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TECHNICAL REPORT

Planar cone-beam computed tomography with a flat-panel detector

S.H. Kim, a D.W. Kim, a H. Youn, b D. Kim, a S. Kam, a H. Jeon b and H.K. Kim c, 1

a School of Mechanical Engineering, Pusan National University, Busandaehak-ro 63beon-gil, Geumjeong-gu, Busan 609-735, South Korea
b Department of Radiation Oncology, Pusan National University Yangsan Hospital, 20, Geumo-ro, Mulgeum-eup, Yangsan-si, Gyeongsangnam-do, South Korea
c School of Mechanical Engineering and the Center for Advanced Medical Engineering Research, Pusan National University, Busandaehak-ro 63beon-gil, Geumjeong-gu, Busan 609-735, South Korea

E-mail: hokyung@pusan.ac.kr

ABSTRACT: For a dedicated x-ray inspection of printed-circuit boards (PCBs), a bench-top planar cone-beam computed tomography (pCT) system with a flat-panel detector has been built in the laboratory. The system adopts the tomosynthesis technique that can produce cross-sectional images parallel to the axis of rotation for a limited angular range. For the optimal operation of the system and further improvement in the next design, we have evaluated imaging performances, such as modulation-transfer function, noise-power spectrum, and noise-equivalent number of quanta. The performances are comparatively evaluated with the conventioonal cone-beam CT (CBCT) acquisition for various scanning angular ranges, applied tube voltages, and geometrical magnification factors. The pCT scan shows a poorer noise performance than the conventional CBCT scan because of less number of projection views used for reconstruction. However, the pCT shows a better spatial-resolution performance than the CBCT. Because the image noise can be compensated by an elevated exposure level during scanning, the pCT can be a useful modality for the PCB inspection that requires higher spatial-resolution performance.

KEYWORDS: Computerized Tomography (CT) and Computed Radiography (CR); Inspection with x-rays

1 Corresponding author.
1 Introduction

To accommodate high-density device integration at a tiny chip level, circuit line densities in electronic packages are also increasing, hence demanding an increase in package-to-board interconnection density [1]. For the reliability of multilayer printed-circuit boards (PCBs) with electronic chips, therefore, their quality controls are essential by investigating any flaws, such as disconnections, voids, impurities, etc., which can cause electrical malfunction.

Traditional visual inspection cannot work any more for this purpose [1]. Instead it can be an alternative to use x-ray as the probe to look inside of electronic package-PCB systems [2–4]. Simple x-ray projection method however may suffer from less conspicuity of defects in images because a 3D object onto a 2D image can hide the defects. X-ray cone-beam computed tomography (CBCT) can overcome the conspicuity issue because of its space-discriminating capability. For such a reason, the use of CBCT is being widely spread to the industrial nondestructive testing and evaluation (NDT&E) including quality control of products [5]. For the PCB inspection, however, the typical CBCT scanning is impractical because of its thin slab geometry [6–8].

For the dedicated PCB inspection, the authors have developed a bench-top ‘planar’ CBCT (pCT) system, which adopts the ‘tomosynthesis’ technique that can produce cross-sectional images parallel to the axis of rotation for a limited angular range [9]. Although the applications of the digital tomosynthesis technique to industry have been reported, there has been little work on the quantitative evaluation of imaging performances of the industrial tomosynthesis technique. In this study, we evaluate the imaging performances of the pCT system. The imaging performance includes the modulation-transfer function (MTF), the noise-power spectrum (NPS), and the noise-equivalent number of quanta (NEQ). This work will be very helpful to the system design and improve specific imaging/NDT&E task quality of multilayer PCBs.
2 Materials and methods

2.1 The bench-top pCT system

As shown in figure 1(a), a miniaturized volumetric CT system with a flat-panel detector (FPD) was realized on an optical bench. During continuous x-ray irradiation, the object rotates on its axis by an amount of prescribed step angle and then the rotation stays until the FPD produces a projection image. Those motion and image readout were computer-controlled and lasted till the circular scan with a prescribed angular range completed. The distances from the x-ray focal spot to the FPD ($d_{SD}$) and from the focal spot to the axis of rotation ($d_{SA}$) were computer-controlled variables.

The FPD (Shad-o-Box 1548 HS, Teledyne Rad-icon Imaging Corp., Sunnyvale, CA) used a Gd$_2$O$_2$:Tb-based phosphor ($\sim$68 mg cm$^{-2}$) for x-ray detection, and the optical photons from the phosphor were detected by a photodiode array made by complementary metal-oxide-semiconductor (CMOS) process. The CMOS photodiode had 0.099-mm sized pixels arranged in a 1548 $\times$ 1032 format. The maximum frame rate for reading out x-ray images was 20 frames per second (fps).

The x-ray source (Series 5000 XTF5011, Oxford Instruments, Inc., U.S.A.) employed a tungsten anode and could operate up to the maximum power of 50 Watts. A 1-mm thick aluminum sheet was placed close at the beam exit of x-ray tube to mimic the x-ray beam attenuation through a PCB layer. According to the manufacturer, the nominal focal-spot size was 0.035 mm.

Lauritsch and Haerer approach [10] was adopted for pCT reconstruction. The reconstruction algorithm was a modified version of Feldkamp’s CBCT algorithm [11] with the ramp filter. It employed the Hanning window function as the ‘spectral filter’ to reduce high-frequency noise. An additional filtering operation was considered to suppress the frequency response of the out-of-plane blurred structures due to incomplete sampling over the limited angular range [12, 13]. The application direction of the additional filter is perpendicular to the cross-sectional images obtained from the pCT [i.e., the y-axis direction as designated in figure 1(a)]; hence the filter is called the ‘slice thickness filter.’ This filter controls aliasing in the y-axis direction, thus it can make the ‘in-plane’ MTF phase independent [14].

Figure 1. (a) A picture showing the volumetric computed tomography system realized on an optical bench. (b) Water and wire phantoms used for the measurements of NPS and MTF, respectively.
2.2 Measurement and analysis methods

Imaging performances of the system were measured for diverse imaging conditions: 30-120° for the scanning angles, 40-50 kVp for the applied tube voltages, and 1.5-2.5 for the magnification factors. X-ray projections were acquired at every step angle of 1° and at the detector frame rate of 5 fps. All the measurements were performed at a fixed $d_{SD}$ of 656 mm, and thus the magnification factor was determined by varying $d_{SA}$. The CBCT acquisition with the 360° angular scan was also considered for comparison.

For the MTF measurements, a commercial tungsten-wire phantom (QRM-MircoCT-Wire, QRM GmbH, Germany) with a diameter of 0.025 mm was used, as shown in figure 1(b). While the slit-like image was directly reconstructed from the pCT acquisition, the CBCT slit-like image was obtained by applying the Radon transformation to the volumetric wire image reconstructed from the CBCT (i.e., integrating along either the x or y axis). The MTFs were obtained by applying the Fourier transformations to the line-spread functions (LSFs) extracted from the slit-like images. Because the wire was suspended within the phantom cylinder with a small angulation (3°) to the vertical line, the LSFs were highly sampled, hence resulting in aliasing-free MTFs.

For the NPS measurements, a commercial water cylinder phantom (QRM-MircoCT-Water, QRM GmbH, Germany) with a diameter of 33 mm and a height of 66 mm [see figure 1(b)] was used. The water phantom was laid down at a 90° angle on the object holder during the pCT acquisition to obtain the same directional cross-sectional images as the CBCT acquisition. More than 10 of volumes of interest (VOIs) sampled from the reconstructed water phantom were analyzed for the NPS evaluation using the 3D Fourier transform (for zero-mean realizations). The numbers of voxels consisting of the VOIs were 80 $\times$ 80 $\times$ 80 and 50 $\times$ 50 $\times$ 50 voxels for the CBCT and pCT, respectively. The NEQ was calculated by [15]

$$NEQ(u, v, w) = \theta f \frac{MTF^2(u, v, w)}{NPS(u, v, w)},$$

where $\theta$ is the scan angular range and the factor $\theta f$ accounts for radial sampling density. $u$, $v$, and $w$ are the spatial-frequency variables corresponding to the $x$, $y$, and $z$ spatial variables, thus, $f = \sqrt{u^2 + v^2 + w^2}$.

3 Results

Slit-like images obtained for the wire phantom using the CBCT and pCT acquisitions are shown in figure 2. Their corresponding LSFs are also shown in figure 2. While the CBCT-LSF showed a typical Gaussian shape, the pCT-LSF showed the broad undershoot relative to baseline occurring on both sides that was a characteristic of a processed impulse response [16]. Therefore, the pCT-LSF reflected the edge enhancement associated with the filter function used for reconstruction [17]. It was observed that the width of pCT-LSF was narrower than that of CBCT-LSF.

Figure 3 summarizes the MTF, NPS, and NEQ performances for various scan angle ranges. The results were obtained at the magnification factor of 2 and the applied tube voltage of 40 kVp. The pCT-MTF is normalized to 1.0 at the maximum value because the zero-frequency response after reconstruction is not always the highest [17–19]. Although the pCT-MTF slowly moved to the CBCT-MTF (i.e., 360° angular scan) with increasing scan angle, as shown in figure 3(a), the
Figure 2. Slit-like images obtained for wire phantom using the (a) CBCT and (b) pCT acquisitions, and (c) their corresponding line-spread functions.

Figure 3. The Fourier-based metrics of tomography obtained for various scan angle ranges: (a) MTF, (b) NPS, and (c) NEQ, where $f = \sqrt{u^2 + v^2}$. For comparison, the ideal MTF, which is the detector MTF only considering geometrical magnification, is included in (a).

pCT-MTF performance outperformed the CBCT-MTF for the spatial frequencies greater than $\sim 1$ mm$^{-1}$. For comparison, the ideal MTF, which is the detector MTF only accounting for geometrical magnification, is also plotted in figure 3(a). On the other hand, the pCT-NPS performance was rapidly enhanced with increasing scan angle, as shown in figure 3(b), because of the increase in the number of projection views used for reconstruction. These MTF and NPS characteristics were well reflected into the NEQ performance as shown in figure 3(c), and the CBCT-NEQ outperformed the pCT-NEQ.

The dependencies of imaging performances on the kVp are shown in figure 4. The results were obtained at the magnification factor of 2, and the scan angle for pCT was 120°. Both the CBCT and pCT MTFs were independent of kVp, as shown in figure 4(a). On the other hand, the NPSs were degraded with increasing kVp, as shown in figure 4(b), because the number of detected x-ray photons lessened at higher kVp (i.e., lower quantum efficiency of the phosphor at higher kVp). Therefore, the NPS dominated the the NEQ performances, as shown in figure 4(c); the NEQ was degraded as the kVp was increased.
Figure 4. The Fourier-based metrics of tomography obtained for various applied tube voltages: (a) MTF, (b) NPS, and (c) NEQ, where $f = \sqrt{u^2 + v^2}$.

Figure 5. The Fourier-based metrics of tomography obtained for various magnification ratios: (a) MTF, (b) NPS, and (c) NEQ, where $f = \sqrt{u^2 + v^2}$.

The geometric dependencies of imaging performances are shown in figure 5. The results were obtained at 40 kVp, and the scan angle for pCT was 120°. As expected, the MTF was improved with increasing magnification, as shown in figure 5(a). Those MTF changes according to magnification affected the NPS bandwidths; the bandwidth broadened with increasing magnification, as shown in figure 5(b). In contrast, the noise-power spectral densities were slightly decreased with increasing magnification. Because magnification was applied with the fixed $d_{SD}$, variation in the number of ‘primary’ x-ray photons reaching the detector was insensitive to changes in magnification. However, the number of x-ray photons ‘scattered’ from the water phantom would decrease with increasing magnification. The scattered x-ray photons are typically known to contribute to image signal as an additional noise, hence the NPS may be improved with increasing magnification at a fixed $d_{SD}$. The enhancements in MTF and NPS at higher magnification was well reflected into the NEQ performances, as shown in figure 5(c).

4 Discussion

In this study, the image reconstruction for pCT is based on the filtered backprojection (FBP), and the negative side lobes in the pCT-LSF are the result of the edge-enhancement features of the filter function used for FBP reconstruction in limited angular scan. The convolution kernel, which corresponds to the Fourier pair of the standard ramp filter, shows the negative side lobes in the space domain. In addition, the limited angular scan partially fills the spatial-frequency information in the Fourier domain. Therefore, loss of low-frequency information is inevitable and the filter
function enhances mid-frequency content. The low-frequency drop in pCT-MTF can be recovered by increasing angular scan range [18] and it may disappear with complete data sampling. Otherwise, the statistical iterative image reconstruction, which does not require any filter functions, can provide the pCT-MTF without low-frequency drop in limited angular scan [20]. The authors note that the aggressive high-pass filtering operation can yield mid-frequency amplification even with complete data sampling [21]. The low-frequency drop in pCT-MTF is known to decrease large-area object contrast in the reconstructed images [14, 20].

The CBCT-MTF shown in this study corresponds to the ‘axial’ plane MTF. This axial MTF performance is typically worse than the orthogonal plane or ‘longitudinal’ MTF performance. The longitudinal MTF is governed by the interpolation kernel and detector MTF, whereas the axial MTF is further affected by the additional reconstruction filter which is applied to the projection data along the \(x\)-axis direction as designated in figure 1(a) [15, 22]. On the other hand, the pCT-MTF shown in this study corresponds to the ‘in-plane’ MTF; hence the ‘in-depth’ MTF at the orthogonal plane. The characteristics of the in-depth MTF are governed by the angular range of acquisition. The depth resolution decreases with decreasing angular range, resulting in more pronounced smearing of the in-plane feature along the depth of the reconstruction volume [23]. Demonstration volume-rendered and depth-directional pCT images of PCBs for a wide range of scan angles can be found in previous studies [9, 12]. Future work may quantitatively examine the MTF performances at both orthogonal planes in CBCT and pCT that have not shown in this study.

5 Conclusions

The authors have observed that in this experiment the spatial-resolution performance of the pCT is better than that of the conventional CBCT. On the other hand, the CBCT outperforms the pCT in the noise performance, and the CBCT shows better image quality in terms of the number of Poisson-distributed quanta (i.e., NEQ) than the pCT. X-ray exposure in industrial imaging may be of lesser importance compared with that in medical imaging. Therefore, the pCT with a higher exposure, which can compensate image noise, can be a better PCB inspection solution requiring high spatial resolution than the CBCT. To utilize the incident x-ray photon fluence as much as possible in pCT, operation with larger scan angle and higher magnification factor is preferred.

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