A Method to Increase the Spatial Resolution at a Photon-Counting Detector under Charge Sharing

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***Abstract* - Charge sharing limits further improvement of the spatial resolution at photon-counting sensors, have the pixel size under 100 um, because the charge cloud generated by a single X-ray photon can induce multiple counts in not only a dedicated pixel but also adjacent pixels. Charge sharing increases abruptly, as the pixel size decreases below 100 um. In this work, instead of reducing the pixel size affected by charge sharing severely, we propose a modified pixel shift technology (PST) for photon-counting detectors to improve the spatial resolution without the reduced pixel size. To verify the PST, MTF were performed with a designed chip. However, the chip was not operated perfectly for the image acquisition. Therefore, the commercial detector was used to verify the proposed idea. This study provides an alternative method to achieve improve spatial resolution without reduction of pixel size, when photon-counting detectors suffer from charge sharing.**

I. INTRODUCTION

Since the discovery of X-rays in 1895 by C. Roentgen, X-ray imaging techniques have been widely developed from the early film-based system. Digital imaging systems have replaced film-based systems because of their advantages including easy storage, searching, sharing of images, and diverse image processing [1]. In contrast, the achievable spatial resolution with digital systems is low compared to film-based systems [2].

A photon-counting detector, which has the high spatial resolution, was proposed two decades ago in the digital detector field [3]. It can also counts not only the number of incident X-ray photons but also energy with comparators, have each threshold voltages. And it can acquire a noiseless image with the threshold above the noise level [4].

The increase of the spatial resolution can be achieved through the reducing the pixel size in the photon-counting detectors. However, charge sharing limits further increase of the spatial resolution when the pixel size is reduced below 100 um, as shown in Fig. 1 [5, 6].

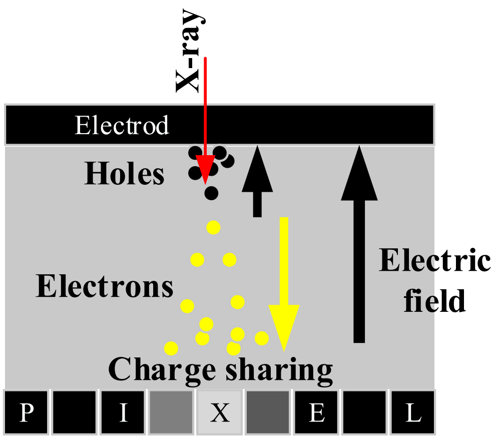

Fig. 1. Charge sharing in a photon-counting detector.

Mutual repulsion causes charges to spread transversally during drift toward the dedicated pixel [7]. The charge cloud finally reaches other pixels instead of a single pixel. The interference by charge sharing, between a dedicated pixel and adjacent pixels, worsens the spatial resolution and the detector consequently loses object information.

A region affected by charge sharing at adjacent pixels with black and pixel area with white are shown in Fig. 2. (a). The area by charge sharing to pixel area ratio (ACPAR) dramatically increases as the pixel size is reduced below 100 um. Fig. 2 (b) represents the ACPAR when the effective diameter of charge sharing is 30 um, measured at Medipix 2 with 1mm CdTe, 60 keV X-ray peak energy, and -300 V bias. The ACPAR is about 3.5 at the pixel size of 25 um whereas the ACPAR presents a value of about 1.3 at the pixel size of 55 um in Fig. 2. (b). This means that further improvement of spatial resolution is limited by charge sharing from the pixel size below 55 um. Furthermore, a fine process is required to implement the same functionality in the reduced pixel area. It increases the process cost for manufacturing a detector.

A number of studies have been carried out in efforts to minimize charge sharing [5, 8, 9]. However, these studies verified that charge sharing is an inevitable effect even at high bias voltage as the pixel size is reduced below few micrometer. Charge summing mode or time-over-threshold

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(ToT) mode was used to correct charge sharing in other studies through circuit [10, 11]. A sophisticated circuit design and additional power consumption are required for these implementations.

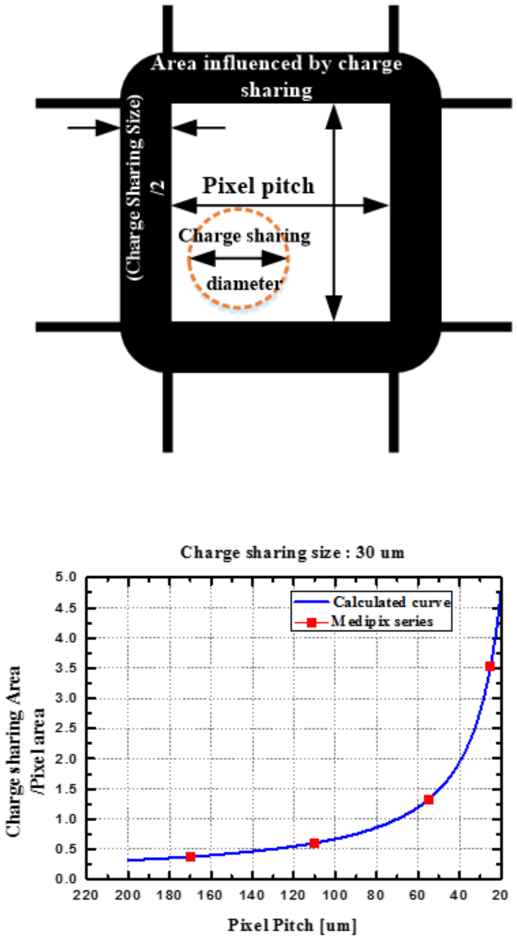


Fig. 2. The influenced region by charge sharing at a pixel (a) and the ACPAR when the diameter of charge sharing is 30 um with pixel size of 55 um.

In contrast, in this study we propose modified pixel shift technology (PST) for the photon-counting detector because further reduction of the pixel size is vulnerable to charge sharing. The modified PST increases the spatial resolution without reducing the pixel size or requiring an additional circuit. The spatial resolution was compared through modulation transfer function (MTF) when the proposed PST was applied. This study provides an alternative method to increase the spatial resolution without redesigning the detector, when further increase of spatial resolution through pixel size reduction is limited by charge sharing.

II. EXPERIMENTS

A. Propose method

An image using detector I has a 3 x 3 array with a 55 um pixel square and an image using detector II has a 6 x 6 array with a 27.5 um pixel square, as shown in Fig. 3. An object, which has one-fourth pixel size, is distinguished clearly in the image with detector II, whereas the information of the object is lost at the image with detector I. Additional increase of the spatial resolution is limited by charge sharing, even though the pixel size is reduced further.

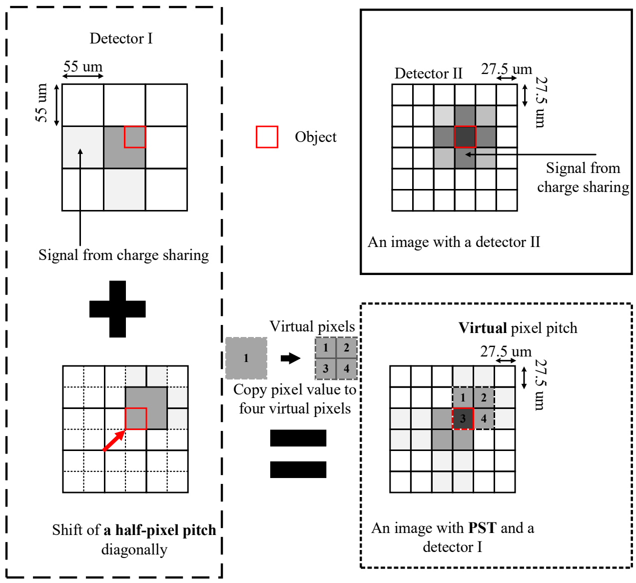
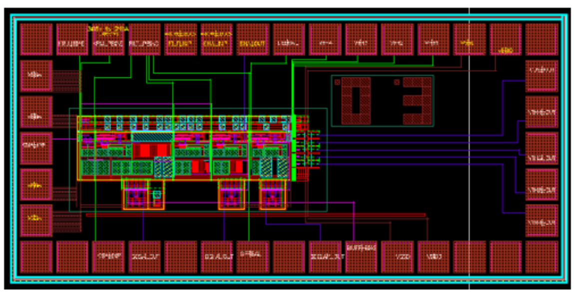


Fig. 3. The reconstructed image with proposed 2-movement PST using detector I and the image with detector II with half-pixel size.

The proposed method provides an alternative to increase the spatial resolution without reducing pixel size. The proposed PST method requires two taken images, as shown in Fig. 3 with a dashed box; one is an image taken conventionally with detector I and the other is an image taken with detector I and shift of a half-pixel size (right- and up- shift 27.5 um) diagonally. Both images are less affected by charge sharing than the image using detector II because of a four times greater pixel area. To acquire a final image with application of the PST, both images are reshaped from a 3 x 3 array to a 6 x 6 array by simply copying each pixel value to four virtual pixels. Finally, both 6 x 6 array images are simply summed, as depicted in Fig. 3 in the small dotted box. The object information with an additional signal around the object can be reconstructed by applying PST to detector I. This shows that spatial resolution of detector I is increased without reduction of the pixel size. The PST is an alternative method for the small pixel size in photon-counting detector to increase the spatial resolution without the redesigning the detector for small pixels.

For the verification of the proposed method, the photon-counting chip was designed. Fig. 4 shows the designed a photon-counting pixel and a PCB for the chip.



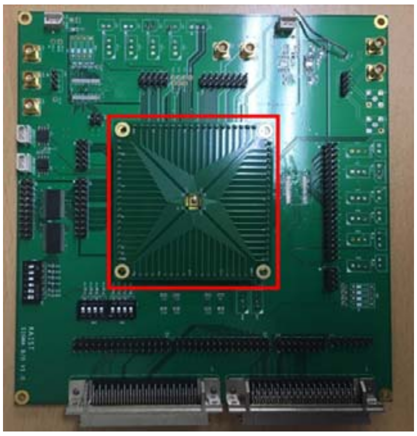


Fig. 4. The designed photon-counting pixel and the PCB.

However, the chip was not operated perfectly. The commercial Medipix 2 detector was used with -300V detector bias voltage and bump bonded to 1mm CdTe.

The diagonal shift distance was changed to find the optimum value in the PST while maintaining the total X-ray flux at summed PST images. The distance is obtained through the pixel size divided by two, three, four, and five (2-, 3-, 4-, 5-movement), respectively. For example, a 3-movement PST image was reconstructed from three taken images. The first image is taken with an object in an arbitrary position. The second image is taken with 18.3 um shift of the object along both x- and y-axis. The third image is taken with a 36.6 um shift of the object toward the x-and y-axis when the pixel size is 55 um. These three images are summed after a reshaping process. To maintain the same X-ray flux for a PST image, the X-ray flux is evenly distributed for each movement.

B. Experiment setup

The X-ray, generated by a tungsten target with a 60 kVp X-ray tube voltage and filtered by an additional 3mm Al, was used for the test. A line phantom was placed 59 cm away from the X-ray source. The photon-counting detector is positioned at 60 cm from the X-ray tube, as shown in Fig. 5.

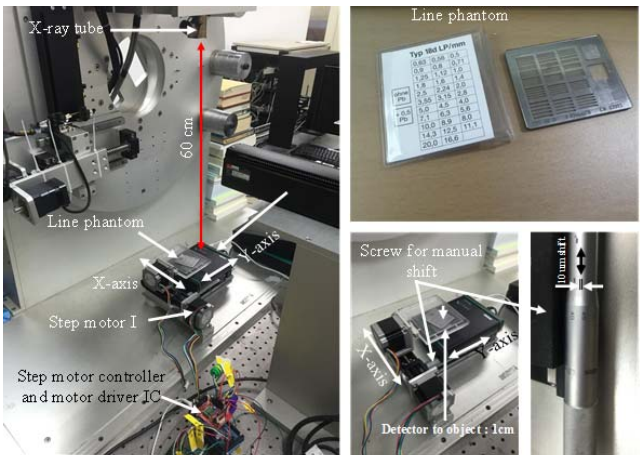


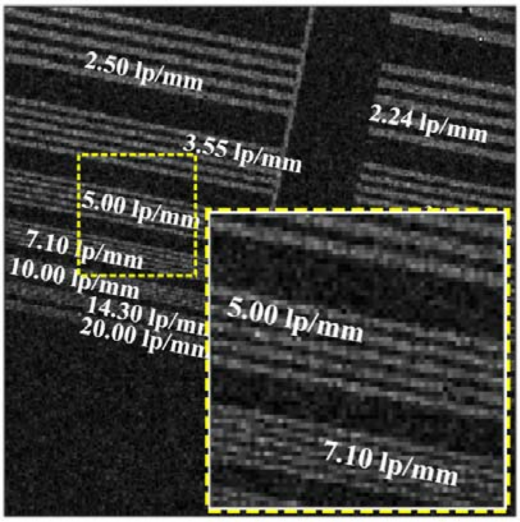
Figure 5. The setup for experiment. Right upper picture represents the line phantom used for MTF. Both right bottom images show implementation for x- and y-axis shift of the detector and magnified screw image to adjust y-axis shift control by hand.

MTF using a line phantom, which was consisted of line pairs from 0.5 to 20 line pairs/mm, was used for comparison of the spatial resolution. The line phantom was composed of PMMA for the body and Pb for line pairs. The line phantom has 2 mm and 0.03 mm thickness for the body and lines. Sophisticated control for shift was required in the scale of micrometer in order to apply the PST. The shift in the micrometer scale along to y-axis was possible with a manual screw along y-axis rail under the plate, as shown in Fig. 5. In the case of movement toward x-axis, the step motor was utilized instead of plate with manual adjustment. A minimum-adjustable distance in using the step motor was 5 um. The control signal for the step motor was generated by the Arduino (due) and supplied through the step motor driver.

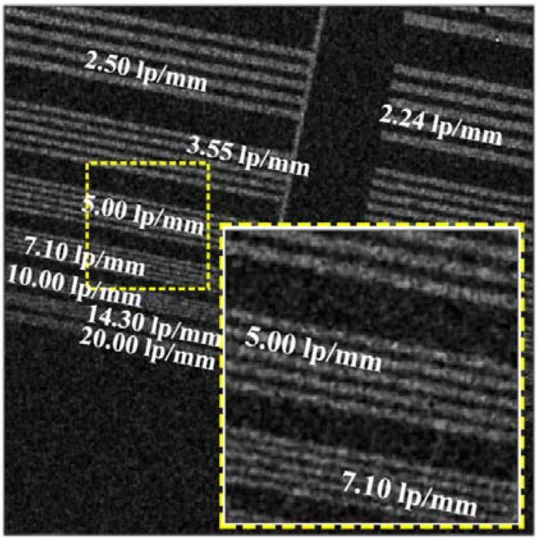
MTF represents the spatial frequency resolution of an image system and how well the object is transferred through the image system in a given spatial frequency. The unit for MTF is line pairs per mm (lp/mm). The concepts of MTF have been explained in detail [12]. In this study, the same spectrum was used for simulation to acquire simulation image with a 27.5 um pixel image and charge sharing, because a detector with a 27.5 um pixel does not exist as control group. The size of 30 um, a representative value of charge sharing was considered for the simplicity of the simulation, even though, the size of the charge sharing depends on the energy.

III. RESULTS AND DISCUSSION

The X-ray line-phantom images and magnified images of the 5.00 and 7.10 lp/mm region are shown in Fig. 6. The line pairs with the 55 um pixel detector was not distinguishable from 7.10 lp/mm. However, visibility of the line pairs with the 55 um pixel detector applied 2-movement PST increased dramatically, as shown in Fig. 6. To compare the spatial resolution performance, MTF was calculated using the acquired images. The results of MTF are summarized in Fig. 7.



(a)



(b)

Fig. 6. The photon-counting image without the PST (a), and image with 2-movement PST (b)

A threshold voltage to reject the scattered X-ray and noise was selected 10 keV. MTF with 55 um pixel was 0.3 at 7.00 lp/mm with the voltage of 10 keV. MTF applied the 2-movement PST with the 55 um pixel showed 0.3 at 10.00 lp/mm and it converged as the number of the PST movements increased at the same threshold due to charge sharing. MTF with 27.5 um pixel and 10 keV threshold showed 0.3 at 13 lp/mm. MTF applying the 2-movement PST increases dramatically but it could not reach the MTF with the 27.5 um pixel at the same threshold voltage and total X-ray flux. Nevertheless, it represented 42% increase of the spatial resolution from 7.00 lp/mm to 10.00 lp/mm without a detector change. The charge sharing limited further improvement of the performance at the spatial resolution, when the number of the movement of the PST increased.

A threshold voltage to reject the scattered X-ray and noise was changed from 10 keV to 30 keV with a 10 keV step. MTF with 55 um pixel was 0.3 at 7.00 lp/mm with the voltage of 10 keV. MTF applied the 2-movement PST with the 55 um pixel showed 0.3 at 10.00 lp/mm and it converged as the number of the PST movements increased at the same threshold due to charge sharing. MTF with 27.5 um pixel and 10 keV threshold showed 0.3 at 13 lp/mm. MTF appling the 2-movement PST increases dramatically but it could not reach the MTF with the 27.5 um pixel at the same threshold voltage and total X-ray flux. Nevertheless, it represented an 42% increase of the spatial resolution from 7.00 lp/mm to 10.00 lp/mm without a detector change. The charge sharing limited futher improvement of the performance at the spatial resolution, when the number of the movement of the PST increased. MTF were also improved slightly as the threshold voltage increases from 10 KeV to 30 KeV.

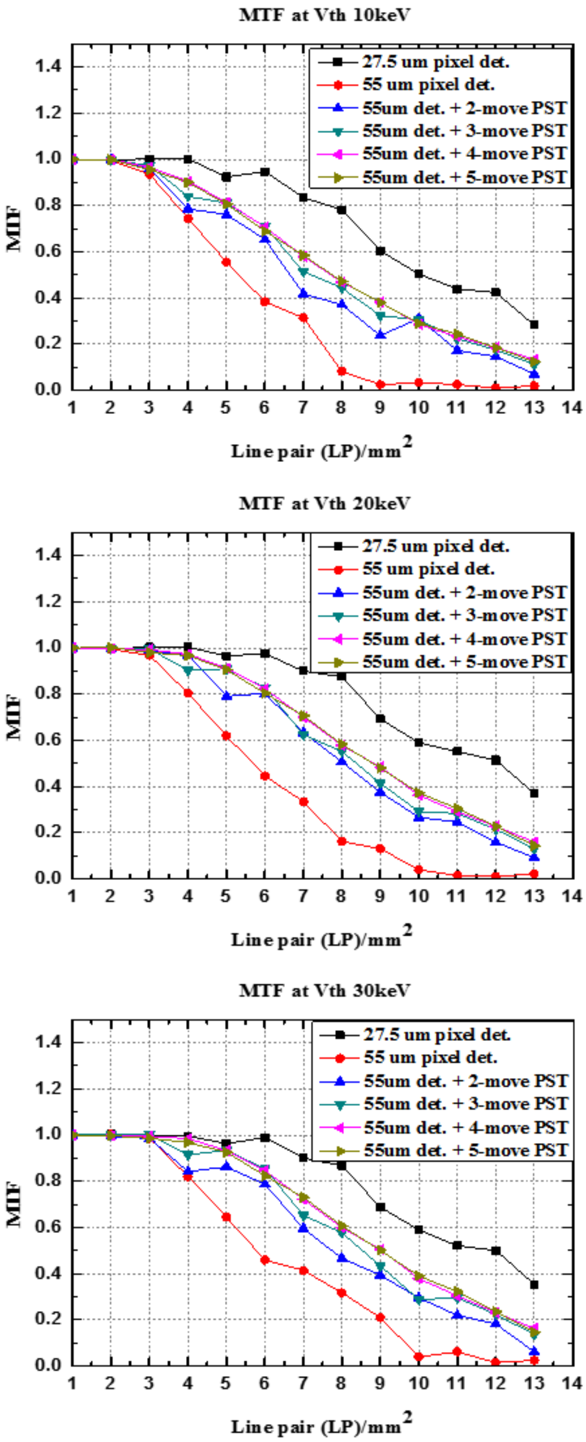


Fig. 7. The measured MTF result with different threshold voltages.

An image with a bolt, a nut, a pin, and a pcb prover is shown in Fig. 8. All images are taken with the equivalent setup as Fig. 5 at the threshold of the 10 keV, and the X-ray tube voltage of 60 kVp. For the comparision between real acquired images, a 110 um pixel image and the same image, applying 55 um shift diagonally, are acquired using XRI-UNO detector at the Medipix mode and simply summing each four 55 um pixels. The 2-movement PST image, has a virtual pixel size of 55 um, are processed using those images. The image applied the 2-movement PST obviously represented the increased spatial resolution. The triangle shapes at the nut are represented in detail at the 2-movement PST image. In the case of the noise, the background image region in the 55 um pixel image contained more noise than the region at the image applied the 2-movement PST.

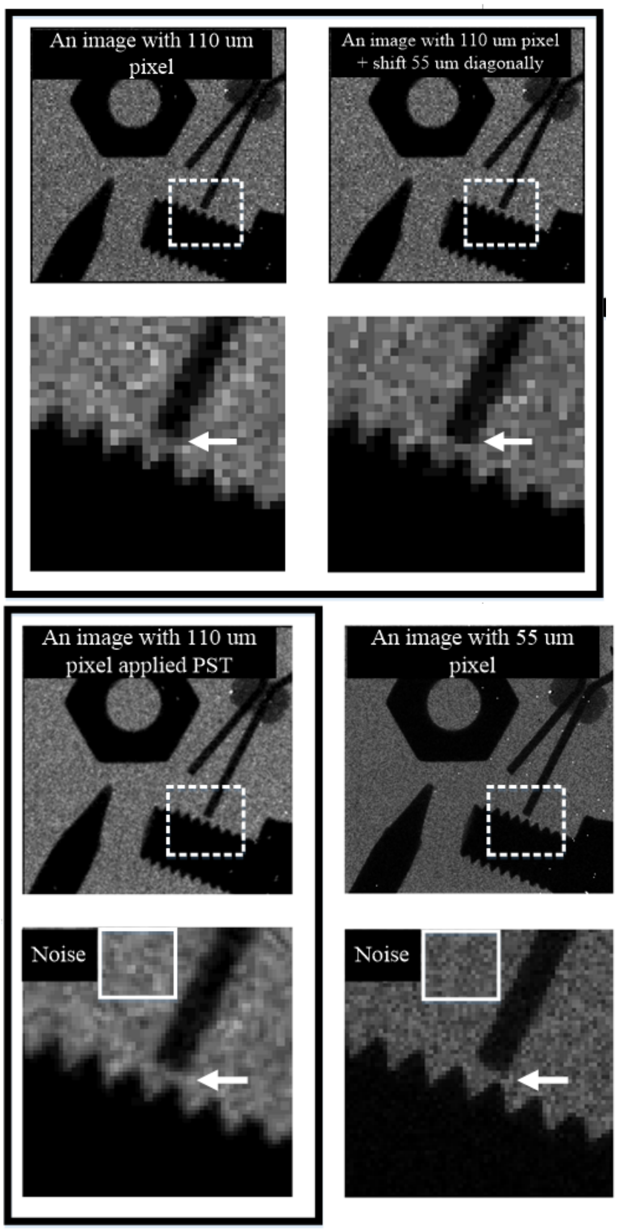


Fig. 8. Two taken images with Medipix2 detector (110 um: 4 pixel bin) and comparison between image applied PST and image with 55 um pixel.

IV. CONCLUSIONS

The photon-counting detector has been developed during the past two decades on the basis of its many advantages, including high X-ray efficiency and low dose image [13]. To increase the spatial resolution, the pixel size should be reduced but it requires a new ASIC design and it induces an increase of the quantum noise. Furthermore, charge sharing degrades achievable image quality corresponding to the reduced pixel size. Therefore, in this study, the PST was proposed for the photon-counting detector to increase the spatial resolution without decreasing the pixel size as an alternative solution. The spatial resolution was investigated through MTF. In addition, 2-, 3-, 4-, and 5-movment PST was applied to find the optimum shift value. The number of movement at PST was saturated after 3-movement PST due to charge sharing. MTF values could not reach the spatial resolution from the simulation result with the 27.5 um pixel size. The PST is a powerful alternative to the photon-counting detector for improving the spatial resolution without a smaller pixel size. Furthermore, pixel size reduction further increases spatial resolution, however, it is limited by charge sharing.

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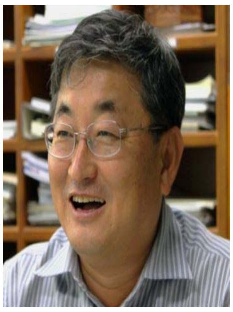

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