An automated sinogram-space ring artifact reduction method in computed tomography

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Abstract
Ring artifacts are very important for the inspection of industrial objects in computed tomography. In many cases, defects appear in the ring artifact region and hamper the automatic inspection process. The ring artifacts will appear if some of the detector cells are not working correctly or completely dead. In this case, correction process is relatively easy because the number of rings in the reconstructed images is not much. Another reason for the ring artifacts is the inhomogeneous detector responsibility in the flat panel detector. If the neighboring detector elements are responding differently in the same condition, ring artifacts will appear as widespread patterns. While many reduction methods have been suggested, they degrade object structures occasionally or do not have much effect for the real world dataset. In this paper, we propose a novel method for automatic ring artifact reduction in sinogram space. By estimating the detector inhomogeneity in the filtered sinogram, this method will work for many real world data with widespread ring artifact patterns.

Keywords: Ring artifact reduction, Industrial computed tomography, Detector inhomogeneity correction, Sinogram-space method.

1 Introduction
Ring artifact occurs often especially in the industrial computed tomography (CT). When the ring artifact appears, it severely degrades the image quality, disturbing the inspection process. Especially during the porosity inspection of aluminum casting parts, ring artifacts over the inspection region can cause wrong classification result.

The ring artifacts will appear if some of the detector cells are not working correctly or completely dead. In this case, correction process is relatively easy because the number of rings in the reconstructed images is not much. Another reason for the ring artifacts is the inhomogeneous detector responsibility. If the neighboring detector elements are responding differently to the same material in the same X-ray intensity, ring artifacts will appear in the reconstructed images as widespread patterns.

There are many efforts to reduce the ring artifacts and one of the major approach is the image space method. In this approach, reconstruction images are generated first, and then ring artifacts are reduced in the image space. In [1], the reconstructed images are transformed to the polar coordinate, and the line removal filters will be applied in the polar coordinate. However, this approach often degrades object details during the line removal or in the coordinate transformation process.

Another major approach is the sinogram space method. In this method, defected detector elements are located as lines in the sinogram space. Then those lines are removed by using moving average or median filter [2]. But this method can also degrade object structures during the averaging process and only applicable when small number of detector elements shows abnormality.

Recently, line-ratio based correction method has been suggested for the widespread ring artifact patterns [3]. This method has shown impressive results without loss of object structures. However, it uses non-filtered sinogram for its line-ratio calculation. It can be less effective for many real cases where the detector inhomogeneities are not very distinct in the non-filtered sinogram.

In this paper, we propose a novel method for automatic ring artifact reduction in filtered sinogram space. By estimating the detector inhomogeneity values in the filtered sinogram space, this method will work for many real world data with widespread ring artifact patterns.

2 Detector Inhomogeneities in Sinogram Space
In this paper, ring artifacts will be corrected in the sinogram space. A sinogram is formed by stacking rows from projection images of every rotation angle. If the resolution of detector is W x H and the number of projection images is N, there will be H sinogram images and single sinogram image has W x N resolution. Since each column of a sinogram contains values from a single detector cell, detector defects will appear as vertical lines in the sinogram image.

In [4], all columns of a sinogram is summed in column direction and correction values for detector inhomogeneities are estimated by mean or median smoothing of those summed values in row direction. It shows good results for widespread ring artifact patterns, but only when detector inhomogeneities are observed in the original, non-filtered sinogram. If the sensitivity difference of detector cells is not distinct in the original sinogram, the amount of correction is small.
In the line-ratio method, they also use non-filtered sinogram for the line-ratio calculation. However, we observe that many real world datasets show very weak detector sensitivity difference in the original sinogram and not easy to extract detector inhomogeneity values. In the filtered sinogram, however, sensitivity difference appears more clearly as vertical lines (Figure 1).

![Figure 1: (a) original (non-filtered) sinogram, (b) filtered sinogram.](image)

In [2], they used filtered sinogram to locate the defective columns. But they focused on correcting relatively small number of non-continuous defect columns, their method is not appropriate for the widespread ring patterns. In our method, detector inhomogeneities will be estimated for every column of the filtered sinogram. By the direct inhomogeneity estimation from the filtered sinogram, widespread ring artifact patterns can be reduced efficiently even when sensitivity difference appears weak in the original sinogram.

### 3 Methods

Figure 1 shows the overall ring artifact reduction procedure proposed in this paper. The automated ring artifact reduction process is composed of four steps. First, subset columns which contain object region are selected. Second, median values are calculated for each column of the filtered sinogram. Third, bias values for each sinogram column are estimated using 1D average filter. Finally, the sinogram is corrected by median and bias values.

![Figure 2: Flow diagram of ring artifact reduction procedure.](image)

#### 3.1 Detector Inhomogeneity Estimation

To estimate detector elements inhomogeneity directly from projection images, the projection images are transformed to sinogram space. If one detector element shows inhomogeneity from its neighboring element, that column will be shown up as a bright or dark vertical line in sinogram image (see Figure 1 (b)). These detector inhomogeneities can be modelled as following equation when assuming detector cell error $E$ is additive [4]:

$$ D(t, \emptyset) = F(t, \emptyset) + E(t) $$

(1)
where $D$ is the distorted sinogram data, $F$ is the ideal sinogram with homogeneous sensitivities, $E$ is the detector cell error from the inhomogeneous response, $t$ refers to detector cell location in the horizontal direction and $\emptyset$ represents the projection angle.

Inhomogeneity of detector elements can be estimated by finding median values along each column in the filtered sinogram (Figure 3. (a)). These median values construct 1D array in the row direction. However, columns near both boundaries can have many air pixels whose values are already saturated, causing the columns not appropriate for inhomogeneity estimation. Air pixels can be found as maximum detector brightness in the non-filtered sinogram and only the columns which have less than 50% of air pixels will be corrected in the next step.

### 3.2 Sinogram Correction

Now, sinogram is corrected for each column using 1D median value array. A median value will be subtracted from all the column elements at the current detector location. Then, the column elements should be adjusted back to the original range because the median value of the column elements is modified to zero during the subtraction. Bias values for each column are calculated by applying average filter to the 1D median value array. These bias values are added back to the subtracted results. Finally, the corrected sinograms are obtained after repeating the above process for all filtered sinograms.

The detector cell error $E$ in Eq. (1) can be expressed below:

$$E(t) = Inhomogeneity(\emptyset) - Bias(\emptyset)$$

Where ‘Inhomogeneity’ refers to 1D median array which is estimated in 3.1 and ‘Bias’ refers to smoothed version of the array. Corrected sinogram $\tilde{F}(t, \emptyset)$ is obtained by subtracting $E(t)$ from the distorted filtered sinogram $D(t, \emptyset)$. Figure 3 (a) shows the plot of estimated inhomogeneity 1D array for the distorted sinogram $D(t, \emptyset)$ and Figure 3 (b) shows estimated inhomogeneity 1D array for the corrected sinogram $\tilde{F}(t, \emptyset)$. Corrections are applied only in the region from $t=100$~$400$ where the air pixels’ ratio is over about 50%.

![Figure 3: (a) estimated inhomogeneity for $D(t, \emptyset)$, (b) estimated inhomogeneity for $\tilde{F}(t, \emptyset)$](image)

Figure 4 shows original filtered sinogram $D(t, \emptyset)$ and corrected filtered sinogram $\tilde{F}(t, \emptyset)$.

![Figure 4: (a) original filtered sinogram, (b) corrected filtered sinogram](image)
In Figure 4 (b), the dark and bright vertical column lines are disappeared effectively after the inhomogeneity correction.

4 Experimental Results

Figure 5 shows one cross section of reconstructed volume after the back-projection of the physical phantom object as in Figure 4. Ring artifacts in the center of the object are reduced efficiently without the loss of the object structures. Standard deviation values along each horizontal center line are 387.27 (a) and 269.03 (b).

![Figure 5: Reconstructed slice (a) without correction and (b) with proposed ring artifact reduction method.](image)

Figure 6 and 7 show another examples of aluminum casting parts which have porosity defects. In both cases, ring artifact patterns over the porosity region are reduced effectively.

![Figure 6: Reconstructed slice (a) without correction and (b) with proposed ring artifact reduction method.](image)

![Figure 7: Reconstructed slice (a) without correction and (b) with proposed ring artifact reduction method.](image)
Figure 8 shows the ring artifact reduction result of rock specimens using the proposed method. In Figure 8 (a), ring artifact patterns appear as vertical lines near the center column since the reconstructed slices are extracted in the frontal direction. After the artifact reduction process, those ring patterns are reduced while preserving the object structures.

5 Conclusion
In this paper, we propose a novel method for automatic ring artifact reduction in sinogram space. While various reduction methods have been suggested, they often do not show much effect for the real world dataset. Many datasets showed very weak detector sensitivity difference in the original sinogram. By estimating the detector inhomogeneity in the filtered sinogram, proposed method works well for many real world data with widespread ring artifact patterns.

References