts incoming photons for a specified exposure time to obtain the attenuation value of a subject. In this case, when charge sharing occurs, it is impossible to distinguish between incoming photons and previously counted photons. Therefore, to find the pixel where charge sharing has occurred, it is necessary to prevent photons from continuously being incident on the same pixel in a single frame. It is essential to set the acquisition time very short to minimize the overlapping of photons to the same pixel in a single frame. In addition, long x-ray exposure times are dangerous for patients with increased radiation doses in medical applications and limited use due to increased inspection time in industrial applications. Therefore, we set the acquisition time of each frame to 30 us and took 50,000 frames [6]. The total duration of exposure time while capturing the whole image data was 1.5 seconds but maximum frame rate of the detector was 100 fps. Thus, the actual data acquisition time was 10 minutes for 50,000 frames of images.

The detector used in this study to satisfy the above conditions was XRI-UNO with a CdTe sensor mounted on a timepix chip. The detector consisted of 256×256 pixels and had a pitch of 55 μm (14×14 mm). The thickness of CdTe was 1 mm, and the bias voltage applied to the sensor

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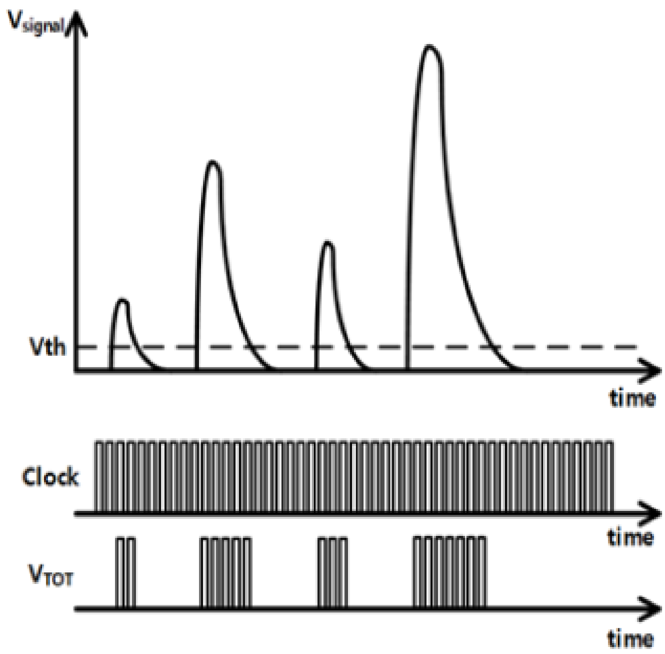

Figure 1. A schematic of the time-over-threshold (ToT) mode.

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was 350 V, which is the default value. The x-ray source was a continuous tube, and the irradiation conditions were an 80-kVp tube voltage and a 5-μA tube current. Example images obtained under these conditions are shown in figure 2.

In the method proposed in this study, images obtained under the above conditions are corrected by the projection method. The pixels where charge sharing has occurred are grouped together through clustering. Thus, the image in figure 2 appears to have photons in 10 pixels but can be grouped into four clusters [2, 6]. The reference pixel is the pixel in which the photon first enters, and is the pixel representing the largest value in one cluster. Eight pixel values around the reference pixel are projected onto the reference pixel to estimate the position where the photon is incident in the reference pixel.

First, the individual pixel values of the surrounding eight pixels are divided by the total value of the charge sharing, and the eight weighting factors to be projected to the sub-pixels are obtained. Then we assign the weighting factors to the sub-pixels closest to each of the eight pixels. Figure 3 shows an example of the projection location. The weighting factor is assigned to the sub-pixels closest to the pixel where the charge sharing has occurred. Therefore, when charge sharing occurs near each plane, weighting factors are assigned to two sub-pixels and three sub-pixels, respectively. When charge sharing occurs near the corner of the reference pixel, the weighting factors are assigned to one corner sub-pixel and three corner sub-pixels, respectively. After the weighting factor of all sub-pixels is calculated, the values in the reference pixel are multiplied, and they are assigned to the sub-pixels at each position.

After the correction is performed on all images, combining the corrected images removes charge sharing, and an improved image is obtained by measuring the position of the incident

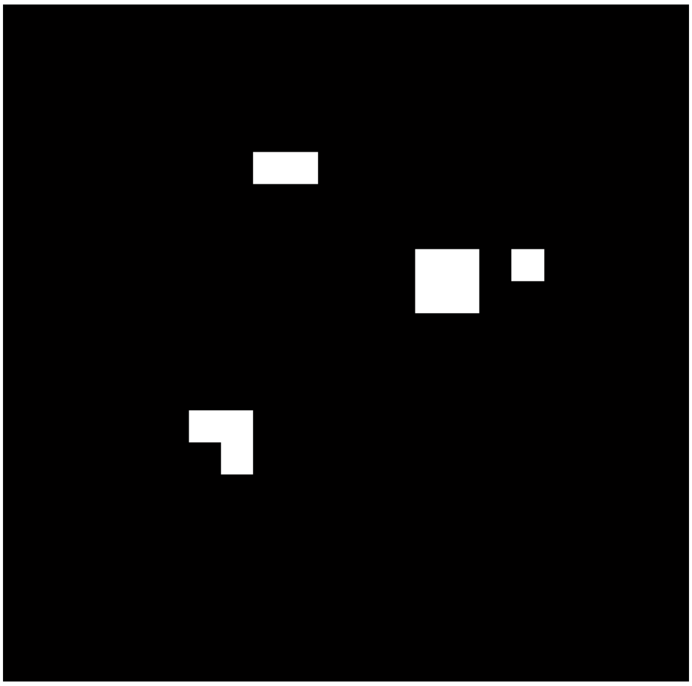

Figure 2. Sample part of an image when charge sharing occurred in a single-frame image.

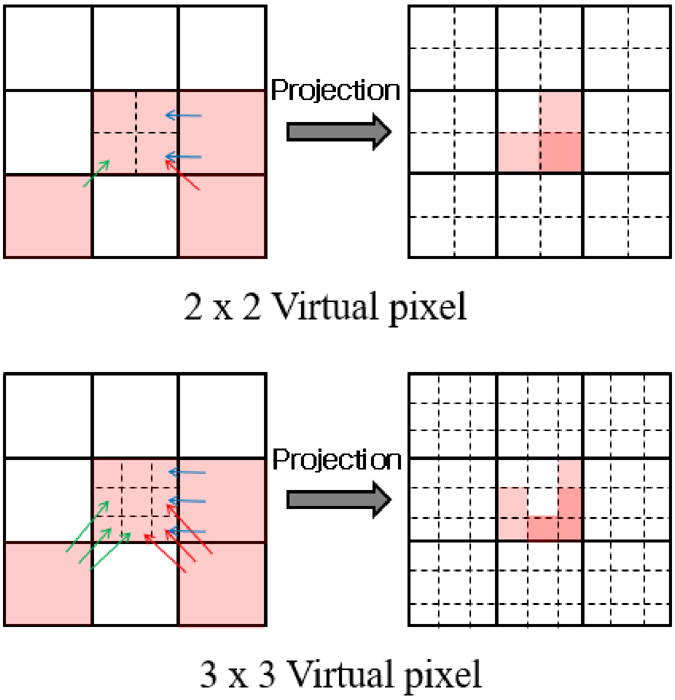

Figure 3. Example of the projection location for sub-pixels.

photons. When an image is corrected by the method proposed in this study, it indicates the position where the photon is estimated from the reference pixel. It cannot be specified exactly in terms of

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one sub-pixel, but it can be represented as the probability distribution of photons entering each pixel of all four and nine sub-pixels, respectively.

To measure corrected image results quantitatively, the modulation transfer function (MTF) was measured to evaluate the resolution performance, and the SNR was measured to evaluate the signal and noise of the corrected image. The MTF was measured using a line phantom that could measure from 1.6 lp / mm to 20 lp / mm. The SNR was measured using a tungsten phantom, covering half of the sensor and measuring signal and noise.

3 Result and discussion

The line phantom image obtained for the resolution evaluation is shown in figure 4 [5, 6]. Here, (a), (b), and (c) of the line phantom image show the original image, a 2×2 sub-pixel image, and a 3×3 sub-pixel image, respectively. Even with the naked eye, we can see that the more sub-pixels are divided, the more distinct the lines in the phantom are.

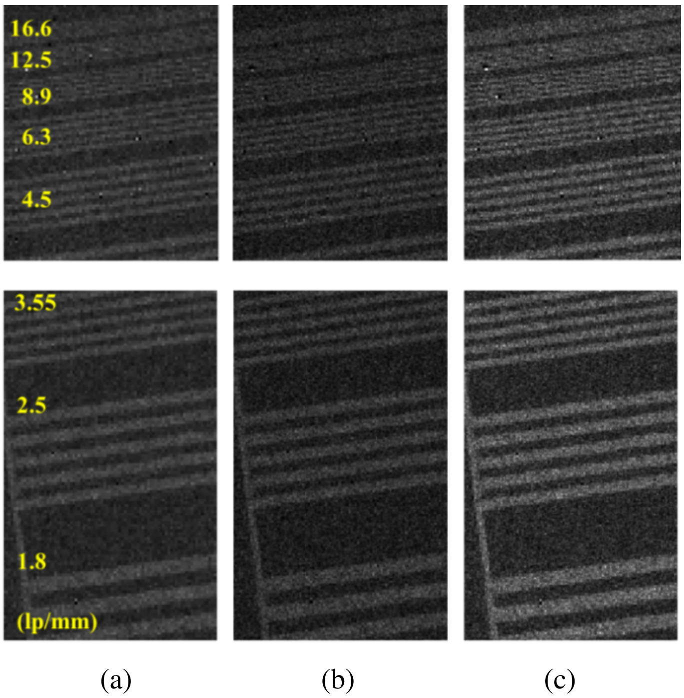

Figure 4. Line phantom image for (a) original image and two corrected images: ((b) 2×2 sub-pixel image and (c) 3×3 sub-pixel image).

The MTF results are shown in figure 5. The MTF values were increased in the 2×2 sub-pixel image and the 3×3 sub-pixel image in comparison to the original image, and slightly increased in the 3×3 sub-pixel image in comparison to the 2×2 sub-pixel image. Resolution was obtained from MTF50, a spatial frequency where the MTF is 50% [9]. The MTF50 and resolution results of the three images are summarized in table 1. MTF50 increased from 2.3 lp / mm to 8.2 lp / mm. In general, the actual image resolution is larger than the pixel pitch. The variation is determined by various noise and image acquisition environments. In this result, the smallest resolution increase compared to the pixel pitch was seen in the 2×2 sub-pixel image.

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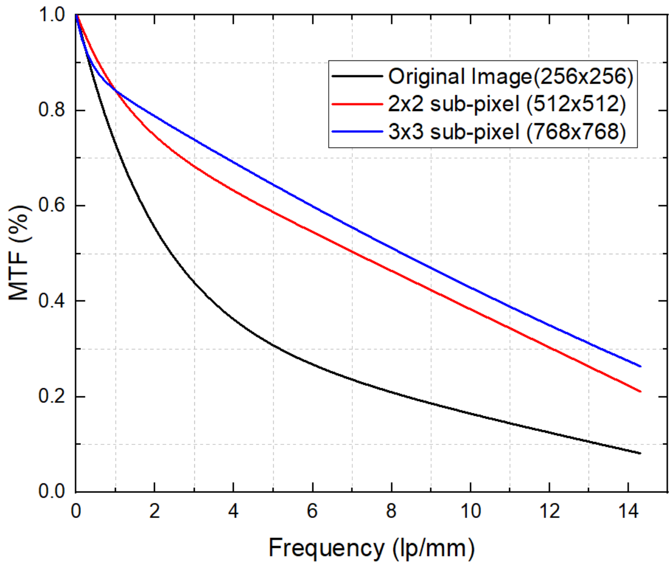

Figure 5. MTF graph of original image (black), 2 × 2 sub-pixel image (red), and 3 × 3 sub-pixel image (blue).

Table 1. MTF50 and spatial resolution for original image and two corrected images.

	Original image	**2 × 2 sub-pixel**	**3 × 3 sub-pixel**
MTF @ 50% (lp/mm)	2.3	7.1	8.2
Resolution (μm)	217	70	61
Pixel size (μm)	55	27.5	18.3

The SNR was obtained by measuring the signal area on the left and the noise area on the right, as shown in figure 6. Thus, 33 dB was measured in the original image and 26.6 dB was measured in the 3 × 3 sub-pixel image with the smallest pixel pitch. The reduction in the SNR of the corrected image was larger than the original image. However, the difference between the 2 × 2 sub-pixel image and the 3 × 3 sub-pixel image was small, similar to the MTF increase pattern.

If the reason for small MTF increment were to be the noise due to data loss caused by the increased number of sub-pixels, the SNR decrease should have been larger. However, the change in both evaluation factors was small. This is because total area of sub-pixels determined by projection method was similar in the 2 × 2 sub-pixel and the 3 × 3 sub-pixel. From the examples of the 2× 2 sub-pixel and 3 × 3 sub-pixel corrections in section 2, figure 2, the total area of corrected pixels were 2260 μm^2 and 2000 μm^2, respectively.

In terms of the MTF, the 3 × 3 sub-pixel has a smaller pixel size, but the MTF cannot be increased significantly because more sub-pixels are filled with values than in a 2 × 2 sub-pixel image and this causes more blurring effect in 3 × 3 sub-pixel image. The size of the sub-pixels was smaller in 3 × 3 sub-pixel case, but the signal size did not decrease significantly as more sub-pixels were filled. Thus, the decrease in SNR was not significant. The quality of the image was affected by the size of the sub-pixel and the number of filled pixels, that is, the total area of corrected sub-pixels.

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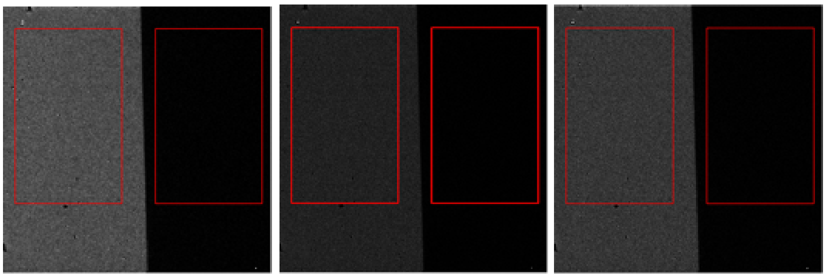

	Original Image	2x2 sub-pixel	3x3 sub-pixel
SNR (dB)	33.11	27.30	26.60
Pixel size (µm)	55	27.5	18.3

(a) (b) (c)

Figure 6. Edge phantom images and SNR values for (a) original image and two corrected images ((b) 2×2 sub-pixel image and (c) 3×3 sub-pixel image).

Therefore, in the previous example, the total area of sub-pixel after correction was about 10 %, which explains the small change of MTF and SNR shown in this study.

Finally, an object image reconstructed by the proposed method is shown in figure 7. To see its applicability in the industrial field, x-ray images of small industrial subjects, such as screws, springs and chips were acquired [5, 6]. In the curved parts of the spring, the image corrected by the proposed method was smoother, and the structure of the chip was also displayed more clearly.

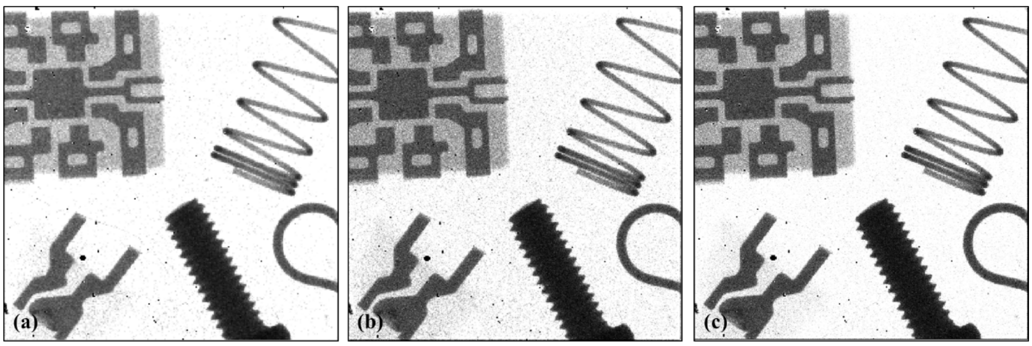

Figure 7. Image of various electric components and parts: (a) original image, (b) 2×2 sub-pixel image, and (c) 3×3 sub-pixel image.

4 Conclusion

In this study, since the probability value of every subpixel was calculated, blurring was inevitable in the image. However, through the minimization of data loss, the sub-pixels were divided into smaller sizes to overcome the image blurring, and thus we showed that it is possible to obtain an image with improved spatial resolution by a factor of four.

In the results reported in section 3, the measured spatial resolution was 60 to 70 µm. This resolution is sufficient to capture images of approximately 250 µm of objects. Therefore, it is suitable to

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use the proposed method in the industrial field rather than the medical field. In particular, it is considered very suitable for inspecting the bonding state of PCBs and chips or inspecting circuit patterns.

By using the charge summing method and center-of-mass method, the image quality can be improved proportionally with increasing number of image frames. In the proposed method case, image quality will not be effective after reaching a certain saturation point even if the number of images increases. However, the image quality was better than the conventional method under the condition of short acquisition time and low number of image frames. In a real environment, it is impossible to take an infinite image and it is necessary to acquire a fewer images within a short period of time. Therefore, we can say that the proposed method yielded a better performance in a real environment than that of the previous methods.

Acknowledgments

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